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Development and Analysis of Irrigation Efficiency and Water Productivity Indices Relationships in Sprinkler Irrigation Systems

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Abstract

Improving water productivity (WP) in agriculture sector, as the main water user, plays an important role in resolving water shortage problems. Increasing irrigation efficiency and upgrading irrigation systems are the main strategies for this object. Different studies have been carried out on irrigation systems evaluation and water-yield relationships but no studies have been investigated the effect of irrigation efficiency indices on WP. In this study, the received water in various parts of the field was calculated based on uniformity coefficient (CU) and irrigation adequacy (pa) equations and then the effect of these indices on crop yield and WP was estimated based on wheat, barley and maize water-yield functions in Karaj and Qazvin regions (Shoor river basin). Results showed that the uniformity coefficient and adequacy have high effect on crops yield and crops WP and integrated study of these indices has high necessarily in irrigation management and deficit irrigation planning. Methodology of this study could have useful applications in design optimization, management and promotion of irrigation systems and in deficit irrigation planning.

Keywords: Uniformity Coefficient, Adequacy, Deficit Irrigation, Crop Yield

Introduction

One of the main challenges of world is water and food security. The increasing food demand and decreasing water allocation suggest that the agricultural sector has to increase agricultural water productivity for producing more food with less water (Cai and Sharma 2010).

This challenge in arid regions of the world, such as Iran, is more complicated. Agriculture sector is the main user of water in developing countries. In Iran, 91% of the supplied water (84 billion cubic meters) belongs to this sector. Hence, increasing water productivity, the attained crop yield or crop value per cubic meter of water, in this sector has very important role in water shortage problems relief.

Water is a critical agricultural input in arid regions that has high effect on crop yield and crop production. In these areas agriculture is no beneficial or even impossible without irrigation. Therefore, irrigation management and irrigation systems upgrading have a high important role in water productivity.

Irrigation systems evaluation is done based on irrigation efficiency indices such as uniformity coefficient, distribution uniformity and application efficiency. These indices affect the irrigation system design and irrigation hydromodule determination. In addition, success of irrigation projects usually expresses with these efficiency indices. In many new studies, water productivity (WP) has introduced as a more comprehensive index for evaluation of water management and study of water use efficiency in agriculture (Kijne et al., 2003; Wichelns, 2002).

Both irrigation efficiency and WP indices have useful applications in irrigation and water management systems evaluations and related studies and each of them will be appropriate regarding to study object. Some of manager and experts prefer WP and some of them prefer irrigation efficiency indices in their decisions and studies (Kijne et al., 2003; Wichelns, 2002). This issue has introduced big confusions in irrigation and water management systems (van Halsema and Vincent, 2012). Therefore, determination of irrigation efficiency indices and WP index relationships can increase agreement between decision makers, engineers, researchers and water users in planning, designing and operating strategies adoption.

Water application uniformity in the field expresses with uniformity coefficient (CU) and this index is the basic parameter in irrigation systems design and evaluation. Increase of CU through irrigation system improvement or system upgrading requires investment. The economic analysis should be applied in this investment regard to increased yield through CU increase. Irrigation adequacy (Pa) is another key management and operational parameter that defines as the percentage of the field receiving the desired amount of water or more. This parameter affects the total applied water in the field and hence affects crop yield and WP.

Various studies have carried out on water distribution and irrigation system effects on crops yield. Spatial soil moisture variation and irrigation distribution nonuniformity had been analyzed theoretically by Warrick and Gardner (1983). Ayars et al. (1991) and Ayars et al. (1990) studied relationships between sugar beet and cotton yield with irrigation uniformity and reported nonuniformity effects on crops yield. Moteos et al. (1997) studied sprinklers uniformity on cotton yield. AdorSim model for water distribution and yield simulation in sprinkler irrigation was developed and presented by Dechmi et al. (2004). This model has been used in water management strategies in the Ebro basin of Spain.

