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Water distribution uniformity and scheduling in micro-irrigation systems for water saving and environmental protection

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Abstract

Micro-irrigation can apply water with high uniformity. However, uniformity alone is not sufficient to achieve the goal of irrigation. Irrigation scheduling is equally important in micro-irrigation systems. The significance of various irrigation schedules and emitter flow uniformities were examined in system design. Several irrigation schedules were compared with an optimal irrigation schedule. The optimal irrigation schedule can achieve optimal return and also provide water saving compared with the conventional irrigation schedule in which the whole field is fully irrigated at the same time. Deep seepage can be eliminated or minimised by scheduling deficit irrigation. An environmental protection irrigation schedule, where the whole field is in deficit, can save more water but will cause some reduction in total return compared to the optimal irrigation schedule. A simple irrigation schedule, in which the total amount of water applied is the same as the amount required, can not only produce nearly optimal yield but also achieve increased water saving when high uniformity is also applied in the design. It is important to specify that the differences in total return and water saving between different schedules are reduced when high uniformity is applied in the design. For high uniformity the effects of crop sensitivity to deficit irrigation are not important and result in only limited (or acceptable) yield reduction and over-irrigation. Since a high proportion of water resources are used for agricultural production, micro-irrigation systems designed with high uniformity can be scheduled to achieve water conservation as well as environmental protection.

Keywords

Micro-irrigation design, deficit irrigation, groundwater contamination, optimal irrigation scheduling, high uniformity.

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Nomenclature

a, b	coefficients of straight line distribution, dimensionless
Cr_1	water cost ratio, dimensionless
Cr_2	pollution cost ratio, dimensionless
CV	coefficient of variation caused by hydraulic design and manufacturer's variation, dimensionless
D_P	percentage of deficit area, dimensionless
E_a	irrigation application efficiency, dimensionless
EU	emission uniformity, dimensionless
h	operating pressure head, m
k	coefficient constant in emitter flow equation
K_y	crop reduction coefficient by deficit irrigation, dimensionless
P_A	fraction of area under a Gaussian (normal) curve, where the fraction of the mean application, *X*, is equalled or exceeded, dimensionless
q	emitter flow rate, l h^{-1}
q_{min}	minimum emitter flow rate, l h^{-1}
$\bar{q}$	average emitter flow rate, l h^{-1}
$\bar{q}_{LQ}$	average of low quarter of emitter discharge, l h^{-1}
Q	total discharge of the drip irrigation system per unit of area, m^3 h^{-1} ha^{-1}
QT	irrigation water applied over the whole crop season per unit of area, m^3 ha^{-1}
T	total irrigation time over the whole crop season, h
V_{ds}	volume of deep seepage per unit of area, m^3 ha^{-1}
W	seasonal irrigation water application under deficit condition per unit of area, m^3 ha^{-1}
W_m	seasonal irrigation water application for maximum yield per unit of area, m^3 ha^{-1}
x	exponential coefficient in emitter flow equation
X	relative irrigation depth, or fraction of the mean application, dimensionless
X_0	optimum irrigation depth, dimensionless
Y	crop yield under deficit condition per unit of area, kg ha^{-1}
Y_m	maximum crop yield per unit of area, kg ha^{-1}
Z	total economic return under deficit irrigation condition per unit of area, US \$ ha^{-1}
ρ_{ds}	cost of the loss of fertiliser and remedial work for environmental pollution (per unit volume) of deep seepage, US \$ m^{-3}
ρ_y	unit cost of production, US \$ kg^{-1}
ρ_ω	unit cost of water, US \$ m^{-3}

Subscripts

0	optimal irrigation scheduling
1	simple irrigation scheduling

a	conventional irrigation scheduling
a+b	environmental protection scheduling
h	hydraulic variation
m	manufacturer´s variation
h, m	hydraulic and manufacturer´s variation

1. Introduction

Micro-irrigation systems can apply irrigation water to fields with high uniformity. However the effectiveness of irrigation depends not only on how the uniformity of the system is designed but also on how the system is used. This requires irrigation scheduling for the irrigation amount and time. A well-designed micro-irrigation system cannot reach its full potential or the goal of irrigation if the decisions on irrigation scheduling are not properly taken.

Irrigation time is determined by the water requirement for a given irrigation interval, the water-holding capacity of the soil, the uniformity of the irrigation system and the irrigation scheduling strategy. The irrigation interval depends on the daily water consumption, the soil moisture storage capacity and readily available soil moisture to maintain the ideal soil moisture content for crops to use. Micro-irrigation (trickle, drip or mini-sprinkler) is designed for high frequency irrigation (daily or a few times a week) to maintain soil moisture at optimal or near optimal level for crops at all times (Barragan & Wu, 2001).

The objective of this work is to investigate the influence of the uniformity and irrigation scheduling on the economic return, water conservation and environmental protection.

2 Micro-irrigation uniformity

The uniformity of irrigation application by micro-irrigation is mainly affected by hydraulic design, manufacturing variations, emitter grouping, emitter spacing and plugging. Of all the factors affecting micro-irrigation uniformity, plugging is the most significant, followed by the grouping of emitters for low density tree crops and emitter spacing for high density row crops. Both the hydraulic design and the manufacturing variations, provided they are designed within a specified range, are less significant (Wu, 1993a).

The total variation of emitter flow, affected by both the hydraulics and manufacturing variations, can be expressed by Eq. (1) (Bralts, et al., 1981):

$$CV^2 = CV_{(m)}^2 + CV_{(h)}^2 \qquad (1)$$

where $CV_{(m)}$ is the coefficient of variation of emitter flow caused by manufacturing variations (dimensionless) and $CV_{(h)}$ is the coefficient of variation of emitter flow caused by the hydraulic design (dimensionless).

Some newly developed turbulent flow emitters are made with manufacturing variations of only 2-5% and low plugging potential.

If four or more emitters per tree are designed for tree irrigation, or the emitter spacing is designed as half of the wetted diameter of the soil wetting pattern for row crops, the coefficient of variation for water application by micro-irrigation can be maintained at less than 10% even with a 5% plugging situation in the field (Wu, 1993a; Wu, 1993b).

The irrigation application function for both low density trees and high density row crops can be considered as a Gaussian (normal) distribution with a *CV* less than 30% (Wu, 1988). The S-curve cumulative distribution function of the Gaussian distribution can be approximated by a straight-line function, as in Fig. 1, which offers a simple solution for irrigation efficiency and scheduling (Wu, 1995).

Given the non-uniform nature of irrigation systems, any given irrigation application will develop a certain degree of deficit and over-irrigation. Deficit areas will cause crop yield reduction while the over-irrigation area will produce deep seepage resulting in wastage of water and fertiliser (and other chemicals), as well as being a potential cause of groundwater contamination.

