Analysis of Labor to Operate Linear Move Irrigation Machines

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SUMMARY

Labor to operate linear move irrigation machines (LMIM) is dependent on several factors: machine, field geometry, pipe networks, hydraulics, operator skill and equipment. A mathematical model that takes into account most of these factors is presented. A time and motion study was carried out to evaluate quantitatively the time required to complete various activities in the operation of LMIM. For moving a linear lateral type fed by a flexible hose, the analysis clearly shows that machine width affects labor consumption significantly.

INTRODUCTION

Several basic types of linear move irrigation machines (LMIM) are used in many localities under a wide variety of conditions. Jensen (1980)

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reviewed the following types: side-roll or wheel-roll, side move with trail-lines and traveling linear laterals. Regarding water supply, LMIM can be equipped with either a traveling pumping plant to take water from a ditch, or with a flexible hose dragged by the LMIM. Other, more complicated, forms of apparatus are also available.

Where labor is a restricted and expensive resource, it becomes one of the major incentives to adopting LMIM and one of the main factors affecting the selection of type and size of LMIM. Labor is a result of several factors: machine type and size, size and topography of the field to be irrigated, hydraulics of the water supply network and operator skill and equipment. The labor activities associated with LMIM are usually applied in the following stages: (1) to move the water supply pipe from one valve to the next, along the travel path (1 in Fig. 1); (2) to move the machine from one row to another while changing its direction of travel (2 in Fig. 1) and (3) to bring the machine to the starting point for a new cycle of irrigation (3 in Fig. 1). An additional stage, the maintenance of LMIM, is carried out once in a season or year, either in the field or in a service location. Not all of the first three operational stages are required for every type of moving irrigation machine. For example, center pivots do not require all of the three operational stages and LMIM equipped with a traveling pumping plant do not require stages 1 and 2.

The objectives of this study were: (a) to analyze systematically the various labor activities carried out during the operation of LMIM and (b) to find the main factors affecting labor consumption, in order to improve decision making and operation of LMIM. The study was limited to one type of LMIM; namely, traveling linear lateral fed by dragged flexible hose, for two reasons: (1) it is very commonly used in many localities and (2) it includes all the operational stages mentioned above. As a consequence, the labor analysis would be the most comprehensive, and can be easily adopted for other, less complicated, LMIM types. (Note: LMIM will be used throughout this paper to represent the traveling linear lateral type of machine.)

Another limitation of the study is that the maintenance stage was not included in the labor analysis, for the following reasons: (a) it includes a wide range of maintenance activities, most of which are not amenable to being analyzed by time and motion techniques; (b) it depends on factors that can neither be related to the field to be irrigated nor to the operating teams and (c) it is executed once in an irrigation season
(usually once a year) and, therefore, is not an operational stage. Therefore, time required for this stage varies widely from several hours to several workdays. Although it might be a significant contribution to the total time per unit area, its time should be evaluated on a local basis.

**MATHEMATICAL MODE**

An irrigation cycle for LMIM usually comprises several stages which differ in their activities, frequency of occurrence and the irrigated area served. Explanation of these stages and definitions of the geometrical factors of the model are given, following Fig. 1.

The basic unit of the field to be irrigated is a plot, the area of which is \( A_p = WL_p \), where \( W \) is the width of both plot and machine and \( L_p \) is the length of the plot. For many machines, \( L_p \) is usually twice the length of the water supply pipe, \( L \), that is continuously dragged on the soil surface by the machine. \( L_p = 2L \) is the maximal length that can be irrigated without operator intervention. The entire field is divided into rows, the width of which is \( W \). The length of the row, \( L_f \), is dependent on field dimensions. Usually, every row includes several plots (4 in Fig. 1). The total length of travel of the machine is \( L_t \) which is the sum of

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**Fig. 1.** Field schematic irrigated by linear move irrigation machine (LMIM).
length of rows. As far as operation goes, three different stages are carried out during the irrigation season. According to their frequencies of occurrence, the stages are as follows. (1) In-row move: water supply pipe is dragged by a tractor from irrigated to successive unirrigated plots. The machine is at the end of an irrigated plot but is ready to start irrigating the next one. The direction of travel is not changed. (2) Inter-row move: machine is to be moved from one row to another and, usually, to change direction of travel. This stage includes stage 1 since water supply pipe has to be moved to another valve. (3) Cycle move: machine is to be moved from the end of the field to the starting point. This stage includes stage 2 and, therefore, stage 1. For several types of LMIM, there is an additional stage. Off-field move: machine is taken out of a field after an irrigation season and is brought back to a field at the start of the next irrigation season (to clear the field of equipment for harvesting and to carry out machine maintenance activities). Other machines, usually the long ones, are left in the field for the next season.