Ortega Alvarez et al. (2004), in study of set sprinkler irrigation system in semi arid region of the Spain reported that economic benefit for barely, maize, garlic, onion crops will attain with high uniformity coefficient (90 %). Colaizzi et al. (2005) in study of water use efficiency in sprinkler and trickle irrigation systems reported that trickle irrigation is the best system according to this index. Grassini et al. (2011) in study of agronomic practices impacts on maize yield reported that applied irrigation water was 41 and 20% less under pivot and conservation tillage than under surface irrigation and conventional tillage, respectively. Their simulations results showed that up to 32% of the annual water volume allocated to irrigated maize in the region could be saved with little yield penalty, by switching current surface systems to pivot, improving irrigation schedules to be more synchronous with crop water requirements and, as a fine-tune option, adopting limited irrigation.

Many studies had showed that main changes in irrigation management are essential to access optimize water use. For example, deficit irrigation as a effective water planning strategy for water use efficiency improve is introduced (Kirda C and Kanber R., 1999; English M., 1990; van Halsema and Vincent., 2012). This strategy can applied with decreasing of adequacy level in irrigation design and management.

Water-yield function has the key role in deficit irrigation optimization. All of studies and methodologies in the field of optimum water allocation in drought conditions use one form of this function (Wichelns, 2002). The result of these studies usually expresses as the optimum depth of irrigation for each crop in the cropping pattern. It should be noticed that always some parts of the field reaches water more than this optimum level and some parts reaches less than it. This fact is because of avoidable nonuniformity of water distribution in the field. CU and Pa determine that somewhat of field will be over-irrigated than target irrigation depth and somewhat will be under-irrigated than that. These indices also determine that this over-irrigation and under-irrigation intensity is to some extent. Therefore, this is essential that received water in each part of the field and those differences from desired irrigation depth, that is not necessarily the full irrigation depth, be estimated regards to CU and Pa values. These differences form desired depths will lead to difference from desired crop yield and WP.

In this study, the received water in various parts of the field was calculated based on uniformity coefficient (CU) and irrigation adequacy (Pa) equations and then the effect of these indices on crop yield and WP was estimated based on wheat, barley and maize water-yield functions in Karaj and Qazvin regions (Shoor river basin). Although the application of this method has been illustrated for sprinkler irrigation, it could be used for other irrigation systems as well.

Materials and methods

Irrigation efficiency equations and Indices

Irrigation efficiency in sprinkler irrigation is defined as (Keller and Bliesner, 1990):

$$E_{pa} = DE_{pa} R_e O_e \qquad (1)$$

Where, pa: irrigation adequacy (%), E_{pa}: application efficiency in pa (%), O_e: the ratio of received water to the entered water to the system, R_e: the effective fraction of irrigation water (it is evidence for drift and evaporation losses during the irrigation event). DE_{pa}: Distribution Efficiency in various pa and CU values (Keller and Bliesner 1990):

$$DE_{pa} = 100 + \left[(606 - 24.9\, pa + 0.349\, pa^2 - 0.00186\, pa^3)\right] \times (1 - CU/100) \qquad (2)$$

CU: coefficient of uniformity developed by Christiansen (%). It is one of the most important parameters used to represent sprinkler irrigation uniformity. It mathematically expresses as (Christiansen, 1941; Keller and Bliesner 1990):

$$CU = 100.(1 - \frac{\sum X}{n.m}) \quad (3)$$

Where, z: individual depth of catch observations from CU test (mm), $X = |z - m|$: absolute deviation of the individual observations from the mean (mm), $m = (\sum z)/n$: mean depth of observations (mm); and n: number of observations.