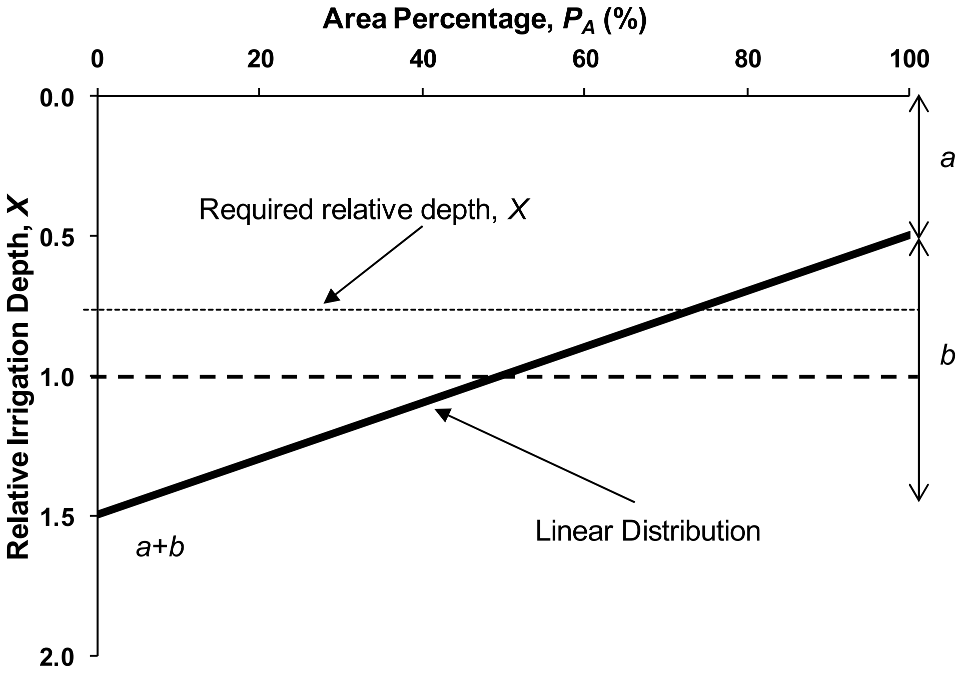

Fig. 1. A linear water application model for micro-irrigation; *X*, relative irrigation depth; P_A, percentage of area where the *X*-value is equalled or exceeded; *a* and *b*, coefficients of straight line distribution.

2.1. The linearised water application function

The linearised water application function is plotted as shown in Fig. 1, using the fraction of area P_A against the irrigation scheduling parameter *X* (dimensionless), where *X* is the relative irrigation depth, or fraction of the mean application; P_A (dimensionless) is the fraction of area, under a linearised Gaussian curve, where *X* is equalled or exceeded. The straight-line distribution in the dimensionless plot can be specified by a minimum value *a* and a maximum value (*a*+*b*) in the *X*-scale in Fig. 1. The value of the coefficient b specifies the uniformity of the water application and can be determined by (Wu, 1988; Barragan & Wu, 2001):

$$CV = 0.29b \tag{2}$$

The value of a can be simply determined through:

$$a = 1 - 0.5b \tag{3}$$

If the required irrigation depth is determined by the depth to achieve maximum yield, the relative irrigation depth, X, can be shown as:

$$X = \frac{W_m}{QT} \tag{4}$$

where W_m is the required amount of water for the total crop season to achieve maximum yield per unit of area in $m^3\ ha^{-1}$; Q is the total discharge of the drip irrigation system per unit of area, $m^3\ h^{-1}\ ha^{-1}$; T is the irrigation time over the total crop season in h; and QT is the irrigation volume applied over the whole crop season per unit of area in $m^3\ ha^{-1}$.

The application efficiency, E_a, of a drip irrigation system is a measure of how well the irrigation water is applied; it is the percentage of water applied that is stored in the root zone and is available for plant use (dimensionless). It can be expressed in decimal as:

$$E_a = X(1 - D_P) \tag{5}$$

where D_P is the deficit percentage, dimensionless, (expressed in decimal) and is defined as the ratio of the volume of water in deficit to the total volume required. The deficit percentage can be derived from the triangle above the horizontal line X in Fig. 1:

$$D_P = \frac{(X - a)^2}{2bX} \tag{6}$$

The volume of deep seepage per unit of area V_{ds} in $m^3\ ha^{-1}$ is determined from the triangle below the horizontal line X in Fig. 1:

$$V_{ds} = \frac{1}{2b}(a + b - X)^2 QT \tag{7}$$

The significance of micro-irrigation scheduling can be seen in Fig. 1 where X can be selected to cause over-irrigation as well as deficit irrigation in the field. With a given uniformity of the irrigation system in which a and b can be determined, any value of X in the range of a and (a+b) will cause a certain deficit percentage and deep seepage volume, which can be calculated with Eqs. (6) and (7). Therefore, the choice of X in irrigation scheduling will affect water conservation, economic return and environmental pollution. When $X < a$ there will only be over-irrigation and no deficit condition. In the case where $X > (a+b)$, there will be no over-irrigation.

The errors introduced by using the straight line function in place of the S-curve for the normal distribution can be analyzed by comparing the E_a and D_P values calculated by both methods (Wu, 1988; Anyoji & Wu, 1994). Per example for $CV \le 10\%$ and $X = 1$ the difference between the calculated values are $\le 0.3\%$.

2.2 A linear crop response model

The effects of deficit irrigation on crop yield can be shown by a linear response model and expressed as follows (Dorrenbos & Kassam, 1979):

$$\left(1 - \frac{Y}{Y_m}\right) = K_y\left(1 - \frac{W}{W_m}\right) \tag{8}$$

where Y_m is the maximum crop yield corresponding to a maximum water application per unit of area in kg ha^{-1}; Y is a crop yield under a deficit water application per unit of area in kg ha^{-1}; W is an irrigation application for a deficit condition for the total crop season per unit of area in m^3 ha^{-1}; and K_y is a reduction coefficient which is a constant for a particular crop (dimensionless).

When a micro-irrigation system is designed with a set uniformity, the straight line with a known value of a and b can be determined. The parameter X can be selected between the values of a and a+b and plotted as a horizontal line as shown in Fig. 1. The triangle formed above the horizontal line specifies deficit irrigation and will cause yield reduction. The total yield in the field affected by the irrigation system uniformity *CV*, and the value of *X* can be determined (Wu, 1995):

$$Y = Y_m - \frac{Y_m K_y}{2b}\left(X - 2a + \frac{a^2}{X}\right) \tag{9}$$

3. Micro-irrigation scheduling

The dimensionless value *X* is, in fact, a parameter for irrigation scheduling. Each individual decision on irrigation scheduling will be presented as a horizontal line in Fig. 1. Different micro-irrigation schedules expressed by *X* are explained as follows:

$X < a$	Over-irrigation is scheduled throughout the field. There is no deficit condition in the field.
$X = a$	This is a conventional irrigation schedule based on the minimum emitter flow or water application. The field is fully irrigated except the point of minimum irrigation application.
$X = X_0$	This is an optimal irrigation schedule which is located between *a* and *a*+*b*.
$X = 1$	This is a simple irrigation schedule in which the total amount applied, *QT*, is the same as the amount required, W_m.
$X = a+b$	The irrigation schedule is based on the maximum emitter flow or maximum irrigation application. The whole field is under deficit condition except the point of maximum water application. There is no deep seepage.
$X > a+b$	Too little irrigation is scheduled. The whole field is in deficit irrigation condition where there is no deep seepage for the whole field.

3.1. Optimal irrigation schedule

As Fig. 1 shows, the horizontal line expressed by a value of X can be moved up and down within the limits between a and $a+b$. Each X value represents an irrigation schedule which can be determined by Eq. (4). In an economic analysis considering the cost of water, price of crop, yield reduction from deficit irrigation, cost of fertiliser loss from over-irrigation and remedial costs for environmental pollution (Wu, 1995), the total return can be expressed as:

$$Z = Y_m \rho_y \left[1 - \frac{K_y (X-a)^2}{2bX} - \frac{1}{X} Cr_1 - \frac{1}{2bX} (a+b-X)^2 Cr_2 \right] \tag{10}$$

where Z is the total return corresponding to a given X under deficit irrigation conditions per unit of area in US \$ ha^{-1}; Cr_1 and Cr_2 are the water cost ratio and pollution cost ratio respectively (dimensionless) and are defined as:

$$Cr_1 = \frac{W_m \rho_\omega}{Y_m \rho_y} \tag{11}$$

and

$$Cr_2 = \frac{W_m \rho_{ds}}{Y_m \rho_y} \tag{12}$$

where ρ_y is the unit cost of production in US \$ kg^{-1}; ρ_w is the unit cost of water in US \$ m^{-3}; and ρ_{ds} is the cost of the loss of fertiliser and remedial work for environmental pollution per unit volume of deep seepage, in US \$ m^{-3}.

