تحقیقات منابع آب ایران
**Iran-Water Resources Research**

سال دوم، شماره ۲، پاییز ۱۳۸۵
**Volume 2, No. 2, Fall 2006 (IR-WRR)**
1-9

# Comparison of Two Methods for Deficit Irrigation of Sorghum

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**Abstract**
Shortage of water is the most important limiting factor for crop production in arid and semi-arid regions of Iran. Higher efficiencies for the present water supply can be obtained by deficit irrigation. Seasonal and intra-seasonal approaches for deficit irrigation for Sorghum are compared in this study. The data for deficit irrigation were collected at the Bajgah area, a semi-arid region, located 16 km north of Shiraz, in southern Iran. Time pattern distribution of applied water was not considered in their seasonal approach and the cost-benefit ratio analyses are performed on an annual basis. Decision making in the intra-seasonal approach is based on water allocation at different growth stages of crop. The results showed that there are some differences between the two approaches as far as the optimal water reduction is concerned. Seasonal approach showed a constant water reduction (18%) irrespective of water cost variation, while the intra-seasonal method offered higher allowable water reduction of 23% for unit water cost of 10 Rls $m^{-3}$ which may lead to a more economical water use. However, the result obtained in the intra-seasonal method is sensitive to the unit water cost and the allowable water reduction becomes lower than that of seasonal approach at the higher unit water cost. These results confirmed a previous result on Corn about the differences for the two approaches. Meanwhile, there is a substantial difference between the results for Sorghum and Corn in two different approaches.

***Keywords:*** Economic analysis, Optimum irrigation, Seasonal deficit irrigation, Intra-seasonal deficit irrigation

# مقایسه دو روش کم‌آبیاری سورگم

**علیرضا سپاسخواه[۱] ، بیژن قهرمان[۲]، شاهرخ زندپارسا[۱] و محمدمهدی قاسمی[۱]**

**چکیده**
کمبود آب مهم ترین عامل محدود کننده تولیدات زراعی در مناطق خشک و نیمه خشک ایران است. کاربرد کم آبیاری موجب بازده بالای مصرف آب با منابع آبی موجود می‌شود. در این مقاله روشهای فصلی و درون فصلی برای کم آبیاری سورگم (نوعی ذرت علوفه‌ای) مقایسه شدند. داده‌های کم آبیاری برای این پژوهش در منطقه باجگاه با شرایط نیمه خشک واقع در ۱۶ کیلومتری شمال شیراز (جنوب جمهوری اسلامی ایران) جمع آوری شد. توزیع زمانی آب کاربردی در روش فصلی منظور نگردید و تحلیل نسبت هزینه به درآمد براساس توابع تولید و هزینه فصلی انجام شد. در روش درون فصلی تصمیم گیری بر اساس تخصیص آب در مراحل مختلف رشد گیاه انجام شد. نتایج نشان داد که در میزان کاهش بهینه آب تفاوت‌هایی بین دو روش وجود دارد. در روش فصلی با مقادیر مختلف قیمت آب مقدار ثابتی برای کاهش بهینه آب (۱۸٪) بدست آمد، در حالیکه روش درون فصلی مقدار بالاتری از کاهش بهینه آب (۲۳٪) را برای قیمت آب ۱۰ ریال در متر مکعب ارایه داد که ممکن است منجر به مصرف اقتصادی‌تر آب شود. به هر حال نتایج حاصل از روش درون فصلی به قیمت واحد آب حساس بوده و در مقادیر بالای قیمت واحد آب، مقدار مجازکاهش مصرف آب در این روش از روش فصلی کمتر است. نتایج حاصله از این پژوهش تفاوت بین روشهای فصلی و درون فصلی را که در پژوهش قبلی برای ذرت بدست آمده است تایید می‌کند. در ضمن اختلافات اساسی بین نتایج حاصل برای سورگم و ذرت در روشهای فصلی و درون فصلی وجود دارد.

***کلمات کلیدی:*** تحلیل اقتصادی، آبیاری بهینه ،کم آبیاری فصلی ،کم آبیاری درون فصلی

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## Introduction

Shortage of irrigation water is the most important limiting factor for crop production in arid and semi-arid regions with scarce water resources. Rationing techniques, including the use of simple rationing, involves the application of a rule or a set of rules stipulating who has priority to receive water and in what quantities. The primary difficulty with simple rationing is the inherent arbitrariness. Simple rationing is nevertheless frequently applied in agricultural settings as policies which demand each user to reduce the water usage by a specific percentage. On the other hand, seasonal crop production functions suggest a more regulated deficit to reduce agricultural water demands.