Received water in the field parts

The basic method for determining several sprinkler irrigation distribution parameters uses a normal cumulative probability density function of irrigation depth to represent the distribution of water in the root zone following irrigation and soil water redistribution (Hart and Reynolds, 1965). The standard deviation describing the shape of the distribution is defined by the irrigation uniformity coefficient (CU) for a given irrigation application system. Receiving irrigation water in any point of the field could be calculated from (Smesrud and Selker, 2001):

$$i_j = \left(\frac{CV}{0.1975}\right)\left[p_j^{\,0.135} - (1 - p_j)^{0.135}\right] + 1 \quad (4)$$

$$F(\sim;\ ) = \left(\frac{CV}{0.224}\right)\left[\ ^{1.135} - \sim^{1.135} + (1 -\ )^{1.135} - (1 - \sim)^{1.135}\right] + \ - \sim \quad (5)$$

Where: pj: probability of any given point of ground (pa=1- pj); ij receiving the irrigation depth; ~ and : the cumulative probability density limits. $F(\sim;\ )$; The area under the cumulative probability density curve between the limits of ~ and that is equal to volume of received water between the probability limits (always: $0 \le \sim_i \prec\ _i \le 0.95$); CV: coefficient of variation that can be calculated based on CU (Hart, 1961):

$$CV = \frac{1 - CU}{\sqrt{2/\pi}} \quad (6)$$

The most important parameter for estimating yield in various parts of the field is the mean received water in any part of the field (In_i) that can calculate from Eq. (7):

$$In_i = \frac{I_t}{\left(\frac{CV}{0.1975}\right)\left[(1 - pa)^{0.135} - (pa)^{0.135}\right] + 1} \times \frac{F(\alpha_i;\beta_i)}{\beta_i - \alpha_i} \quad (7)$$

Where, I_t is the target irrigation depth.

Irrigation uniformity has significant effect on crop yield and uniformity coefficient (CU) is a critical indicator in evaluation of irrigation systems efficiency. In the other word, received water in various parts of the field depends on irrigation uniformity and hence crop growth and yield in these parts depends on irrigation uniformity. Another key parameter that affects the received water in the field, is adequacy (pa). In this study, the received water in various parts of the field in a range of CU and pa values was calculated and then crop yield was calculated regard to these received water amounts. Local water-yield functions were used for estimating crop yields .

Water- yield function

Field studies data in the Shoor river basin were used for extracting maize, wheat and barley water-yield functions. These crops are the main crops in the region. The field data are shown in table 1 to table 3.

Table 1. Field study data used for water-yield function of maize (Mirlatifi and Sotudeh nia, 2002)

Irrigation amount (mm)	736	630	506	503	567	385	451	328
Yield (ha)	10648	5046	5089	11339	12624	6181	6319	2359

Table 2. Field study data used for water-yield function of barely (Farhadi bansouleh, 1998)

Irrigation amount (mm)	319	292	265	238	185	163	141	108	89	70	51
Yield (ha)	6148	6032	5828	5957	5526	5108	5132	4958	4515	3405	3296

Table 3. Field study data used for water-yield function of wheat (Golkar, 1998)

Irrigation amount (mm)	435	400	365	330	295	260	225	190	130	105	80	54
Yield (ha)	5532	5859	5628	5638	5307	4818	5117	4852	4229	3641	3174	3074

The fitted second order water yield functions for the above mentioned crops have been shown in Fig. 1.