The optimum irrigation schedule can be determined by taking the first derivative with respect to X for Eq. (10) and setting $dZ/dX = 0$. The optimum irrigation schedule can be expressed as:

$$X_0 = \sqrt{\frac{a^2 + 2b(Cr_1 / K_y) + (a+b)^2 (Cr_2 / K_y)}{1 + (Cr_2 / K_y)}} \tag{13}$$

where X_0 is the X value to achieve optimum return.

The optimum return can be obtained by using X_0 for X in Eq. (10) and is shown as:

$$Z_0 = Y_m \rho_y \left[1 - \frac{K_y (X_0 - a)^2}{2bX_0} - \frac{1}{X_0} Cr_1 - \frac{1}{2bX_0} (a + b - X_0)^2 Cr_2 \right] \quad (14)$$

where Z_0 is the total return of the optimal irrigation scheduling per unit of area in US \$ ha^{-1}.

The optimum irrigation amount, QT_0, can be determined from Eq. (4):

$$QT_0 = \frac{W_m}{X_0} \quad (15)$$

where QT_0 is the irrigation water applied for the optimum irrigation schedule over the whole crop season per unit of area in m^3 ha^{-1}; and T_0 is the optimum irrigation time schedule over the whole crop season in h.

3.2. Conventional irrigation schedule

A conventional irrigation schedule is determined by moving the horizontal line for relative irrigation depth as shown in Fig. 1 to point *a* in the *X*-scale or $X = a$. This schedule will maintain the whole area fully irrigated. As Fig. 1 shows, when $X = a$, there will be no deficit condition. The irrigation schedule for this case can be determined by Eq. (4):

$$QT_a = \frac{W_m}{a} \quad (16)$$

where QT_a is the irrigation water applied for the conventional irrigation scheduling over the whole crop season per unit of area in m^3 ha^{-1}; and T_a is the irrigation time for the conventional irrigation schedule over the whole crop season in h.

The total return can be determined with Eq. (10):

$$Z_a = Y_m \rho_y \left[1 - \frac{1}{a} Cr_1 - \frac{b}{2a} Cr_2 \right] \quad (17)$$

where Z_a is the total return of conventional irrigation scheduling per unit of area in US \$ ha^{-1}.

A conventional irrigation is generally applied by furrow and sprinkler irrigation to irrigate fully the whole area without any deficit condition. This irrigation strategy can achieve maximum yield based on the assumption that over-irrigation will not reduce the yield. However, this irrigation practice uses too much water and the deep percolation caused by over-irrigation may cause groundwater contamination.

3.3. Simple irrigation schedule

A simple irrigation schedule can be determined by using $X = 1$ in Eq. (4):

$$QT_1 = W_m \tag{18}$$

where QT_1 is the irrigation water applied for the simple irrigation scheduling over the whole crop season per unit of area in m^3 ha^{-1}; and T_1 is the irrigation time for the simple irrigation schedule over the whole crop season in h.

The total return will be determined with Eq. (10) as:

$$Z_1 = Y_m \rho_y \left[1 - \frac{K_y (1-a)^2}{2b} - Cr_1 - \frac{1}{2b}(a+b-1)^2 Cr_2 \right] \tag{19}$$

where Z_1 is the total return of simple irrigation scheduling per unit of area in US \$ ha^{-1}.

3.4. Irrigation strategy for environmental protection

When environmental pollution from deep percolation is a major concern, the irrigation strategy can be set to eliminate or minimise deep percolation by using an irrigation schedule where $X = a + b$. This is done by rearranging Eq. (4):

$$QT_{a+b} = \frac{W_m}{a+b} \tag{20}$$

where QT_{a+b} is the irrigation water applied for the environmental protection scheduling over the whole crop season per unit of area in m^3 ha^{-1}; and T_{a+b} is the irrigation time for the environmental protection schedule over the whole crop season in h.

The total return will be determined by rearranging Eq. (10):

$$Z_{a+b} = Y_m \rho_y \left[1 - \frac{K_y b}{2(a+b)} - \frac{1}{a+b} Cr_1 \right] \tag{21}$$

where Z_{a+b} is the total return for environmental protection scheduling per unit of area in US \$ ha^{-1}. This schedule will result in the total field operating under deficit irrigation condition except at the point where $X = a + b$. There will be yield reduction in the deficit irrigation area according to the uniformity of water application. This irrigation schedule can be used to prevent environmental pollution by allowing an acceptable yield reduction.

4. Micro-irrigation for water conservation

Different irrigation strategies require different total applied irrigation amounts and will produce total return differences. Water conservation can be realised by comparing any two of the irrigation strategies (Wu & Barragan, 2000; Wu et al., 2006).

4.1. Comparing the optimal schedule with the conventional irrigation schedule

Water saving from the optimal irrigation schedule compared with the conventional irrigation schedule can be obtained from Eqs. (15) and (16) as:

$$\frac{QT_a - QT_0}{W_m} = \frac{1}{a} - \frac{1}{X_0} \tag{22}$$

The difference in total return for these two irrigation schedules can be determined from Eqs. (14) and (17) as:

$$\frac{Z_0 - Z_a}{Y_m \rho_y} = \left(\frac{1}{a} - \frac{1}{X_0} \right) Cr_1 - K_y \frac{(X_0 - a)^2}{2bX_0} + \frac{1}{2} \left[\frac{b}{a} - \frac{1}{bX_0} (a + b - X_0)^2 \right] Cr_2 \tag{23}$$

4.2 Comparing the simple irrigation schedule with the conventional irrigation schedule

Water saving from the simple irrigation schedule compared with the conventional irrigation schedule can be obtained from Eqs. (16) and (18) as:

$$\frac{QT_a - QT_1}{W_m} = \frac{1}{a} - 1 \tag{24}$$

The difference in total return between these two schedules can be determined from Eqs. (17) and (19) as:

$$\frac{Z_1 - Z_a}{Y_m \rho_y} = \left(\frac{1}{a} - 1\right) Cr_1 - \frac{K_y (1-a)^2}{2b} + \frac{1}{2}\left[\frac{b}{a} - \frac{(a+b-1)^2}{b}\right] Cr_2 \tag{25}$$

4.3. Comparing the simple irrigation schedule with the optimal irrigation schedule

The simple irrigation schedule can achieve water saving compared with the optimal schedule. This can be determined from Eqs. (15) and (18) as:

$$\frac{QT_1 - QT_0}{W_m} = 1 - \frac{1}{X_0} \tag{26}$$

The difference in total return between these two schedules can be determined from Eqs. (14) and (17) as:

$$\begin{aligned}\frac{Z_1 - Z_0}{Y_m \rho_y} = &\left(\frac{1}{X_0} - 1\right) Cr_1 + \frac{K_y}{2b}\left[\frac{(X_0 - a)^2}{X_0} - (1-a)^2\right] \\ &+ \frac{1}{2b}\left[\frac{(a+b-X_0)^2}{X_0} - (a+b-1)^2\right] Cr_2\end{aligned} \tag{27}$$

