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Maximizing Irrigation Water Productivity by Optimizing Leaching Fraction

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Abstract: The importance of maximizing irrigation water productivity is increasing as the water resources still decreasing and deteriorating due to environmental interactions. An optimal irrigation water depth (including leaching water depth) was estimated in order to maximize water unit volume productivity by using the optimal leaching fraction (LF), which is calculated by the new proposed model—unit yield ratio (UYR%) and irrigation depth ratio (IDP). A computer program was constructed to apply this model for several crops irrigated by two water resources—river and well. The water salinity of river was 1.1 dS/m and the well salinity was 3.85 dS/m. The results showed that there is an optimal leaching requirement (LR) value for each crop irrigated by any water resource. The maximum UYR% of the alfalfa irrigated by saline well water was 58.45% with the optimal LF = 0.4, while the maximum UYR% of the bean irrigated by river water was 78.58% with the optimal LR = 0.2. The optimal LF is saving water by increasing the productivity of irrigation water unit volume, especially when using saline irrigation water, for example, an increase of IDP for alfalfa by only 20%, followed by an increase of UYR% about 47.5% (from 12% to 57%) by increasing LF from 0.1 to 0.3.

Key words: Leaching fraction, crop productivity, saline irrigation water.

1. Introduction

As water resources are decreased in quantity and affected in quality, reusing saline water for irrigation has been of interest for decades, especially when other water supplies became scarce during the drought [1]. Using saline water for irrigation purposes must be followed by increasing leaching fraction (LF) in order to maintain acceptable salt water balance within the depth of root zone. LF is defined as the amount of water that is needed to maintain crop productivity [2]. The crop relative yield varied inversely with the soil water salinity, so increasing LF was improving crop production. But the irrigation water unit volume productivity was not related directly to the crop yield, it may be decreased in spite of increasing in the yield. Observing of the irrigation water quality and its potential impact on the crops is essential to optimize the crop productivity. As the irrigation water was evaporated, the dissolved salt was accumulated in the soil profile, so another water depth more than irrigation requirements must be supplied to leach the excess salt quantities. The additional water quantity was defined as leaching requirements (LR) and varied directly with the water salinity. Its ratio to the irrigation water requirements was defined as LF [3]. The most common assessment to characterize irrigation water salinity is the electrical conductivity (EC). There is a linear relationship between electrical conductivity of irrigation water (EC_w) and the total dissolved salts (TDS) [4], as Eqs. (1) and (2):

If $EC_w < 5$ dS/m:

$$\text{TDS (mg/L)} = 640 \times EC_w\ \text{(dS/m)} \quad (1)$$

If $EC_w \geq 5$ dS/m:

$$\text{TDS (mg/L)} = 800 \times EC_w\ \text{(dS/m)} \quad (2)$$

A nonlinear equation was proposed to express the relationship between EC_w and TDS for saline irrigation water [5], as Eq. (3):

If $EC_w \geq 6$ dS/m:

$$\text{TDS (mg/L)} = 617 \times EC_w\ \text{(dS/m)} + 23 \times \{EC_w\ \text{(dS/m)}\}^2 \quad (3)$$

The salinity effect on the crops can be explained as

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a matrix of three water salinity effects verses five specific field conditions. The water salinity effects are the osmotic potential, toxicity and infiltration effects, while the field conditions are the crop sensitivity, soil texture, climate, drainage efficiency and irrigation management [6]. Because the crop tolerance itself changes with its growth stages from seedling to harvesting, using saline water in irrigation is more complicated than the matrix mentioned above [7]. Salinity does not affect the yield of any crop until it exceeds a critical salinity limit for that crop (threshold point), then the yield decreases linearly with the salinity after this critical point. The yield potential as a percentage ratio (YR%) can be estimated by Eq. (4) [8, 9]:

$$YR\% = 100 - b \times (EC_e - a) \quad (4)$$

where, a: threshold point of given crop; b: decreasing in yield as a percentage ratio per unit increase in salinity (increase by 1 dS/m); EC_e: salinity of soil water extract (dS/m).