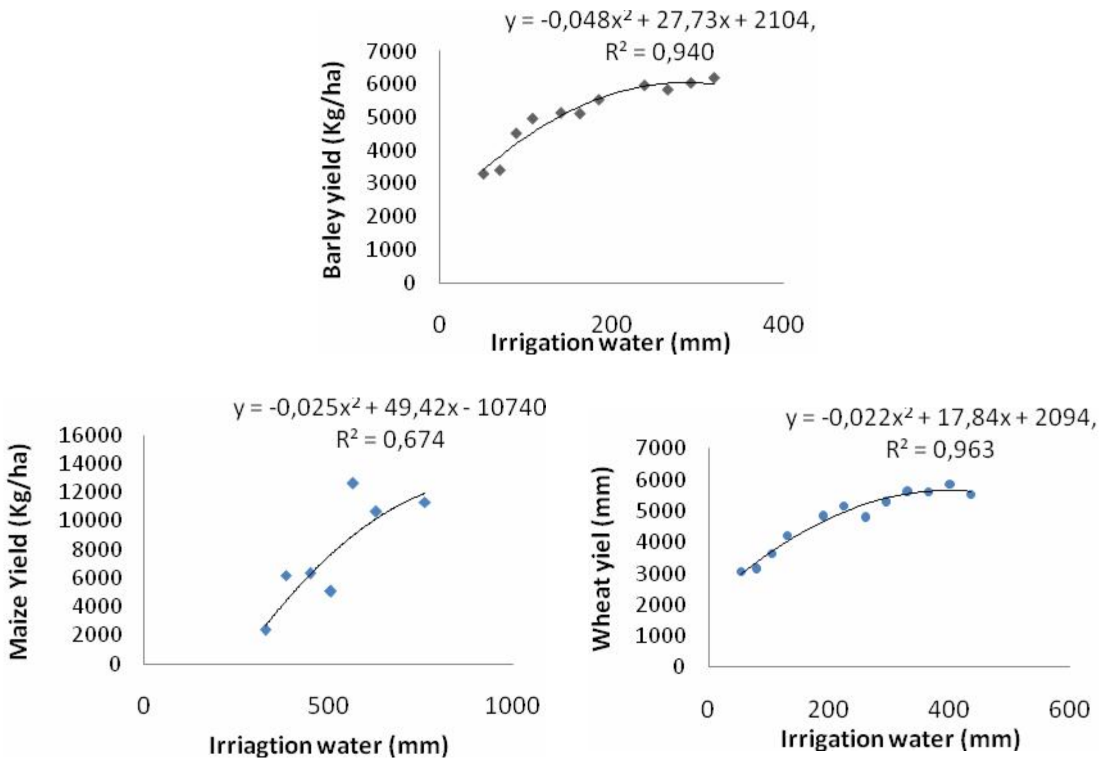

Figure 1. Water –yield functions in study area

Water Productivity

In agricultural sector, water productivity (WP) defines as the crop yield or the benefit and the crop value per cubic meter of water. WP may be measured by a series of indices, which describe its various aspects, e.g., physical and economic WP, irrigation WP, rainwater productivity, and ET WP. Individual indices serve various purposes (Cai et al., 2010). ET and irrigation water productivity can be defined as (Kijne et. La (2003):

$$WP_{ET} = \frac{Y\,(kg\ ha^{-1})}{ET\ (m^{3}\ ha^{-1})} \qquad (8)$$

$$WP_{I} = \frac{Y\,(kg\ ha^{-1})}{I\ (m^{3}\ ha^{-1})} \qquad (9)$$

Where Y is crop yield ($kg.ha^{-1}$), ET is evapotranspiration amount in growth season ($m^{3}.ha^{-1}$), I is seasonal irrigation amount ($m^{3}.ha^{-1}$), WP_{ET} is evapotranspiration water productivity and WP_I is irrigation water productivity.

From the irrigation perspective, the last form of water productivity equation is more applicable and useful in evaluation of irrigation management strategies effect on water productivity where water (as well as other inputs) is subject to a transformation process of crop or biomass production, owned and managed by the farmer (van Halsema and Vincent, 2012).

Denominator of the equation can be expressed in the term of net irrigation or gross irrigation amounts (I_n and I_g). It should be noticed that, the effect of the most important irrigation index, Irrigation efficiency (Ea), on water productivity can be investigated by putting the gross irrigation amount (I_g) in denominator of the equation. I_g is the base of irrigation Hydromodule calculation and is more important in economic analysis (Kijne et al., 2003):

$$WP_I = \frac{Y\,(kg\ ha^{-1})}{I_g\,(m^3\ ha^{-1})} = \frac{Y\,(kg\ ha^{-1})}{\frac{I_n\,(m^3\ ha^{-1})}{E_a\,(ratio)}} \qquad (10)$$

Irrigation efficiency and Water Productivity relationships

By combination of the irrigation efficiency and water productivity relationships, useful relationships are extractable for irrigation and water management. The Steps of used methodology in this study can be summarized as follow:

1- Calculation of received water (In_i) in various parts of the field base on CU and pa with equation (7)

2- Calculation of crop yield in various parts of the field (Y_i) regard to received water in these parts (In_i) with water-yield functions. Local water yield functions in this study:

Barely:

$$Y_i = -0.048 In_i^{\,2} + 27.72 In_i + 2104 \qquad (11)$$

Wheat:

$$Y_i = -0.022 In_i^{\,2} + 17.84 In_i + 2094 \qquad (12)$$

Maize:

$$Y_i = -0.025 In_i^{\,2} + 49.42 In_i - 10740 \qquad (13)$$

Validated agro-hydrological models such as AquaCrop can be used for crop yield prediction in this step.

3- Calculation of total crop yield in the field:

$$Y_t = \sum_{i=1}^{n} (\ _i - \sim_i) \times Y_i \qquad (14)$$

Where, Y_t : total crop yield of the field, i: field part number, Y_i :crop yield in i*th* part of the field. Other parameters are defined as before.

4- Calculation of WP (with combination of equations 2, 10 and 14):

$$WP = \frac{\frac{Y_t}{I_n}}{\left\langle 100 + \left[(606 - 24.9\,pa + 0.349\,pa^2 - 0.00186\,pa^3)\right](1 - \frac{CU}{100}) \right\rangle . O_e . R_e} \qquad (15)$$

The effect of technical and management parameters of irrigation systems (such as uniformity coefficient, adequacy, deficit irrigation, wind losses, sewage losses and …) on WP can be studied with this methodology. In this study, the effect of uniformity coefficient and adequacy on WP, as the key parameters, have been studied and discussed.

Results

Water Productivity index for different values of uniformity coefficient and adequacy are shown in Fig (2), (3) and (4) for wheat, barley and wheat respectively.

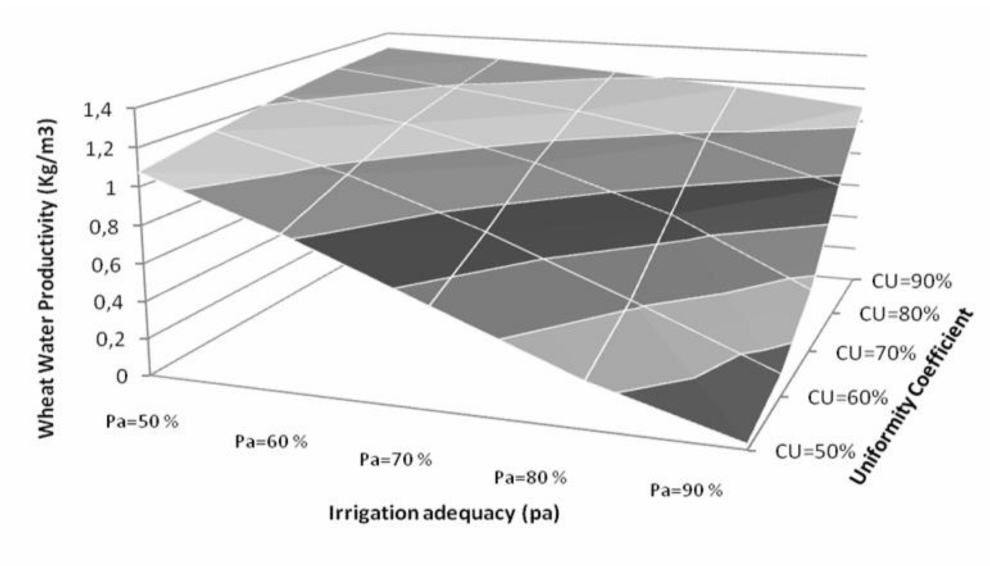

Figure 2. Water Productivity for different values of adequacy and uniformity for wheat