Water use efficiency (WUE) or recently named water productivity (WP) is defined as the ratio of crop yield to the applied water. The main objective of deficit irrigation is to enhance water use efficiency/water productivity (WP). This goal can be achieved either by decreasing irrigation water to an amount less than the maximum requirement or by cutting off the least productive irrigation event at given growth stages of crop. These water management steps reduce the amount of applied water and consequently enhance the water use efficiency/water productivity. Water management in deficit irrigation is conceptually different from full irrigation. In deficit irrigation, the irrigation manager should decide on the level of deficit throughout the growing season or certain level of deficit at a given growth stage of crop. In the case of deficit irrigation, the water saved by deficit irrigation of one piece of land might be used to irrigate additional land, thus increasing farm income. The potential increase in farm income is an opportunity cost of water.

More than 50% of the irrigation water in the Islamic Republic (I.R) of Iran is supplied by groundwater from pumping private water wells. In many regions there is a negative water balance due to over pumping and the water table depth has increased. In this condition, even if the land is limited, uncontrolled withdrawal of groundwater may result in water shortage. In Iran, land is generally not a limiting factor, therefore saved water under deficit irrigation may be used to augment the area under irrigation.

There are two approaches in deficit irrigation management. English (1990) proposed a seasonal approach, which depends only on annual relationships of cost and revenue of applied water. On the other hand, intra-seasonal approaches may be used for deficit irrigation (Ghahraman & Sepaskhah, 1997a, b; Zand-Parsa et al., 2001; Sepaskhah & Ghahraman, 2004). In this approach, time distribution of applied water seems to play an important role in crop production. This is due to pronounced effects of water deficit at certain critical growth stages of crops. Of course these approaches may not give similar results (Ghahraman et al., 2001). In this regard, crops with different sensitivities may respond differently to the deficit irrigation, i.e. a water sensitive crop like Corn may not tolerate deficit irrigation in contrast to a non-sensitive crop like Sorghum.

This study made a comparison between outcomes of seasonal and intra-seasonal approaches of deficit irrigation based on annual relationships of cost and revenue of applied water. The differences are compared based on the maximization of dated water production function for Sorghum in a semi-arid region in Iran.

## Mathematical Optimization

Different approaches have been developed to determine optimum water allocation for a cropping pattern or a single crop (Barrett and Skogerboe, 1980; English, 1990; Ghahraman & Sepaskhah, 1997, 1999). Two different algorithms are applied in this study for a single crop, i.e., Sorghum:

### Seasonal Approach

In a seasonal approach, two different equations were derived by English (1990) as follows:

$$P_c \partial Y/\partial W = \partial C/\partial W \qquad (1)$$

$$W(P_c \partial Y/\partial W - \partial C/\partial W) = P_c Y - C \qquad (2)$$

where $P_c$ is the price per unit weight of crop, W is depth of applied water, Y is crop yield, and C is the total production cost. All the parameters are used on per-unit-area-of-land basis. Equation (1) derived from a non limiting condition in which marginal productivity of water is equal to the marginal cost of water (the cost for producing one extra unit of product). Equation (2) derived from a limiting condition in which the amount of water multiplied by marginal profit per unit volume of water (the benefit obtained from producing one extra unit of product) equals the total profit.

### Intra-seasonal Approach

A mathematical relationship between relative yield and the relative ET was proposed by Jensen (1968) as follows:

$$Y_a/Y_p = \Pi_i^n (ET_{ai}/ET_{pi})^{\lambda i} \qquad (3)$$

where i and n denote different crop growth stages and the number of growth stages, respectively. $Y_a$ and $Y_p$ are the harvested yields obtained at deficit and full irrigation conditions, $\lambda_i$ is sensitivity index of crop to the water stress at each crop growth stage, and $ET_{ai}$ and $ET_{pi}$ are actual and potential evapotranspirations, respectively. However, relative grain yield may be a sound definition for $Y_a/Y_p$. Nairizi and Rydzewski (1977) and Meyer et al. (1993) approximated the $(ET_a/ET_p)_i$ by $(W_a/W_p)_i$, where $W_a$ and $W_p$ stand for applied water and potential water needs, respectively. It should be noted that this is valid only when deep percolation is almost negligible. Furthermore, rainfall during the growing season is considered negligible. This approximation is not valid for systems where water application efficiency is low. With low water application efficiency, deficit irrigation in arid and semi-arid areas may respond differently for the first irrigation in the growing season. This is due to the fact that soil water can supply some of the plant water requirements. However in this condition the readily available soil water is used up before each deficit irrigation is applied. Therefore, the value of $W_a$ is taken equal to the amount of applied water.