4.4. Comparing the irrigation schedule for environmental protection with the optimal irrigation schedule

More water saving can be achieved by using the schedule for environmental protection because the whole area is under deficit irrigation. However, there will be yield reduction caused by deficit irrigation. Water saving can be determined from Eqs. (15) and (20) as:

$$\frac{QT_{a+b} - QT_0}{W_m} = \frac{1}{a+b} - \frac{1}{X_0} \tag{28}$$

The total return reduction can be determined from Eqs. (14) and (21) as:

$$\frac{Z_0 - Z_{a+b}}{W_m} = \frac{K_y}{2}\left[\frac{b}{a+b} - \frac{(X_0 - a)^2}{bX_0}\right] + \left[\frac{1}{a+b} - \frac{1}{X_0}\right]Cr_1 - \frac{1}{2bX_0}(a+b-X_0)^2 Cr_2 \tag{29}$$

4.5. Comparing the irrigation schedule for environmental protection with the simple irrigation schedule

Water saving from the irrigation schedule for environmental protection compared with the simple irrigation schedule can be determined from Eqs. (18) and (20) as:

$$\frac{QT_1 - QT_{a+b}}{W_m} = 1 - \frac{1}{a+b} \tag{30}$$

The total return reduction can be determined from Eqs. (19) and (21) as:

$$\frac{Z_1 - Z_{a+b}}{W_m} = \frac{K_y}{2}\left[\frac{b}{a+b} - \frac{(1-a)^2}{b}\right] + \left[\frac{1}{a+b} - 1\right]Cr_1 - \frac{1}{2b}(a+b-1)^2 Cr_2 \tag{31}$$

Eqs. (22), (24), (26), (28), and (30) show that water saving can be achieved by comparing two irrigation schedules. Different irrigation schedules will also result in different total returns as shown in Eqs. (23), (25), (27), (29) and (31).

5. Hydraulic design in micro-irrigation systems

The goal of designing irrigation systems is to achieve the required uniformity for irrigation in the field. Emission uniformity, *EU*, is one of the uniformity parameters used for micro-irrigation system design. It is expressed as a function of hydraulic variation, the manufacturing variations and the number of emitters which can be grouped together as a unit for irrigation application. When the manufacturing variation expressed by the coefficient of variation and the number of emitter groups are selected and designed, the required hydraulic variation can be determined for hydraulic design based on set design criteria for emission uniformity.

The *EU* value can be determined based on emitter type, field layout, and the topographic situation in the field (ASAE, 2000). Other design criteria for micro-irrigation systems are determined using an economic analysis of optimal irrigation scheduling and the expected relative return based on the availability of water resources and considerations of environmental pollution and groundwater contamination (Wu & Barragan, 2000). In both cases the range of *EU* values range from 65% to 95%.

To estimate design emission uniformity in terms of $CV_{(m)}$ and pressure variations at the emitter, Eq. (32) for *EU* is suggested (ASAE, 2000):

$$EU = \frac{\bar{q}_{LQ(h,m)}}{\bar{q}_{(h,m)}} = (1 - 1.27\frac{CV_{(m)}}{\sqrt{N}})\frac{q_{\min(h)}}{\bar{q}_{(h)}} \tag{32}$$

where *EU* is the emission uniformity (dimensionless); $\bar{q}_{LQ(h,m)}$ is the average of low quarter of emitter discharge caused by hydraulic variation and the manufacturer's variation in l h^{-1}; $\bar{q}_{(h,m)}$ is the average of emitter discharge caused by hydraulic variation and the manufacturer's variation in l h^{-1}; *N* is the number of emitters grouped as a unit such as, for example, several emitters designed for a tree (dimensionless); $q_{min(h)}$ is the minimum emitter flow by hydraulic design in l h^{-1} ; and $\bar{q}_{(h)}$ is the average emitter flow by hydraulic design in l h^{-1}.

For point-source emitters, values of $CV_{(m)}$ less than 5% are considered excellent, and those between 5% and 7% as average, whereas values greater than 7% would range from marginal to poor (ASAE, 2000). It is generally desirable to design emission uniformities within a sub-unit that range from 85% to 95% for most micro-irrigation system types and crops on uniform topography and mildly sloped (< 2%) fields. Higher *EU* values are desired for higher cash value crops, systems that are also used for chemigation purposes, and when other economic or environmental constraints favour the additional cost associated with higher design *EU* values. However, these criteria may be difficult to achieve with fields that have steep or undulating topography and/or field slopes that exceed 2% and *EU* values of 80% may be acceptable (Clark et al., 2006).

Wu et al. (2006) and Barragan et al. (2006) presented Eqs. (33) and (34):

$$CV = 0.77(1 - EU) \tag{33}$$

$$EU = \frac{\bar{q}_{LQ(h,m)}}{\bar{q}_{(h,m)}} = 1 - \sqrt{\left[1 - \frac{q_{\min(h)}}{\bar{q}_{(h)}}\right]^2 + \left[\frac{1.27CV_{(m)}}{\sqrt{N}}\right]^2} \tag{34}$$

The discharge characteristics of a drip emitter can be described by:

$$q = k \cdot h^{x} \tag{35}$$

where q is the emitter discharge rate in l h^{-1}, h is the emitter operating pressure head in m, k is a constant varying by drip emitter model and units used, and x is an emitter discharge exponent that also varies with the emitter model.

From Eqs. (34) and (35) the pressure ratio $h_{\min}/\bar{h}$ can be calculated and used to begin the micro-irrigation system design, where $h_{\min}$ is the minimum pressure head in m; and $\bar{h}$ is the average pressure head in m (Barragan & Wu, 2005; Juana et al., 2004; Clark et al., 2006).

6. Efficient water use for optimum return and water saving

A complete computer simulation was carried out for Eqs. 22-23; 24-25; 26-27; 28-29 and 30-31 to determine the increase in total return and water saving using the following combinations:

CV = 2.5%, 5%, 10%, 20%, 30% or EU = 97%, 94%, 87%, 74%, 61%

Ky = 0.7, 1, 1.3

Cr_1 = 0, 0.01, 0.1

Cr_2 = 0, 0.2, 0.6, 1, 2, 5.

From Eqs. (5), (6) and (7) the E_a, D_P and V_{ds} values were also determined for $X = a$, $X = 1$, $X = a+b$ and $X = X_0$.

For $CV \leq 10\%$; $0 \leq CV_{(m)} \leq 10\%$; and N = 1, 2, 4, 8; from Eqs. (1) and (34) the $CV_{(h)}$ and $h_{\min}/\bar{h}$ values were determined. When $h_{\min}/\bar{h}$ is known the hydraulic design can be started.

The range of CV assigned in the simulation was based on the field situation that a total variation of CV=30% was most likely the maximum variation for micro-irrigation. Several high uniformity design systems, CV < 10%, were included. The selected CV values provide a reasonable range of uniformity of micro-irrigation systems.

The K_y values show the additional effects on the economic analysis of crop sensitivity to deficit irrigation. The reduction coefficient K_y resulting from deficit irrigation is in a range from 0.7 to 1.3 (Dorrenbos & Kassam, 1979).

The Cr_1 values were selected based on the data collected for irrigation of vegetables in Hawaii (Wu, 1995). The cost ratio Cr_2 is difficult to determine since the information about cost induced by deep seepage is not readily available. The range of Cr_2 used in this simulation is arbitrarily assumed from 0 to 5 with the consideration that the cost induced by unit volume of deep seepage ρ_{ds} is 50 or more times higher than the unit cost of water ρ_w.

7. Results and discussion

A total of 30 tri-dimensional figures were plotted to show the simulation results. Six of these figures were selected to show some of the simulation results (Figs. 2, 3, 4, 5, 6 and 7).