As can be seen from Fig. 1, stage 1 is the most frequent (even several times in a day), stage 2 is usually executed a few times during the irrigation cycle and stage 3, if at all, is executed only once in an irrigation cycle (in some places, stages 2 or 3 are not essential). Consequently, each stage serves different irrigated areas: stage 1 serves the area of a plot, \( A_p \); stage 2 the area of a row, \( A_R = WL_r \); and stage 3 serves the total area, per irrigation cycle \( A_t = WL_t \).

Each of the stages requires a different amount of labor and, as mentioned above, serves a different area. In order to bring labor for all stages to a common denominator, a labor per unit area has been defined; i.e. labor amount required to execute a stage divided by the area it serves. The dimension of this unit is, therefore, h/m². The difference in frequencies between the stages has been taken into account by relating the labor per unit area to an irrigation cycle.

Total labour time required for every stage includes two factors: \( T_d \)—direct time, which is the time during which stages are actually executed in the field, and \( T_i \)—indirect time, which is required to arrive at the machine and to leave it after carrying out the stage. Let \( T_1 \) be the total time per unit area to execute stage 1 during an irrigation cycle, then:

\[
T_1 = N \left( \frac{T_d + T_i}{A_p} \right)
\]  

where \( N \) is the number of times that stage 1 is executed during an irrigation cycle.
Since \( N = \frac{L_t}{L_p} \) and \( A_p = WL_p \), then, from eqn (1):

\[
T_1 = \frac{L_t}{W} \left( \frac{T_d + T_{in}}{L_p^2} \right) \quad (h/m^2)
\] (2)

The same procedure has been applied for stage 2 assuming that the indirect time, \( T_{in} \), is as for stage 1. In order to simplify calculations, the direct time, \( T \), for the second stage, \( T_2(2) \) is related to \( T_d \) of stage 1 by the coefficient, \( K_R \), where \( T_d(2) = K_R T_d \). Since the area served is \( A_r = WL_t \), and the number of times stage 2 is executed is \( \frac{L_t}{L_r} \), then:

\[
T_2 = \frac{L_t}{W} \left( \frac{K_R T_d + T_{in}}{L_r^2} \right) \quad (h/m^2)
\] (3)

The same considerations and procedure for stage 3 yields:

\[
T_3 = \frac{L_t}{W} \left( \frac{K_c T_d + T_{in}}{L_t^2} \right) \quad (h/m^2)
\] (4)

where \( K_c \) is the coefficient relating direct time of stage 3 to that of stage 1: \( T_d(3) = K_c T_d \).

The total time per irrigation cycle per unit area is:

\[
T = T_1 + T_2 + T_3
\] (5)

Substituting eqns (2), (3) and (4) into (5), gives:

\[
T = \frac{L_t}{W} \left( T_d \left( \frac{1}{L_p^2} + \frac{K_R}{L_t^2} + \frac{K_c}{L_t^2} \right) + T_{in} \left( \frac{1}{L_p^2} + \frac{1}{L_t^2} + \frac{1}{L_r^2} \right) \right) \quad (h/m^2)
\] (5(a))

or:

\[
T = \frac{1}{W L_t} \left\{ T_d \left( \left( \frac{L_t}{L_p} \right)^2 + K_R \left( \frac{L_2}{L_t} \right)^2 + K_c \right) + T_{in} \left( \left( \frac{L_t}{L_p} \right)^2 + \left( \frac{L_1}{L_r} \right)^2 + 1 \right) \right\}
\] (5(b))

From eqns 5(a) and 5(b) it is seen that time per unit area decreases with \( WL_t \), which is the irrigated area, and \( L_p \) and \( L_t \), which are the lengths of plots and rows, respectively. Another group of parameters includes \( T_d \), \( T_{in} \), \( K_R \) and \( K_c \). These parameters are related to the operators of LMIM and also are dependent on the type of machine and on the equipment available for moving the water supply pipe.