Maas and Grattan [10] improved a relation between EC_w and EC_e depending upon LF values from 10% to 30% of irrigation water requirements. EC_e can be estimated from the observed value of irrigation water source salinity (EC_w) as Eqs. (5) and (6), and depends on the modified salt balance equation [11, 12]:

$$EC_e = EC_w \times FC \quad (5)$$

$$FC = (1 + LF)/(3 \times LF) \quad (6)$$

where, FC: salinity concentration factor.

As the soil salinity decreased with increasing LF, crop production was improved, but the irrigation water depth also increased, so an optimal irrigation water depth, including LF, can be estimated in ordure to maximize the water unit productivity.

The objective of this paper was to optimize irrigation water depth to maximize irrigation water productivity.

2. Theory and Methodology

A new term called unit yield ratio (UYR%) has been introduced and defined as a ratio of crop relative yield to the irrigation depth percentage (IDP), while IDP was defined in this paper as LF plus the unity, i.e., if LF = 0.2, then IDP is 1.2 = 1 + 0.2. As a relationship between salinity and yield was calculated using Eqs. (4)-(6), the irrigation depth ratio (IDR) was estimated as Eq. (7):

$$IDP = LF + 1 \quad (7)$$

Then the unit yield ratio (UYR%) will be calculated as Eq. (8):

$$UYR\% = YR\%/IDR \quad (8)$$

The minimum LF in this paper was 0.1, and its maximum allowable value was assumed to be 0.5, so the IDR values range was from 1.1 to 1.5. The UYR% value was calculated as iterations for LF values from the minimum value (0.1) to the maximum value (0.5) by an increment 0.02, then select the maximum UYR% value which means the optimal combination of the yield (YR%) and total depth of the irrigation water (IDR).

A computer program was constructed to apply this model for several crops irrigated by two water resources—river and well. Six crops of different tolerance to salinity were selected in this study, alfalfa, bean, tomato, potato, wheat and soybean. The optimal irrigation water depth including leaching water depth was estimated by the new proposed model (UYR% and IDP) in order to maximize the water unit volume productivity. This model applied to several crops irrigated by two assumed irrigation water sources—Euphrates river and ground water. The river water salinity was 1.1 dS/m and the well salinity was 3.85 dS/m. Crops mentioned above were selected in order to observe the validity of the proposed theoretical model. These crops salinity tolerance data were given in Table 1.

3. Results and Discussion

As the minimum LF value was assumed to be 0.1, the proposed IDR and the factor of concentration (FC) were estimated by Eqs. (7) and (6), respectively, then the relative yield (YR%) and the unit yield ratio (UYR%)

Table 1 Salt tolerance of herbaceous crops[1] (after Maas 1993) [9].

Crop	Salt tolerance		Rating
	Threshold point (dS/m) (*a* value in Eq. (4))	Slope (%) (*b* value in Eq. (4))	
Barley	8.0	5.0	T
Bean	1.6	9.5	MS
Soybean	5.0	20.0	MT
Wheat	6.0	7.1	MT
Alfalfa	2.0	7.3	MS
Potato	1.7	12.0	MS
Tomato	0.9	9.0	MS
Peach	1.7	21.0	S

[1] These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices.
T = tolerant, MT = moderately tolerant, MS = moderately sensitive and S = sensitive.

Table 2 Sample of calculations for alfalfa (*a* = 2 and *b* = 7.3) irrigated by saline water (EC_w = 3.85 dS/m).