The computer simulation results can be summarized as follows:

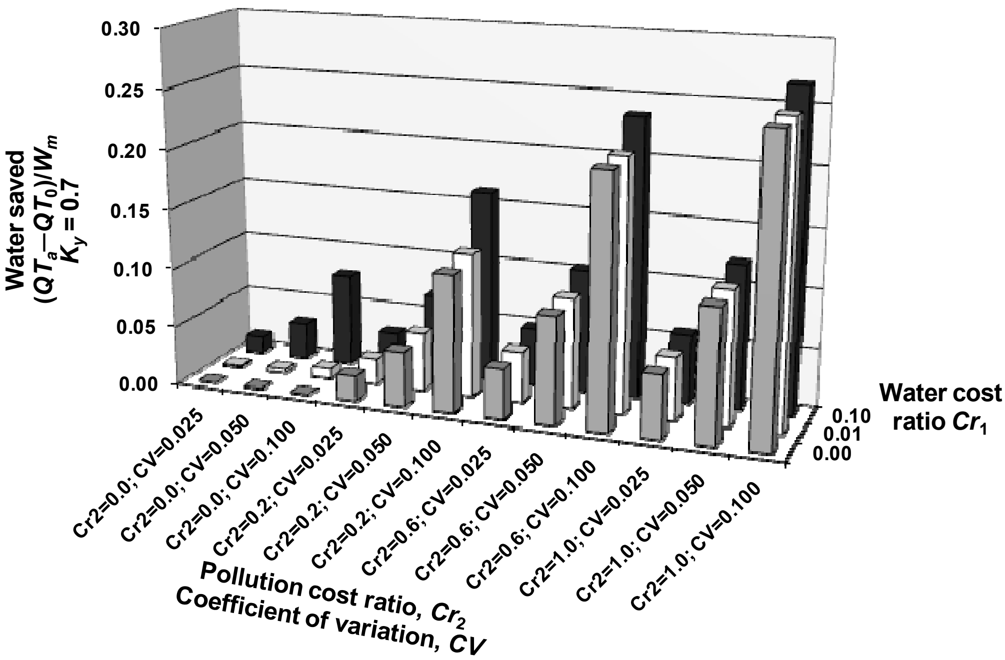

Fig. 2. Amount of water saved by applying optimal irrigation schedule compared with the conventional schedule one; $(QT_a–QT_0)/W_m$, water saved; Q total irrigation discharge; W_m seasonal water application for maximum yield; T_a and T_0, time for conventional and optimal irrigation schedule, respectively; CV, coefficient of variation; Cr_1, water cost ratio; Cr_2 pollution cost ratio; (for reduction coefficient K_y = 0.7).

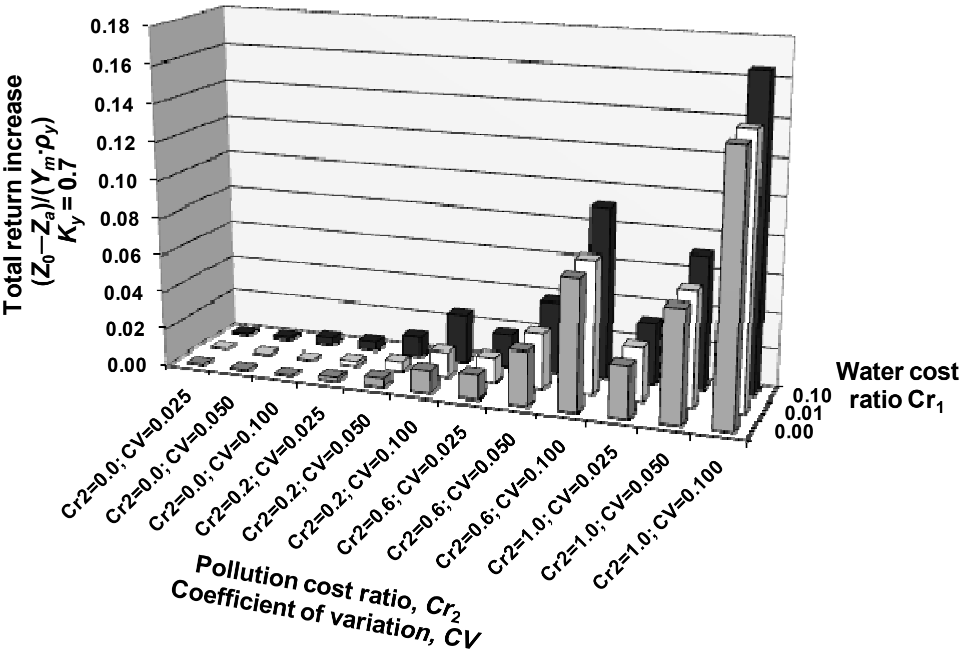

Fig. 3. Total return increase by applying optimal irrigation schedule compared with the conventional schedule one; $(Z_0 – Z_a)/(Y_m\, \rho_y)$, increase in total return; Z_a and Z_0 total economic return for conventional and optimal irrigation schedule, respectively; Y_m, maximum crop yield; ρ_y, unit cost of production; *CV*, coefficient of variation; Cr_1, water cost ratio; Cr_2 pollution cost ratio; (for reduction coefficient K_y = 0.7).

7.1. Comparing the optimal schedule, X_0, with the conventional irrigation schedule, X = a

A comparison of the conventional and optimal irrigation schedules shows that not only water is saved, but also total return is increased using the optimal schedule (see, for example, Figs. 2 and 3).

A trend towards a decrease in economic return and water saving was obtained for higher values of K_y, (maximum for K_y = 0.7 and minimum for K_y = 1.3). For constant values of K_y the trend shows an increase in economic return and water saving. This can be seen in Figs. 2 and 3, where a higher increase in return and water saving can be obtained from higher values of *CV*, Cr_1 and Cr_2 implying lower uniformity of the micro-irrigation system, a higher cost of water and an area with more severe pollution problems.

Water saving with respect to the amount for maximum yield, W_m, can be achieved from a few percent to over 100%. The amount of saving depends on the uniformity of the micro-irrigation system, CV, the reduction coefficient caused by deficit irrigation, K_y, and two cost functions Cr_1 and Cr_2 (see Fig. 2).

The increase in total return can range from a few percent to nearly 100% depending on the uniformity of micro-irrigation system, CV, the reduction coefficient, K_y, and two cost functions Cr_1 and Cr_2 (Fig. 3). When a high uniform irrigation, $CV \leq 10\%$, is designed and used the difference between the conventional and optimal irrigation schedules will be reduced.

For CV=10% the conventional irrigation schedule will produce a maximum yield reduction of about 17% compared with the optimal yield (see Fig. 3 for $K_y = 0.7$; Cr_1=0.10 and Cr_2=1). In this case too much water will be used, about 27% (see Fig. 2 for K_y =0.7; Cr_1=0.10 and Cr_2=1).

For coefficient of variation CV=5% the maximum yield reduction will only be about 7% (for $Ky = 0.7$). In this case, the amount of water saved will be about 12% (for Ky =0.7).

For coefficient of variation $CV = 10\%$ the deep seepage V_{ds} can be minimized to < 17% of the total amount applied, QT, will cause a deficit $D_P = 0\%$ and the application efficiency will be $E_a > 82\%$, Eqs. (5), (6) and (7).

For coefficient of variation $CV = 5\%$ the values will be $V_{ds} < 9\%$ of QT, $D_P = 0\%$ and $E_a > 91\%$. The conventional irrigation schedule, $X = a$, which provides full irrigation for the whole field, not only wastes too much water but also reduces the total return compared with the optimal irrigation schedule.

A conventional irrigation schedule can be used only when water is inexpensive and there is no concern for environmental pollution. Under these conditions, the uniformity of the irrigation system (or application) is not significant, and a less uniform irrigation system can be used. In Figs. 2 and 3 it can be seen (for K_y = 0.7, Cr_1 = 0 and Cr_2 = 0) that both the maximum yield reduction and water saving are negligible (for all *CV* values from 2.5% to 30%). For the other K_y values maximum yield reduction and water saving are also negligible.