A method to estimate and analyze the latter parameters and several measured results are presented for two basic types of LMIM: (a) a 72 m width single tower portable machine and (b) a 360 m width multi-tower machine.
TIME ESTIMATION

According to the well known PERT Three-Estimate Approach (Hillier & Lieberman, 1980), three time estimates are required to estimate the average time of every activity. They are:

1. Optimistic time—$T_a$—best or shortest time to complete an activity.
2. Most likely time—$T_m$—time that has greatest probability to complete an activity.
3. Pessimistic time—$T_b$—the worst or longest time for the completion of the activity.

Time is a stochastic variable, which, according to the PERT method, has a probability distribution with the following moments:

Average:

$$T = \frac{1}{3}(2T_m + \frac{1}{2}(T_a + T_b))$$

(6)

and Variance:

$$\sigma_T^2 = (\frac{1}{6}(T_b - T_a))$$

(7)

Time estimation for the various activities of the operational stages was carried out by means of questionnaires distributed to very experienced operators.

The results of the questionnaires are given in Tables 1 and 2 for stages 1 and 2, respectively, for a 72-m linear move irrigation machine. These tables include a list of activities for each stage to be carried out by either a one-man or a two-man team. Table 1 shows that the average time for one man to complete stage 1 (in-row move) according to eqn (6) is 27.38 min with standard deviation $\sigma_T = 3.82$ min (eqn (7)) and coefficient of variation, $CV = \sigma_T/T = 13.94\%$. Two operators completed stage 1 within $8.30 + 10.09 = 18.39$ min with standard deviation of 3.82 min and $CV = 20.75\%$. From Table 2, stage 2, for one man, $T_d = 48.06$ min; $\sigma_T = 6.35$ min; $CV = 13.21\%$; and for a two-man team: $T_d = 34.86$ min; $\sigma_T = 6.35$ min; $CV = 18.22\%$.

The results show that the direct time of a two-man team is shorter than the time required by one man to complete both stages. Also, from
### Table 1

**Time Estimate for Stage 1 (Min)**

<table>
<thead>
<tr>
<th>Activity</th>
<th>1st man</th>
<th>2nd man</th>
<th>1st man</th>
<th>2nd man</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close irrigating valve</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Disconnect main pipe from valve</td>
<td>1.2</td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Disconnect secondary pipe</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Pipe drainage</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Travel to machine</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Wait to drainage</td>
<td>1.9</td>
<td>1.9</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Connect main pipe to tractor</td>
<td>0.5</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Drag tractor</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Travel to machine</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Connect pipe to valve</td>
<td>0.2</td>
<td>0.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Adjust microprocessor</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Open valve</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Operate and control</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Total**

<p>| 18.5 | 26.1 | 41.4 | 27.38 | 5.5 | 7.6 | 13.9 | 8.30 | 4.0 | 9.5 | 18.5 | 10.09 |</p>
<table>
<thead>
<tr>
<th>Activity</th>
<th>1-man team</th>
<th>2-man team</th>
<th>1-man team</th>
<th>2-man team</th>
<th>1-man team</th>
<th>2-man team</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_a$</td>
<td>$T_m$</td>
<td>$T_b$</td>
<td>$T$</td>
<td>$T_a$</td>
<td>$T_m$</td>
</tr>
<tr>
<td>Close irrigating valve</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>0.50</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Disconnect main pipe from valve</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.23</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Tractor to machine</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.00</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Disconnect main pipe from machine</td>
<td>0.2</td>
<td>1.0</td>
<td>3.0</td>
<td>1.20</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Connect main pipe to drum</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>1.00</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Wind main pipe</td>
<td>3.0</td>
<td>5.0</td>
<td>10.0</td>
<td>5.50</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Tractor with main pipe to other valve</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.00</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Connect pipes</td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
<td>1.08</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Unwind pipe</td>
<td>7.0</td>
<td>8.0</td>
<td>10.0</td>
<td>8.17</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Connect machine to tractor</td>
<td>2.0</td>
<td>3.0</td>
<td>5.0</td>
<td>3.17</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Drag machine to new valve</td>
<td>3.0</td>
<td>5.0</td>
<td>8.0</td>
<td>5.17</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Disconnect tractor</td>
<td>2.0</td>
<td>3.0</td>
<td>5.0</td>
<td>3.17</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Connect pipe to machine</td>
<td>0.5</td>
<td>1.5</td>
<td>3.0</td>
<td>1.25</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Adjust microprocessor</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.20</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Adjust emitters</td>
<td>—</td>
<td>4.0</td>
<td>7.0</td>
<td>4.50</td>
<td>—</td>
<td>4.0</td>
</tr>
<tr>
<td>Travel to valve</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.00</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Open valve</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td>1.92</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Travel to machine</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.00</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Operate and Control</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.00</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31.3</strong></td>
<td><strong>46.4</strong></td>
<td><strong>69.4</strong></td>
<td><strong>48.06</strong></td>
<td><strong>16.6</strong></td>
<td><strong>21.4</strong></td>
</tr>
</tbody>
</table>
the results, the ratios between the times for stages 1 and 2, which is $K_R$, were:

1 man: $K_R = \frac{48.06}{27.38} = 1.76$; 2 men: $K_R = \frac{34.86}{18.39} = 1.90$

Indirect time is defined as the time for the operators to come to the machine and to leave it after completing their task. It depends on many factors, most of which are neither related to the machine type nor to the team, but to other factors such as distance to service center, type of vehicle used (slow or fast), situation of roads, and so forth. The range of indirect time might, therefore, vary widely even for the same field and machine. Unlike direct time, the indirect time is linearly dependent on the number of operators; for example, it is doubled for a two-man team compared to a single operator.

**IN-SITU TIME MEASUREMENTS**

In addition to time estimates, many time measurements were taken in the field while irrigating during 1983, mainly to examine the time estimates of the various activities. All of these measurements were in the range between optimistic and pessimistic times, $T_a$ and $T_b$ in Tables 1 and 2 (Amir et al., 1984). It was also found that the average time to carry out stage 3 was $T_d = 47.80$ min (two-man team) and therefore:

$$K_e = \frac{47.80}{18.39} = 2.60$$

**DISCUSSION**

The irrigated area per irrigation cycle, $A_i = WL_i$, depends on the actual irrigation duration within the cycle, taking into account certain spare time as a safety factor, $\beta$, i.e.:

$$\beta = \frac{T_{ac}}{T_{cy}}$$

where $\beta$ is the safety factor, $T_{ac}$ is the actual time available for irrigation during an irrigation cycle (h) and $T_{cy}$ is the number of hours in an irrigation cycle (h).
For a given inlet discharge, \( Q \) (liters/s), and the application amount required, \( M \) (m\(^3\)/m\(^2\)); the area irrigated during an irrigation cycle is:

\[
A_t = \frac{QT_a}{M} = \frac{Q(\beta T_{cy})}{M} \quad (\text{m}^2)
\]

Since \( A_t = WL_t \), then, from eqn (9):

\[
L_t = \frac{Q}{W} \frac{\beta T_{cy}}{M}
\]

\( \beta T_{cy} \) and \( M \) are predetermined constants. Therefore, from eqn (10), \( L_t \) is linearly dependent on the 'specific discharge' of the machine, \( Q/W \), defined as the inlet discharge per unit width of the machine (length of machine's boom). By substituting eqn (10) into eqn (5(b)) one gets:

\[
T = \frac{M}{Q \beta T_{cy}} \left\{ T_d \left( \left( \frac{L_t}{L_p} \right)^2 + K_r \left( \frac{L_t}{L_t} \right)^2 + K_c \right) + T_{in} \left( \left( \frac{L_t}{L_p} \right)^2 + \left( \frac{L_t}{L_t} \right)^2 + 1 \right) \right\}
\]

(11)

One of the main factors implicitly affecting the total time, \( T \), is the diameter of the flexible hose. In eqn (11), the discharge, \( Q \), and \( L_p \) are both in the denominator. Once the hose has been selected (material, brand), its coefficient of roughness, \( C \), is given. Therefore, the diameter of the hose and the pressure head, \( H \), required at the water supply valve, are to be solved simultaneously by one of the flow equations, e.g. Hazen Williams (Jensen, 1980). High-pressure head increases energy by either reducing the hose diameter and its cost or by increasing discharge and thus reducing labor. The evaluation of labor time, \( T \), versus hose diameter, \( D \), could be done by substituting \( D = F(Q, L, C, H) \) instead of \( Q \) or \( L_p \) in eqn (11). Usually, the variability of flexible hose diameters is limited and, from practical considerations, this factor becomes an independent variable in the design process of LMIM, and thus has a key role in determining labor requirements.