LF	IDR	FC	EC_e = FC × 3.85 (dS/m)	YR%	UYR%
0.10	1.10	3.67	14.11	11.60	10.54
0.12	1.12	3.11	11.98	27.15	24.24
0.14	1.14	2.71	10.45	38.32	33.61
0.16	1.16	2.42	9.30	46.71	40.27
0.18	1.18	2.19	8.41	53.39	45.09
0.20	1.20	2.00	7.70	58.39	48.66
0.22	1.22	1.85	7.12	62.62	51.33
0.24	1.24	1.72	6.63	66.20	53.39
0.26	1.26	1.62	6.22	69.19	54.92
0.28	1.28	1.52	5.87	71.75	56.05
0.30	1.30	1.44	5.56	74.01	56.93
0.32	1.32	1.38	5.29	75.98	57.56
0.34	1.34	1.31	5.04	77.81	58.07
0.36	1.36	1.26	4.85	79.20	58.23
0.38	1.38	1.21	4.66	80.58	58.39
0.40	1.40	1.67	4.49	81.82	58.45
0.42	1.42	1.13	4.34	82.92	58.39
0.44	1.44	1.09	4.20	83.94	58.29
0.46	1.46	1.06	4.07	84.89	58.14
0.48	1.48	1.04	4.01	85.33	57.65
0.50	1.50	1.00	3.85	86.50	57.66

were calculated using Eqs. (4)-(8). For example, for alfalfa irrigated by saline water, if LF = 0.1, then from Eq. (7), IDR = 1.1, from Eq. (6), FC = (1 + 0.1)/(3 × 0.1) = 3.67, and from Eq. (5), EC_e = 3.85 × 3.67 = 14.11 dS/m. Then the relative yield of alfalfa can be estimated from Eq. (4) using salinity data (Table 1), as YR% = 100 – 7.3 × (14.11– 2) = 11.60%, and then, the unit yield ratio from Eq. (8), as UYR% = 11.60%/1.1 = 10.54 (Table 2), respectively. The same procedure was used for all other values of LF for alfalfa irrigated by saline water (Table 2) and for bean irrigated by river water (Table 3). From both tables, it is clear that the UYR% values increase with increasing LF, until it reaches a maximum value, then it will be decreased in spite of increasing LF. Fig. 1 showed the relationship between UYR% and LF for alfalfa, while Fig. 2 explained the same relation for bean. Both curves has an inflection point, which mean there is an optimal value of UYR%, followed by maximum yield ratio for a unit depth of the irrigation water expressed as IDP. The relationship between LF and UYR% in both Figs. 1 and 2 was represented by the 2nd order nonlinear equation with acceptable regression value (R^2) (0.93 and 0.99, respectively). In Fig. 2, the other curve was expressed as the 3rd order nonlinear equation. The R^2 value was decreased from 0.99 to 0.89.

In Table 4, the relative yield (YR%) and the unit yield ratio (UYR%) were calculated for tomato and potato irrigated by river water, using the same procedure that used for bean as explained in Table 3 and Fig. 2. It is clear that the UYR% values increase with increasing LF, until it reaches a maximum value, then it will be decreased after reaching the optimal LF value. Fig. 3 explained the relationship between UYR% and LF for tomato, while Fig. 4 explained the same relation for potato. Both curves has an inflection point, which mean there is an optimal value of UYR%, followed by maximum yield ratio for a unit depth of the irrigation water. R^2 about the same value in Fig. 3 for the 2nd and 3rd order nonlinear equation was 0.94 and 0.99, respectively.

Two crops irrigated by saline water were shown in Table 5. Wheat and soybean UYR% for each LF value was calculated. Fig. 5 explained the optimal LF for wheat, while Fig. 6 explained the same relation for soybean. R^2 values for both curves were greater than 0.95.

The optimal LF that proposed in this research was saved irrigation water by increasing the productivity of irrigation water unit volume especially when using saline irrigation water, for example, increase of IDP for alfalfa by only 20%, followed by increase of UYR about 47.5% (from 12% to 57.5%) by increasing LF from 0.1 to 0.3.

Increasing LF greater than the optimal value was followed by increasing relative yield of the crop, but the UYR% was decreased. That mean the relative yield increasing was followed by losing a quantity

Table 3 Sample of calculations for bean (*a* = 1.6 and *b* = 9.5) irrigated by river water (EC_w = 1.1 dS/m).