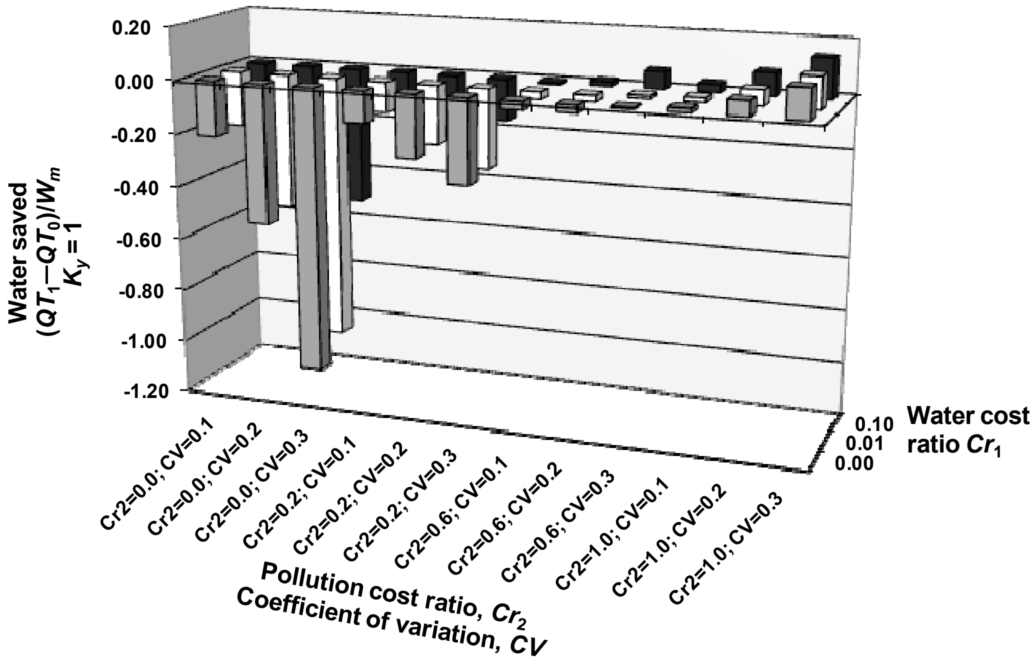

Fig. 4. Amount of water saved by applying optimal irrigation schedule compared with the simple schedule one; $(QT_1–QT_0)/W_m$, water saved; *Q* total irrigation discharge; W_m seasonal water application for maximum yield; T_1 and T_0, time for simple and optimal irrigation schedule, respectively; *CV*, coefficient of variation; Cr_1, water cost ratio; Cr_2 pollution cost ratio; (for reduction coefficient K_y = 1); (minus sign specifies water saving).

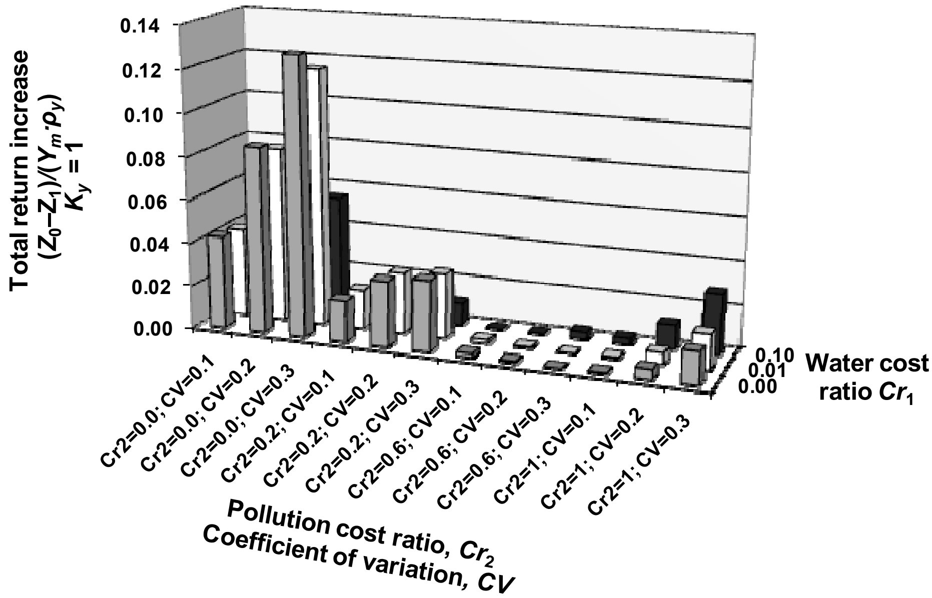

Fig. 5. Total return increase by applying optimal irrigation schedule compared with the simple schedule one; $(Z_0–Z_1)/(Y_m\,\rho_y)$, increase in total return; Z_1 and Z_0 total economic return for simple and optimal irrigation schedule, respectively; Y_m, maximum crop yield; ρ_y, unit cost of production; *CV*, coefficient of variation; Cr_1, water cost ratio; Cr_2 pollution cost ratio; (for reduction coefficient $K_y = 1$).

7.2. Comparing the optimal schedule, X_0, with the simple irrigation schedule, X = 1

The simple irrigation schedule can save even more water compared with the optimal schedule when Cr_2 is less than 0.6 as shown in Fig. 4 (minus sign specifies water saving). However, this will cause some reduction in the total return depending on the cost of water Cr_1, remediation costs for environmental pollution Cr_2, coefficient of crop sensitivity to deficit irrigation K_y, and coefficient of variation *CV* (see Figs. 4 and 5).

For remediation costs for environmental pollution $Cr_2 < 0.6$ water savings increase as the K_y values increase (minimum for $K_y = 0.7$ and maximum for $K_y = 1.3$). However, for remediation costs for environmental pollution $Cr_2 > 0.6$ water savings are reversed and the simple irrigation schedule uses more water than the optimal one (Fig. 4).

For CV = 10% the simple irrigation schedule (X = 1) will produce a maximum yield reduction compared with the optimal yield (X_0) of about 6% (for K_y = 1.3), 4% (for K_y = 1) and 3% (for K_y = 0.7) In this case, the maximum water saving will be 21%, when the cost of water Cr_1 = 0 and the remediation costs for environmental pollution Cr_2 = 0 (for all K_y values). For Cr_2 > 1 the simple irrigation schedule will use more water than the optimal one (see Figs. 4 and 5).

For CV = 5% the maximum yield reduction in this case will only be about 3% (for K_y = 1.3 and Cr_2=0). The maximum water saving will be about 9%, when the remediation costs for environmental pollution Cr_2 = 0 and Cr_1=0 (for all K_y values). For $Cr_2 \geq 1$ the simple irrigation schedule will use more water than the optimal one (see Figs. 4 and 5).

This shows the importance of designing micro-irrigation systems with high uniformities and accurately calculating the amount of water required to achieve the maximum yield, W_m.

When the system is designed for high uniformity, CV < 10%, deep seepage V_{ds} can be minimised to < 5% of the total amount applied, QT, will cause only a deficit D_P < 5% and the application efficiency will be E_a>95%, Eqs. (5), (6) and (7).

For CV = 5% the values will be V_{ds} <3% of QT, D_P <3% and E_a>97%.

7.3. Comparing the optimal schedule, X_0, with the environmental irrigation schedule, $X = a+b$

A comparison of the optimal irrigation schedule with the environmental protection irrigation schedule indicated that there are definitely water savings when using the environmental protection irrigation schedule, though there is also a fall in total return.

The trend towards a decrease in return, and an increase in water saving, was obtained for higher values of K_y (minimum for K_y = 0.7 and maximum for K_y = 1.3). For constant values of K_y the reduction in water saving as well as in total return will increase as the *CV* value increases, but will decrease with respect to increased Cr_1 and Cr_2 values.