Quantitatively, the effects of both \( Q \) and \( L_p \) can be evaluated by differentiating \( T \) with respect to \( Q \) and \( L_p \). Relating \( \partial T/\partial Q \) to \( T \) (eqn (11)) yields:

\[
\frac{\partial T}{T} = -\frac{\partial Q}{Q}
\]

or:

\[
\frac{\Delta T}{T} = -\frac{\Delta Q}{Q}
\]

where \( \Delta T \) and \( \Delta Q \) are small increments of \( T \) and \( Q \), respectively.
As a result, from eqn (12), an increase of inlet discharge would decrease labour at the same rates, and vice versa.

The effect of $L_p$ on $T$ can be evaluated by the same procedure. That is:

$$\frac{\partial T}{\partial L_p} = -\frac{2}{WL_p^3}(T_d + T_{in})$$

Replacing $\partial T$ by $\Delta T$ and $\partial L_p$ by $\Delta L_p$ yields:

$$\Delta T = -\frac{2}{WL_p^3}(T_d + T_{in}) \frac{\Delta L_p}{L_p}$$  \hspace{1cm} (13)

Dividing $\Delta T$ (eqn (13) by $T$ (eqn 5(b)), yields:

$$\frac{\Delta T}{T} = -\frac{T_d + T_{in}}{T_d\left(1 + K_R\left(\frac{L_p}{L_r}\right)^2 + K_c\left(\frac{L_p}{L_i}\right)^2\right) + T_{in}\left(1 + \left(\frac{L_p}{L_r}\right)^2 + \left(\frac{L_p}{L_i}\right)^2\right)} \frac{2\Delta L_p}{L_p}$$  \hspace{1cm} (14)

The terms $K_R(L_p/L_r)^2$, $K_c(L_p/L_i)^2$ and $(L_p/L_r)^2$ are usually smaller than $1/2$, therefore:

$$\frac{\Delta T}{T} = -\frac{2\Delta L_p}{\alpha L_p} \hspace{1cm} 1 \leq \alpha \leq 2$$  \hspace{1cm} (15)

That is, the length of water supply pipe which usually is half the length of the plot, $L_p$, also affects labor requirements in the same direction as inlet discharge does, but less effectively, since $2/\alpha \geq 1$.

$L_r$, the length of the row (Fig. 1), affects $T$ in the same direction as $L_p$ and $Q$. That is, $T$ decreases with $L_r$ due to the fact that the number of times stage 2 is carried out during an irrigation cycle is reduced with the increase of $L_r$.

The contributions of stages 2 and 3 to the total labor time are small compared to stage 1. According to eqn (5(b)), these contributions are $K_R(L_p/L_r)^2$ for stage 2, and $K_c(L_p/L_i)^2$ for stage 3 (see numerical values in the example).

Depending on the geometrical dimensions of the field to be irrigated, stage 2 or 3 might be avoided. When length of row is large relative to machine speed, the machine might complete a cycle of irrigation at the same row; thus, stage 2 is avoided. When the irrigated field is divided into two equal rows, a machine finishes an irrigation cycle at the end of the second row and is moved to the starting point for a new irrigation cycle by means of stage 2, thus avoiding stage 3.
EXAMPLE

The following example presents typical operation of two moving linear laterals as applied to cotton in Israel during 1983. Data are as follows: water daily deficit = 7 mm/day; and irrigation cycle duration = 7 days, of which only 132 h are to be used (out of $7 \times 24 = 188$ h, $\beta \approx 70\%$).