LF	IDR	FC	EC_e = FC × 1.1 (dS/m)	YR%	UYR%
0.10	1.10	3.67	4.04	76.83	69.84
0.12	1.12	3.11	3.42	82.71	73.85
0.14	1.14	2.71	2.98	86.89	76.22
0.16	1.16	2.42	2.66	89.93	77.53
0.18	1.18	2.19	2.41	92.31	78.22
0.20	1.20	2.00	2.20	94.30	78.58
0.22	1.22	1.85	2.04	95.82	78.54
0.24	1.24	1.72	1.89	97.25	78.42
0.26	1.26	1.62	1.78	98.29	78.01
0.28	1.28	1.52	1.67	99.34	77.61
0.30	1.30	1.44	1.58	100	76.92
0.32	1.32	1.38	1.52	100	75.75
0.34	1.34	1.31	1.44	100	74.63
0.36	1.36	1.26	1.39	100	73.53
0.38	1.38	1.21	1.33	100	72.46
0.40	1.40	1.17	1.28	100	71.43
0.42	1.42	1.13	1.24	100	70.43
0.44	1.44	1.09	1.20	100	69.44
0.46	1.46	1.06	1.17	100	68.49
0.48	1.48	1.04	1.14	100	67.57
0.50	1.50	1.00	1.10	100	66.67

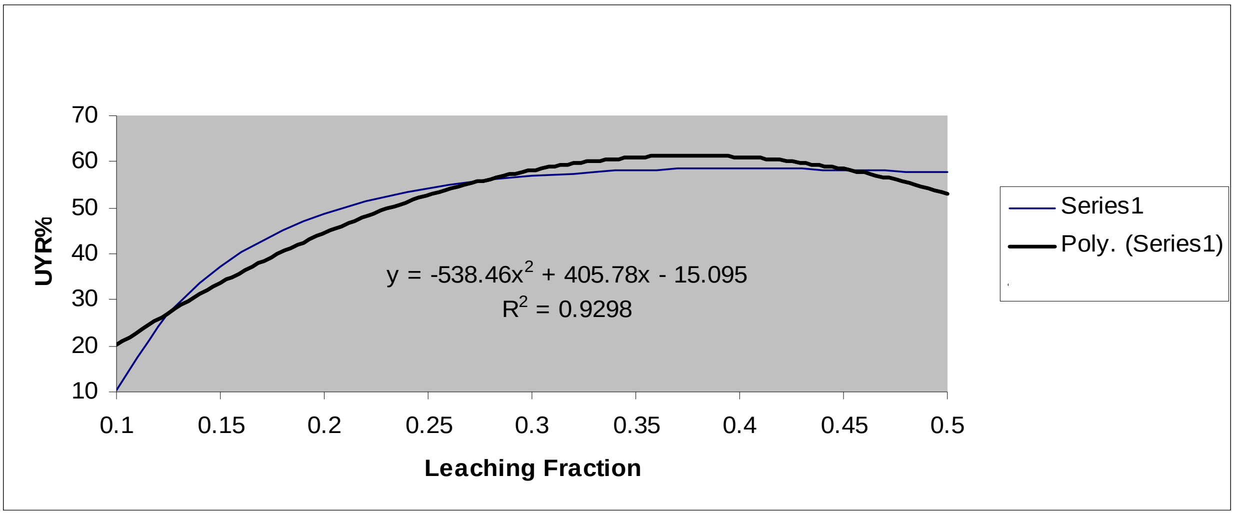

Fig. 1 The relation between UYR% and LF for alfalfa irrigated by saline water.