When there is an environmental concern in polluting nearby streams or underlying ground water, the environmental protection schedule will prevent the possibility of pollution. In such as situation the system should be designed as uniform as possible.

For *CV*=10% the environmental protection irrigation schedule ($X = a+b$) will produce only about 10% (for K_y = 0.7), 15% (for K_y = 1) and 19% (for K_y = 1.3) maximum yield reduction compared with the optimal yield. The maximum water saving will be 35% (for K_y = 1.3).

For *CV* = 5% the yield reduction in this case will only be about 2% (for K_y = 0.7) and 10% (for K_y = 1.3). The range of water saving will be from 17% (for K_y = 1.3) to 6% (for K_y = 0.7).

If the overall coefficient of variation is *CV* = 10% the deep seepage will be V_{ds} = 0, will cause only a deficit D_P =15% and the application efficiency will be E_a = 100%, Eqs. (5), (6) and (7).

7.4. Comparing the simple irrigation schedule, X=1, with the conventional irrigation schedule, X=a

A comparison of the simple irrigation schedule with the conventional irrigation schedule indicates that there are water savings when using the simple irrigation schedule (for all K_y values and all remediation costs for environmental pollution, Cr_2). However, an increase or decrease in total return will depend on the cost of water Cr_1, remediation costs for environmental pollution Cr_2, and the coefficient of uniformity *CV*.

If the system is designed based on a uniformity with *CV* values between 5% and 10%, water saving and the increase or decrease in total return are only limited (or acceptable).

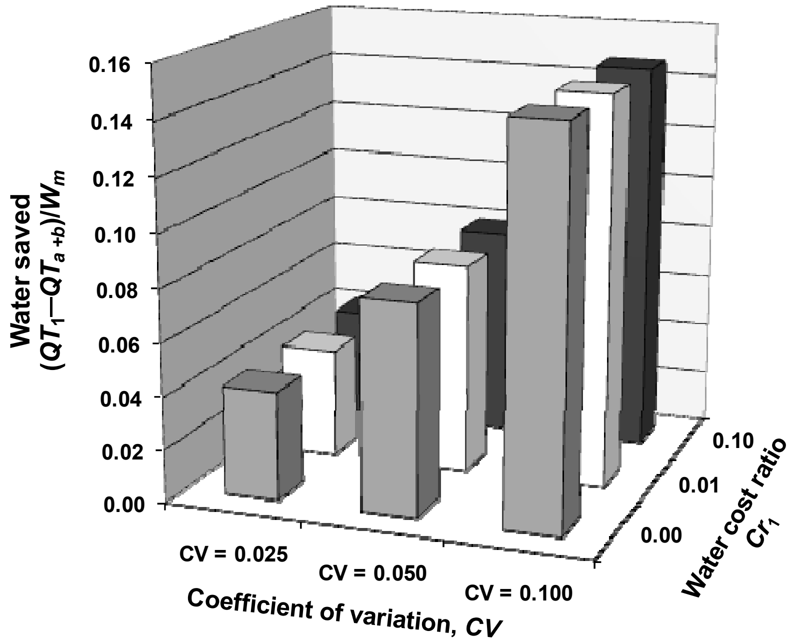

Fig. 6. Amount of water saved by applying simple irrigation schedule compared with the environmental protection schedule one; $(QT_1–QT_{a+b})/W_m$, water saved; Q total irrigation discharge; W_m seasonal water application for maximum yield; T_{a+b} and T_1, time for environmental protection and simple irrigation schedule, respectively; CV, coefficient of variation; Cr_1, water cost ratio; (for all Cr_2 pollution cost ratio and all K_y reduction coefficient).

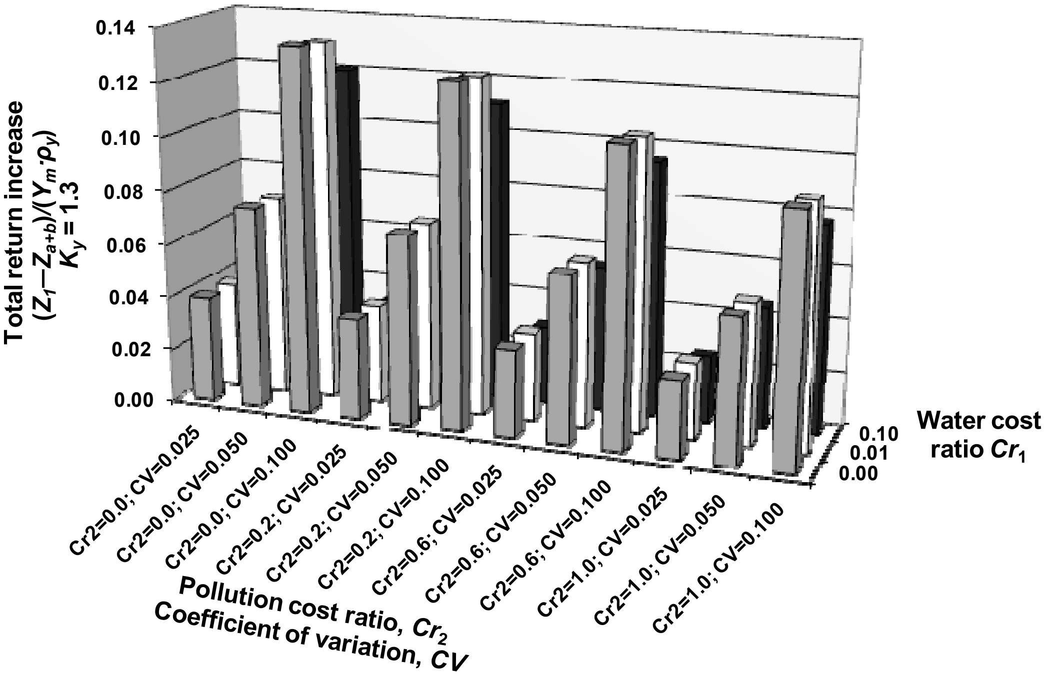

Fig. 7. Total return increase by applying simple irrigation schedule compared with the environmental protection schedule one; $(Z_1-Z_{a+b})/(Y_m \rho_y)$, increase in total return; Z_{a+b} and Z_1 total economic return for environmental protection and simple irrigation schedule, respectively; Y_m, maximum crop yield; ρ_y, unit cost of production; *CV*, coefficient of variation; Cr_1, water cost ratio; Cr_2 pollution cost ratio; (for reduction coefficient $K_y = 1.3$).

7.5. Comparing the simple irrigation schedule, X=1, with the environmental irrigation schedule, X=a+b

A comparison of the simple irrigation schedule with the environmental irrigation schedule indicates that there are water savings when using the environmental irrigation schedule (for all K_y values and all remediation costs for environmental pollution, Cr_2). However, there will be a decrease in total return depending on the cost of water Cr_1, the remediation costs for environmental pollution Cr_2, and the coefficient of uniformity *CV*, (see Figs. 6 and 7). For constant values of K_y the total return reduction will increase as the *CV* value increases, but will decrease with respect to increased Cr_1 and Cr_2 values.

If the system is designed on the basis of a uniformity with *CV* values between 5% and 10%, the water saving and the decrease or increase in total return are only limited (or acceptable).

7.6. Overall results

When the price of water and remediation costs are available (or can be estimated), the optimal irrigation, $X = X_0$, will achieve the optimal return, Z_0, Eqs. (13) and (14).

Deep seepage, V_{ds} (Eq. 7), can be eliminated or minimised by scheduling deficit irrigation, ($a<X<a+b$). When a drip irrigation system is designed for *CV* between 5% and 10%, and scheduled for 10% deficit irrigation, Eq. (6), deep seepage, V_{ds}, can be minimised to less than 1% of the total amount applied, *QT*.