(a) **Small, 72 m machine**: 106 mm pipe, $Q = 120$ m$^3$/h. Application amount is approximately 50 mm (7 mm/day $\times$ 7 days) or 500 m$^3$/ha. Total area to be irrigated is, therefore:

$$A_t = \frac{120 \times 132}{500} = 31.68 \text{ ha}$$

$$L_t = \frac{A_t}{W} = \frac{31.68 \times 10^4}{72} = 4400 \text{ m}$$

In that particular field $L_f = 1600$ m and $L_p = 400$ m. Tables 1 and 2 give, for one man, $T_d = 27.38$ min and $K_R = 1.76$. $K_c$, which is the ratio between stages 1 and 3, is estimated as $K_c = 2.60$. In this particular case, indirect time was approximately 12 min.

Substituting these values into eqn (5(b)) yields:

$$T = \frac{1}{72 \times 4400} \left\{ 30 \left( \left( \frac{4000}{400} \right)^2 + 1.76 \left( \frac{4400}{1600} \right)^2 + 2.60 \right) + 12 \left( \frac{4400}{400} + \frac{4400}{1600} + 1 \right) \right\} = 0.0179 \text{ min/m}^2$$

which is approximately 3 h per hectare per irrigation. Resulting from the last expression, the contributions of the three stages are 89.8\%, 8.7\% and 1.5\%, respectively, out of the total labor required.

(b) **Large, 360 m machine**: 125 mm pipe, $Q = 190$ m$^3$/h. In this particular case, due to long travel in stage 3, actual irrigation duration was 125 h. Therefore:

$$A_t = \frac{125 \times 190}{500} = 47.5 \text{ ha}$$

$$L_t = \frac{47500}{360} = 1320 \text{ m}$$

$L_p = 330 \text{ m}$ (1320:4)
In this case, stage 2 was not executed; therefore

\[ T = \frac{1}{360 \times 1320} \left\{ 30\left(\frac{1320^2}{330}\right) + 2.60 \right\} + 12\left(\frac{1320^2}{330} + 1\right) \]

\[ = 0.0016 \text{ min/m}^2 = 16 \text{ min/ha} \]

Only 16 min per irrigation per hectare were required for operating the large machine while 180 min per hectare per irrigation were required for the short one. This is mainly due to the larger width of the machine, partly due to the larger inlet discharge, and the fact that actual irrigation time (125 h) is shorter than in the small machine (132 h).

Note: The numerical results of the example do not include labor time required for the maintenance stage, which is considerably higher for the long machine than for the short one.

The amount of labor per unit area required even by the small machine, 3 h per hectare per irrigation, is considerably small compared to solid sprinkling systems for which the equivalent time is 15 to 20 h per hectare per irrigation.

Resulting from this study, during the 1983 irrigation season, efforts were made to reduce the time of stage 1. As a consequence, it was reduced by approximately 50% from 27.83 min to 12 to 15 min by a single operator. Since stage 1 requires 90% of the total time, the reduction of its time reduces the entire labor requirement by more than 45%, to approximately 1.5 h per hectare per irrigation.

**CONCLUSIONS**

Labor requirements for the operation of linear move irrigation machines are evaluated by a mathematical model, a time and motion study and *in situ* measurements from which the following conclusions can be deduced.

1. Input per unit area is significantly reduced with an increase in machine's width.
2. Water supply pipes affect labor through two factors: diameter and length. An increase of pipe diameter increases inlet discharge under a given pressure head and, according to sensitivity analysis, decreases labor per unit area. Also, length of pipe affects labor per unit area in the same direction.
(3) The number of operators in a team depends mainly on the indirect time factor. When this factor is large, a one-man team would be preferred. This problem can be effectively dealt with using the mathematical model and the time estimate methodology.

(4) In situ measurements of time for various activities in the operation of LMIM supported time estimates that were based on questionnaires.

(5) The main contributor to the total time is stage 1, while stages 2 and 3 are secondary factors. Therefore, for a given machine and hydraulic set up, reduction in stage 1 time would have the most efficient results in reducing total time.

ACKNOWLEDGEMENTS

Our thanks are due to the many people that helped carry out this work: teams from Ramat-David Metal Works and Coor Shnitzky, Israel; cotton growers from several Kibbutzes; S. Golan, J. Jerom and R. Hajajra from Newe Ya'ar, and the student, D. Cohen, from Technion. Thanks are also due to our colleague, Dr A. Garcia, Texas A&M University, for reviewing, and to Ms Candis Merrill, Texas A&M University, for typing, this paper.

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