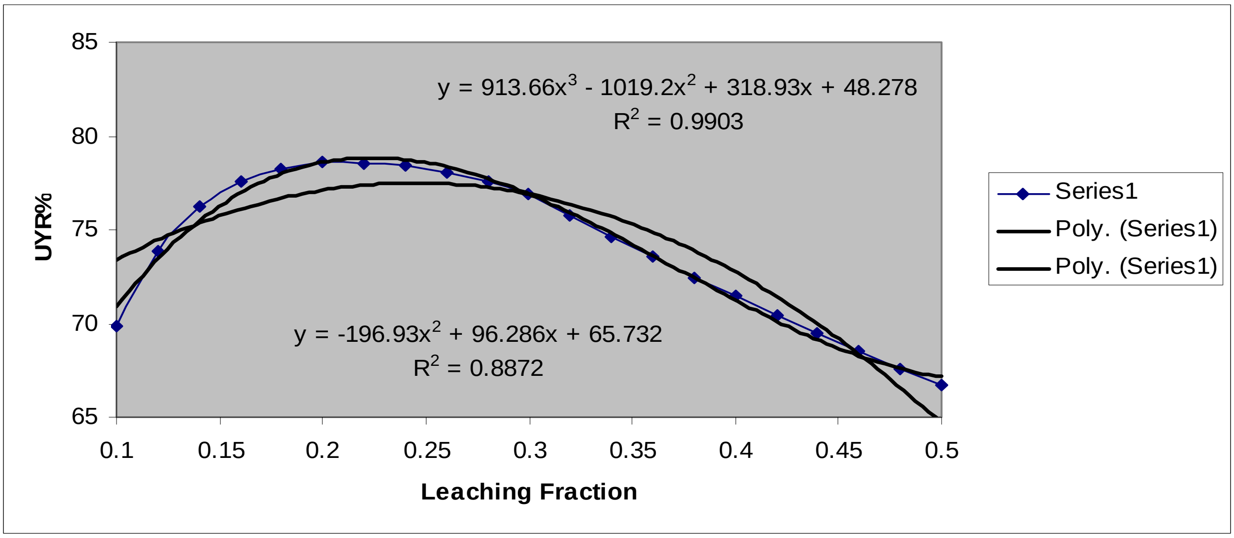

Fig. 2 The relation between UYR% and LF for bean irrigated by river water.
Thin lines correspond to the 2nd order polynomial and thick lines correspond to the 3rd order polynomial.

Table 4 The optimal UYR% for two crops irrigated by river water.

LF	IDR	FC	EC_e = FC × 1.1 (dS/m)	Tomato (a = 0.9, b = 9.0)		Potato (a = 1.7, b = 12)	
				YR%	UYR%	YR%	UYR%
0.10	1.10	3.67	4.04	71.74	65.21	71.92	65.38
0.12	1.12	3.11	3.42	77.32	69.04	79.36	70.86
0.14	1.14	2.71	2.98	81.28	71.30	84.64	74.25
0.16	1.16	2.42	2.66	84.16	72.55	88.48	76.28
0.18	1.18	2.19	2.41	86.41	73.22	91.48	77.53
0.20	1.20	2.00	2.20	88.30	73.58	94.00	78.33
0.22	1.22	1.85	2.04	89.74	73.56	95.92	78.63
0.24	1.24	1.72	1.89	91.09	73.46	97.72	78.81
0.26	1.26	1.62	1.78	92.08	73.08	99.04	78.60
0.28	1.28	1.52	1.67	93.07	72.71	100.00	78.12
0.30	1.30	1.44	1.58	93.88	72.22	100.00	76.92