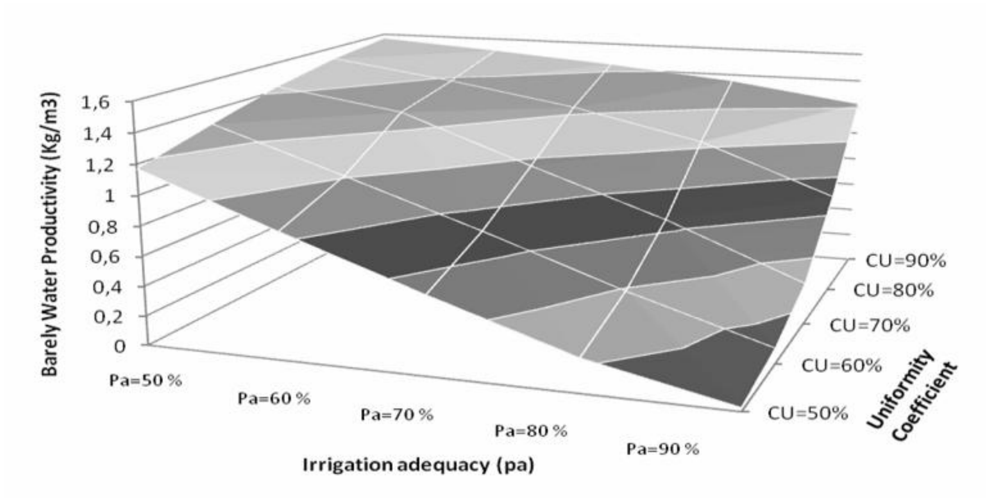

Fig 3. Water Productivity for different values of adequacy and uniformity for barely

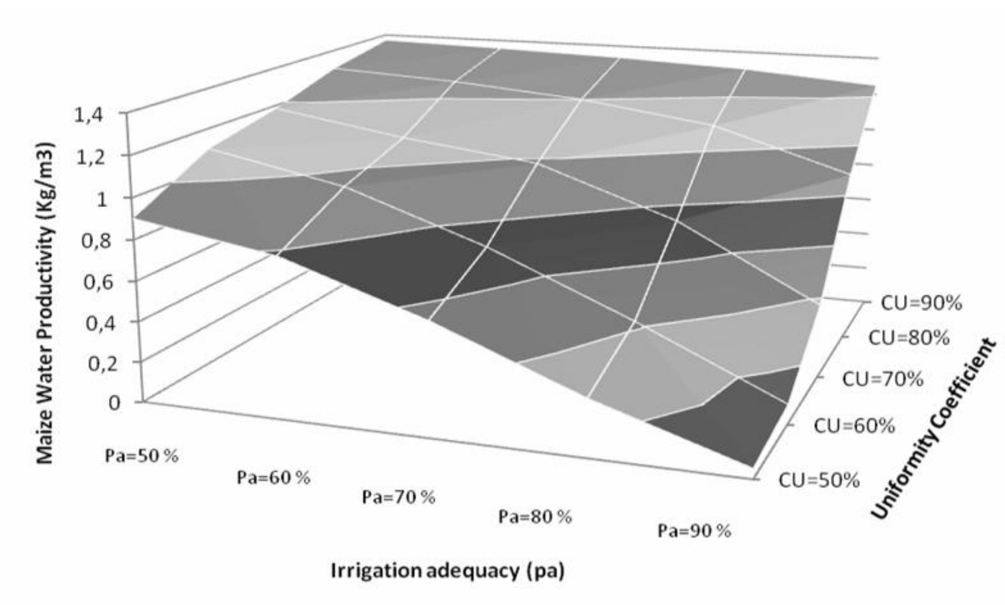

Figure 4. Water Productivity for different values of adequacy and uniformity for maize

These figures illustrate that both CU and irrigations adequacy have significant effect on WP and the intensity of this effect depends on water-yield function. These results could be used for irrigation scheduling, optimum crop pattern determination and WP optimization studies. In this regard, Figures 5, 6 and 7 show the fitted relationships between WP and CU for various values of irrigation adequacies (pa) in the study area for wheat, barley and maize, respectively.