The two cost ratios, Cr_1 and Cr_2, Eqs. (11) and (12), are two economic indicators in the determination of proper irrigation schedules. Information of both these ratios may not be available. However, if high uniformity is designed for the micro-irrigation system, the significance of these two ratios will be reduced.

For $CV < 10\%$ the simple irrigation schedule ($X = 1$) can be used when the two cost ratios, Cr_1 and Cr_2, are not available.

The complete computer simulation shows the significance of drip irrigation design in regard to the selection of design criteria. If the system is designed based on a CV<10% value both the conventional ($X = a$) and the simple ($X = 1$) irrigation schedules can be used with only limited (or acceptable) yield reduction and over-irrigation. Both the conventional ($X = a$) and the simple ($X = 1$) irrigation schedules are very easy to use in field irrigation.

The economic analysis above did not include the capital cost of the irrigation system. However, since the optimal scheduling requires a minimum uniformity in the micro-irrigation system to achieve an expected fixed return, a minimum cost for the irrigation system is, in fact, used in the economic consideration (Wu & Barragan, 2000). The economic analysis was made without considering the cost of the micro-irrigation system, fertilisers and chemicals, the land farm labour and all operating costs. It can only be considered to be a partial economical analysis, although it does show the effect of uniformity in system design and irrigation schedules on water conservation, yield return and environmental pollution.

It is interesting to notice that all four irrigation schedules will merge to only one schedule ($X = 1$), when the uniformity of water application is total (CV = 0% or EU = 100%). Therefore, when a high uniform irrigation is designed and used the difference between the specified irrigation schedules will be reduced.

It is very easy to design a micro-irrigation system for coefficient of variation $CV \leq 10\%$ (or EU = 87%). By selecting, for example, emitters with a manufacturer's coefficient of variation $CV_{(m)}$ = 5%, an emitter discharge exponent $x = 0.5$ and the number of emitters grouped as a unit $N = 2$, then the coefficient of hydraulic variation will be $CV_{(h)}$=8.7% and the pressure ratio $h_{\min} / \bar{h}$=0.79. If emitters with only 2% manufacturing variation are selected then the hydraulic design can be easily made to maintain a coefficient of hydraulic variation of $CV_{(h)}$=9.8% and the pressure ratio will be $h_{\min} / \bar{h}$=0.76 (see Eqs. (34) and (35)).

Micro-irrigation systems can easily achieve a coefficient of variation uniformity of less than 10%. Under such uniformity the optimal irrigation schedule, $X = X_0$, for micro-irrigation application will be similar to the simple irrigation schedule, X=1.

8. Conclusions

Micro-irrigation can provide an irrigation water application with high uniformity. However, uniformity alone is not sufficient to achieve the goal of irrigation. The irrigation schedule is equally important in micro-irrigation practice.

Since a high proportion of water resources are used for agricultural production, micro-irrigation systems designed with high uniformity can be scheduled to achieve water conservation as well as environmental protection. Protecting the environment from pollution and contamination will become an important issue in the future management of irrigation.

When a high uniform irrigation is designed and used ($CV < 10\%$ or $EU = 87\%$), the differences between the specified irrigation schedules will be reduced. It is very simple to design a micro-irrigation system for a coefficient of variation equal to or less than 10%. The many years of research and the numerous improvements made by manufacturers mean that it is no longer difficult to find emitters with a manufacturing variation of $CV_{(m)} = 5\%$ or less. In such a case the hydraulic design can be easily made to maintain a pressure ratio $h_{min}/\bar{h} = 0.95$ (for $N = 1$) or $h_{min}/\bar{h} = 0.79$ (for $N = 2$).

The K_y values show the additional effects in the economic analysis of crop sensitivity to deficit irrigation. For a high uniformity in the micro-irrigation system the influence of K_y values, when comparing the different irrigation schedules, is not significant and there is only limited (or acceptable) yield reduction and over-irrigation.

The optimal irrigation schedule, X_0, can achieve optimal return and also provide water saving compared with the conventional irrigation schedule, $X = a$. Deep seepage can be eliminated or minimized by scheduling deficit irrigation.

The environmental protection irrigation schedule, $X = a+b$, can save more water but will cause some total return reduction compared with the optimal irrigation schedule. When there is an environmental concern in polluting nearby streams or underlying ground water, the environmental protection schedule will prevent the possibility of pollution.

The simple irrigation schedule, $X = 1$, can be used for the micro-irrigation system when it is designed with high uniformity ($CV < 10\%$ or $EU = 87\%$). This simple irrigation schedule applies the same amount of irrigation as the amount required by evapotranspiration. The simple irrigation schedule is not only able to produce a nearly optimal yield but also to achieve more water saving when the system is designed with high uniformity. The simple irrigation schedule in a high uniformity micro-irrigation system can limit deep seepage to less than 5% and achieve irrigation application efficiency as high as 95%.

References

Anyoji, H., & Wu, I. P. (1994). Normal distribution water application for drip irrigation schedules. *Transactions of the ASAE*, 37, 159-164.

ASAE (2000). Design and installation of microirrigation systems. ASAE EP405.1 DEC99. In: ASAE Standards, St. Joseph, Michigan.

Barragan, J, & Wu, I. P. (2001). Optimal scheduling of a micro-irrigation system under deficit irrigation. *Journal of Agricultural Engineering Research*, 80, 201-208.

Barragan, J., & Wu, I. P. (2005). Simple pressure parameters for micro-irrigation design. *Biosystems Engineering*, 90, 463-475.

Barragan, J., Bralts, V., & Wu, I. P. (2006). Assessment of emission uniformity for micro-irrigation design. *Biosystems Engineering*, 93, 89-97.

Bralts, V. F., Wu, I. P., & Gitlin, H. M. (1981). Manufacturing variation and drip irrigation uniformity. *Transactions of the ASAE*, 24, 113-119.

Clark, G., Haman, D., Prochasca, J., & Yitayew, M. (2006). General system design principles. In F. R. Lamm, J. E Ayars, & F. S. Nakayama (Eds.), *Micro-irrigation for Crop Production* (pp.161-220). Elsevier, Amsterdam.

Dorrenbos, J., & Kassam, A. H. (1979). Yield response to water. *FAO Irrigation Drainage* Paper No. 33. Rome.

Juana, L., Losada, A., Rodriguez-Sinovas, L., & Sanchez, R. (2004). Analytical relationships for designing rectangular drip irrigation units. *Journal of Irrigation and Drainage Engineering*, 130, 47-59.

Wu, I. P. (1988). Linearized water application function for drip irrigation schedules. *Transactions of the* ASAE, 31, 1743-1749.

Wu, I. P. (1993a). Microirrigation design for trees. ASAE Paper No. 93-2128, presented at the ASAE Summer Meeting, Spokane, Washington, June.

Wu, I. P. (1993b). Design considerations of drip irrigation system. Trans., R53, Q44, 15th Congress on Irrigation and Drainage, ICID, the Hague, the Netherlands. September.

Wu, I. P. (1995). Optimal scheduling and minimizing deep seepage in micro-irrigation. *Transactions of the ASAE* 38, 1385-1392.

Wu, I. P. & Barragan, J. (2000). Design criteria for microirrigation systems. *Transactions of the ASAE,* 43, 1145-1154.

Wu, I. P., Barragan, J., & Bralts, V. (2006). Field performance and evaluation. In F. R. Lamm, J. E Ayars, & F. S. Nakayama (Eds.), *Micro-irrigation for Crop Production* (pp. 357-387). Elsevier, Amsterdam.