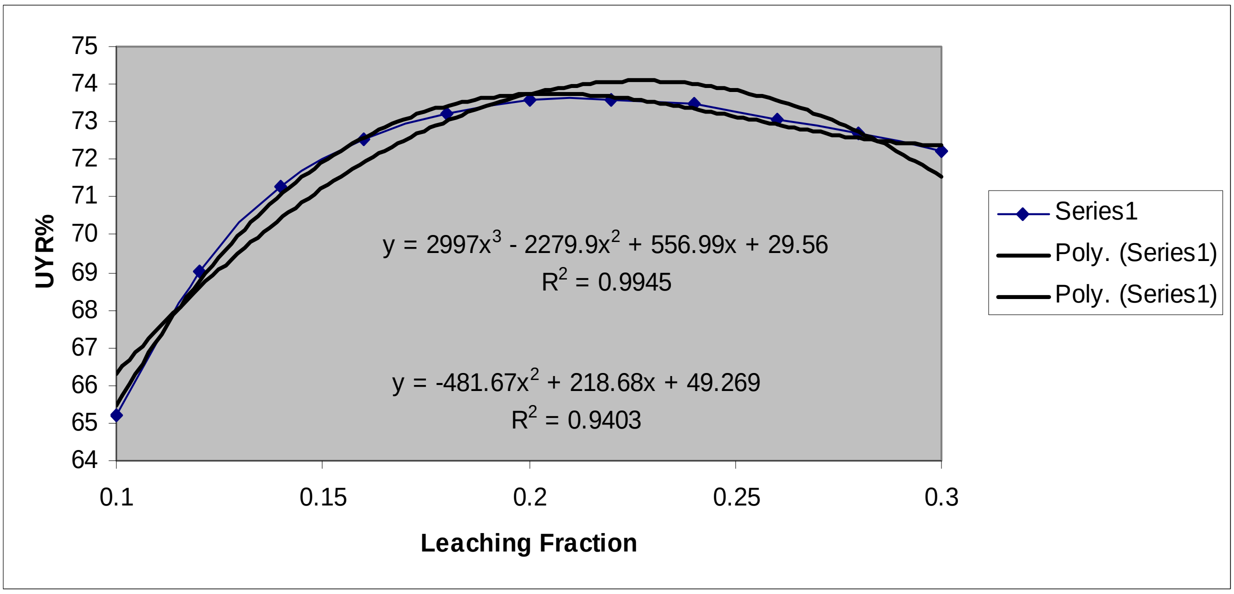

Fig. 3 The relation between UYR% and LF for tomato irrigated by river water.
Thin lines correspond to the 2nd order polynomial and thick lines correspond to the 3rd order polynomial.

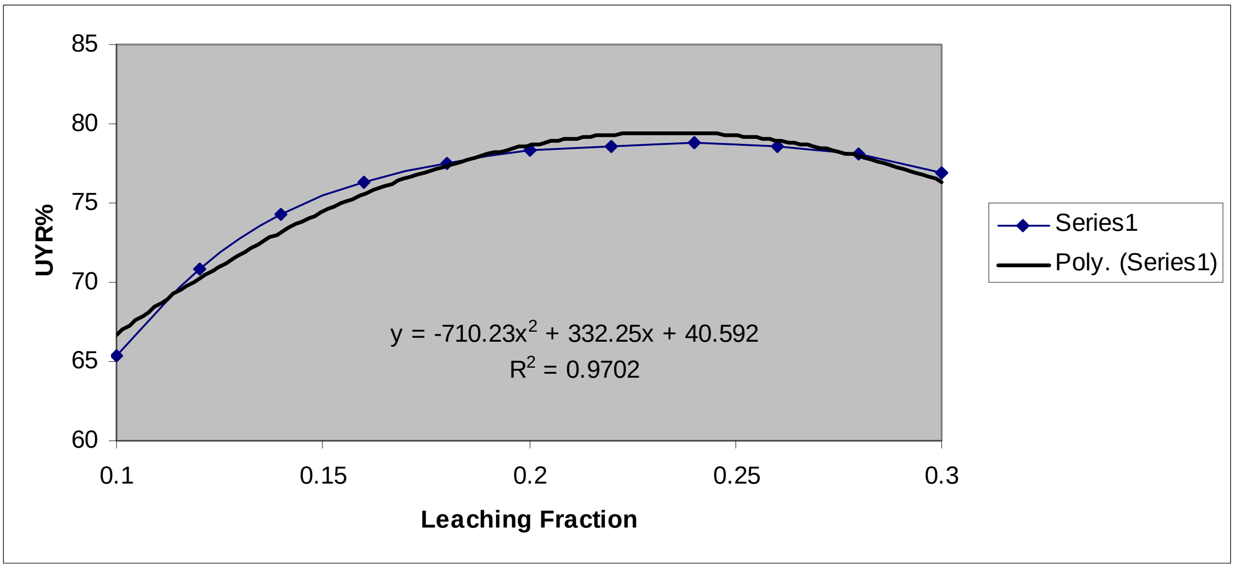

Fig. 4 The relation between UYR% and LF for potato irrigated by river water.