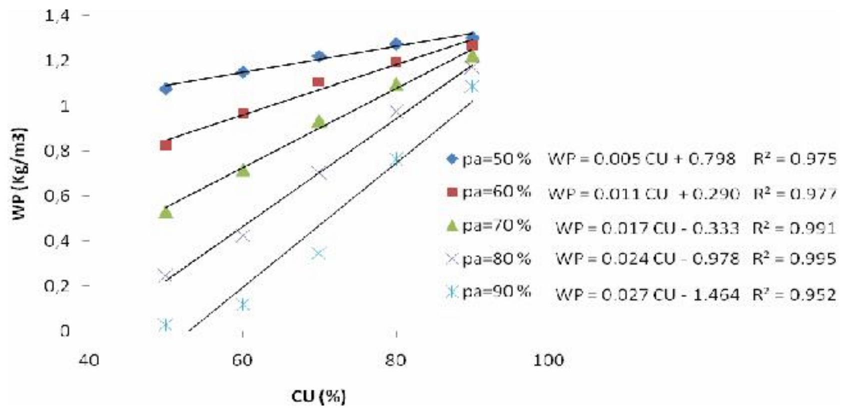

Figure 5. Fitted relationships for WP and CU in various irrigation adequacies for wheat

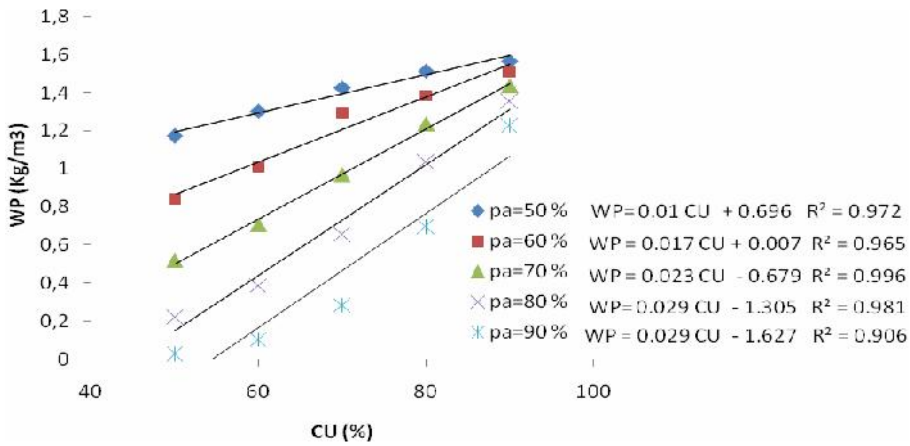

Figure 6. Fitted relationships for WP and CU in various irrigation adequacies for barely

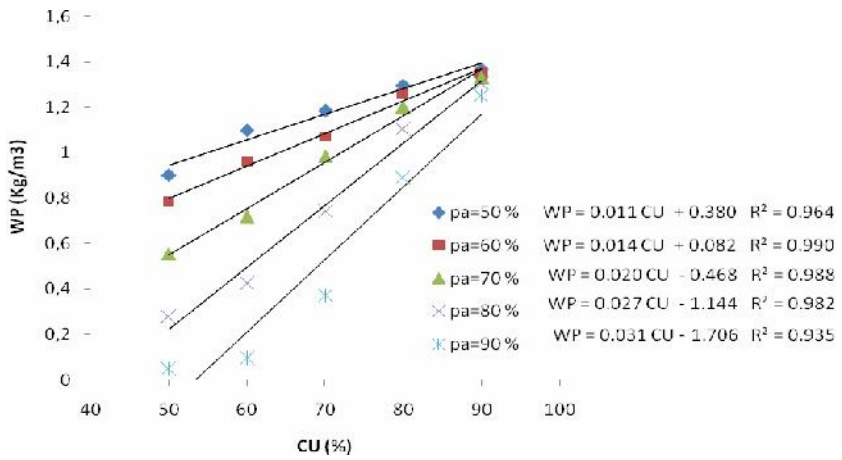

Figure 6. Fitted relationships for WP and CU in various irrigation adequacies for maize