Table 5 The optimal UYR% for two crops irrigated by saline water.

LF	IDR	FC	EC_e = FC × 3.85 (dS/m)	Wheat (a = 6, b = 7.1)		Soybean (a = 5, b = 20)	
				YR%	UYR%	YR%	UYR%
0.10	1.10	3.67	14.11	42.49	38.63	0	-
0.12	1.12	3.11	11.98	57.54	51.38	0	-
0.14	1.14	2.71	10.45	68.41	60.00	0	-
0.16	1.16	2.42	9.30	76.57	66.01	14.00	12.07
0.18	1.18	2.19	8.41	82.89	70.24	31.80	26.95
0.20	1.20	2.00	7.70	87.93	73.28	46.00	38.33
0.22	1.22	1.85	7.12	92.05	75.45	57.60	47.21

(Table 5 continued)

LF	IDR	FC	EC_e = FC × 3.85 (dS/m)	Wheat (a = 6, b = 7.1)		Soybean (a = 5, b = 20)	
				YR%	UYR%	YR%	UYR%
0.24	1.24	1.72	6.63	95.53	77.04	67.40	54.35
0.26	1.26	1.62	6.22	98.44	78.13	75.60	60.00
0.28	1.28	1.52	5.87	100	78.12	82.60	64.53
0.30	1.30	1.44	5.56	100	76.92	88.80	68.31
0.32	1.32	1.38	5.29	100	75.76	94.20	71.36
0.34	1.34	1.31	5.04	100	74.62	99.20	74.03
0.36	1.36	1.26	4.85	100	73.53	100	73.53
0.38	1.38	1.21	4.66	100	72.46	100	72.46
0.40	1.40	1.67	4.49	100	71.43	100	71.43