The results of this study showed that in a given irrigation adequacy level, water productivity reduces by decreasing uniformity coefficient. This reduction is more intensive in higher adequacy levels. Significant coupled effects of irrigation adequacy and uniformity coefficient on crops yield make notes that the uniformity coefficient index alone cannot be a good criterion in irrigation systems evaluation. In addition, in application of deficit irrigation strategies and treatments, irrigation adequacy will not be sufficient alone and considering uniformity coefficient is very importance. Therefore, irrigation evaluation, planning and deficit irrigation optimizing should consider coupled effects of irrigation adequacy and uniformity coefficient.

In irrigation systems with lower uniformity, more irrigation adequacy will lead more discrepancy between over- and under- irrigated areas of the field. This will lead to more difference between crop growth and yield in various parts of the field. Therefore, it can be concluded that in irrigation systems with lower uniformity, lower adequacy levels, as a deficit irrigation strategy, will be more justified.

In another study on irrigation uniformity role on lettuce production and profitability, Hussain (2010) reported where the exiting irrigation uniformity is low, returns can generally be increased with improvements in irrigation uniformity. However, the magnitude of the benefit is dependent on the season, the nature of crop production response and the total applied water.

Conclusion

Crop growth and yield nonuniformity results from unavoidable nonuniformity of water distribution in the field. Usually, in determination of optimum irrigation depth and deficit irrigation optimization, water yield function is the base of optimization and design making process and one value proposes as the optimum value of irrigation depth. Important issue that ignored is the fact that some parts of the field are over- or under- irrigated as compared to the target irrigation depth and intensity of this over and under irrigation depends on uniformity and adequacy values. Therefore, when an irrigation depth treatment is proposed as an optimum option for achieving maximum crop yield or maximum water productivity, this value should be proposed regarding to irrigation adequacy and uniformity coefficient values. In this situation, we can expect that more area of the field had received optimum or near optimum irrigation amount.

The presented relationships and methodology can have useful applications in study of various technical and management factors that affects irrigation uniformity and adequacy, such as irrigation system type, system layout, operation hours, deficit irrigation wind and vapor losses and etc, on crops yield and water productivity.

Rashmanlou et al. (2010) in evaluation of various irrigation systems in the study area reported uniformity coefficient of continuous (center pivot and linear), wheal move and set irrigation systems 89, 82 % and 65.1 %, respectively. These differences between uniformity will lead to have differences in crop yield and consequently will lead to have differences in water productivity in these irrigation systems. With the usual value of adequacy (80 %), maize yield in these systems will be 13, 12 and 8.5 ton/ha approximately. This can be considered in selecting irrigation systems along with other factors related to irrigation system such as costs, limitations and benefits.

Wind and evaporation losses are other main losses in the sprinkler systems. Yacoubi at al. (2010) reported that CU can improved by 15 % with irrigation scheduling at low wind velocity times. This CU increase will be equal to 3.2, 1.8 and 1.2 ton/ha for maize, barley and wheat in Qazvin area, respectively.

Another management in sprinkler irrigation systems operation for CU improvement is “alternative lateral move”. This method can improve CU by 10 % (Keller and Bliesner, 1990) that will be equal to 2.8, 1.2 and 1 ton/ha for maize, barley and wheat in Qazvin area, respectively.

The site-specific part of the method is water yield function that depends on crop type: climatic and regional conditions and it should be extracted for the study area. Water yield function can be obtained by using field study data or by using validated agro-hydrological models such as Aqua Crop.

Irrigation systems managers and engineers are more compatible with irrigation efficiency criteria and concepts and water management experts are more compatible with water productivity index. Presents method can help to make two sides viewpoint closer and to select strategies that provide two side interests and wills.

The present methodology can be applied in irrigation system design and management and optimization process. The method is developed for sprinkler irrigation system but it can be applied in other irrigation systems because CU and adamancy indices are not limited to sprinkler system.

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