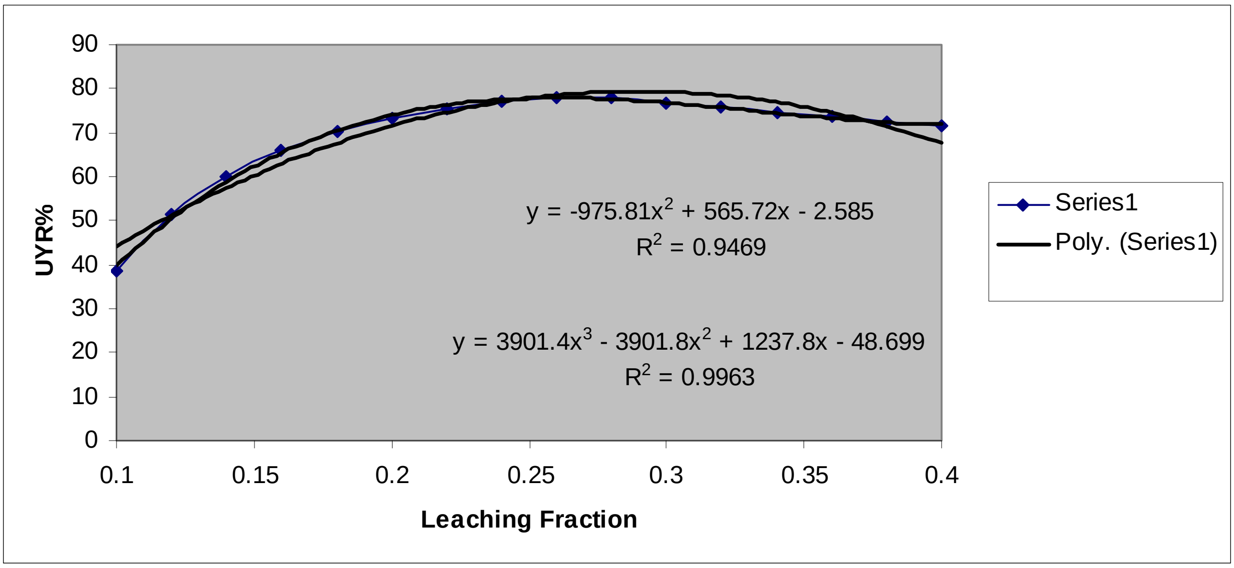

Fig. 5 The relation between UYR% and LF for wheat irrigated by saline water.

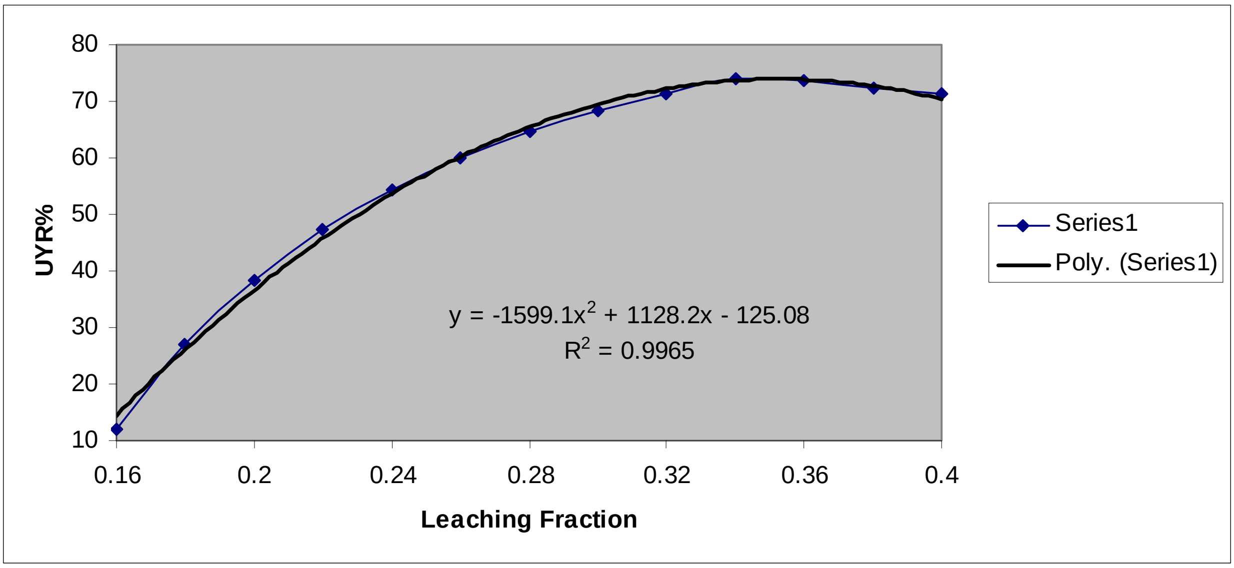

Fig. 6 The relation between UYR% and LF for soybean irrigated by saline water.

of water that can be used to expand the irrigated area and maximize the overall yield of the given irrigation water volume.

4. Conclusions and Recommendation

Results showed that there is an optimal LF value for each crop irrigated by any water resource (good quality river or saline water), in which the horizontal tangent of the nonlinear relation between LF and UYR% was horizontal. And there is a 2nd and 3rd order polynomial relationship between LF and UYR% with high correlation values for all crops selected in this paper.

The optimal LF was saving water by increasing the productivity of irrigation water unit volume especially when using saline irrigation water. Any increasing in relative yield by increasing LF greater than its optimal value was followed by decreasing irrigation water productivity. The optimal LF values for all selected crops were less than 0.34, except for alfalfa irrigated by saline water in which the optimal LF was 0.4.

It is recommended to design a long term field studies using several water quality resources in order to evaluate the proposed theoretical model.

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