The total amount of seasonal irrigation requirement in full irrigation, $\Sigma ET_p$, is reduced by a fraction of x (x<1) for a deficit irrigation. Therefore, the total seasonal water allocated to a given crop is as follows:

$$\Sigma_i(W_a)_i=(1-x).\Sigma_i(ET_p)_i \quad (4)$$

with a logical constraint as follows:

$$0\leq(W_a)_i\leq(ET_p)_i \quad (5)$$

Following the previous simplifying assumptions, Eq. (3) illustrated a nonlinear optimization model, for which the Eqs. (4) and (5) are the constraints. The solution for Eq. (3) can be found in optimization textbooks (e.g., Luenberger, 1984). The details of the solution by Lagrangian multiplier for some crops are presented by Ghahraman and Sepaskhah (1997). There are no field-measurements available for $\lambda_i$ corresponding to different growth stages of Sorghum. Rao et al. (1988), after Doorenbos and Kassam (1979), have proposed a simple multiplicative model similar to Eq. (3), as follows:

$$Y_a/Y_p=\Pi_i^n[1-Ky_i.(1-ET_{ai}/ET_{pi})] \quad (6)$$

where $Ky_i$ is the water sensitivity factor reported by Doorenbos and Kassam (1979). Set of Eqs. (6), (4), and (5) represent an optimization model simplified as $(W_a/W_p)_i=(ET_a/ET_p)_i$. A solution of this model may be found in Ghahraman (2000).

Results show that the relative crop yield reduced as the values of water reduction x increased. On the other hand, the saved irrigation water can be used to cultivate more land. The total cultivated area can be increased by a factor of 1/(1-x). Thus, the ratio of net benefit of deficit irrigation to full irrigation Z (the relative net benefit) was calculated as follows (Ghahraman & Sepaskhah, 1997):

$$Z=[(B/C)(Y_a/Y_p)-1]/\{(1-x)[(B/C)-1]\} \quad (7)$$

in which B is the benefit (revenue) for the unit area and C is the cost of crop production as defined in Eq. (2). Y will be given in Eqn. (8) later, as a function of unit water cost.

In reality, water stress in a specific stage of plant growth may affect the plant growth in other stages. However, in this analysis it was assumed that: 1) there is no interaction between stages of growth, and the analysis is applicable to determinate crops, 2) irrigation water can be applied at any moment on request, 3) rainfall during the growing season is negligible, 4) deficit irrigation just decreases the quantity of yield and its quality is either unaffected or it does not affect the sale price, and 5) irrigation water is applied uniformly.

**Experimental Data**

The data is obtained from an experiment conducted at Bajgah Agricultural Experiment Station for Sorghum (*Sorghum durra* L.). This station is located 16 km north of Shiraz (Fars province, I.R. of Iran) at 29˚32' N and 52˚35' E (elevation 1810 m). There was no rainfall during the growing season. The climate of the study area is semi-arid as reported by Malek (1981). The time of occurrence of different growth stages and their sensitivity index for Sorghum are obtained from Doorenbos and Kassam (1979) and are listed in Table 1. Sorghum evapotranspiration has been measured in the field by Ghasemi (1999). The yield data were obtained from experiments conducted in Bajgah and Kooshkak Agricultural Experiment Stations in Shiraz University (Ghasemi, 1999) for grain Sorghum (Kimia, a local cultivar) at different irrigation intervals (10-, 15-, and 20-day) and different irrigation methods (ordinary furrow, fixed-every-other-furrow, and variable every-other furrow) on clay loam soil, in 1998 (planted at first week of May). The plant population was 133300 per hectare. The EC of irrigation water was 0.5 dS/m. The amounts of applied water for each irrigation treatment were also measured. The Sorghum yield harvested at the last week of October and grain with 14% moisture content was separated from the top and weighed. The relative grain yield was calculated as the ratio of grain yield at different irrigation treatments to that obtained at ordinary furrow irrigation treatment with 10-day intervals and optimized agronomic conditions (maximum yield).

**Table 1- Some characteristics of Sorghum at Bajgah**

| Physiological stage | Date | Ky | Length of period (d) | Potential evapotranspiration $ET_p$ (mm) |
|---|---|---|---|---|
| Planting | 31 May | | | |
| Establishment | 25 June | 0.01 | 25 | 114.1 |
| Vegetation | 30 July | 0.20 | 35 | 189.0 |
| Flowering | 24 August | 0.55 | 25 | 145.0 |
| Yield formation | 13 October | 0.45 | 50 | 270.9 |
| Ripening | 31 October | 0.20 | 18 | 23.1 |
| Entire season | | 0.90 | 153 | 742.1 |

The relationship between grain yield and applied water was determined as water production function (Fig. 1). Furthermore, the relationship between production cost and applied water was also determined for different water prices. These relationships were used in the economic analysis.

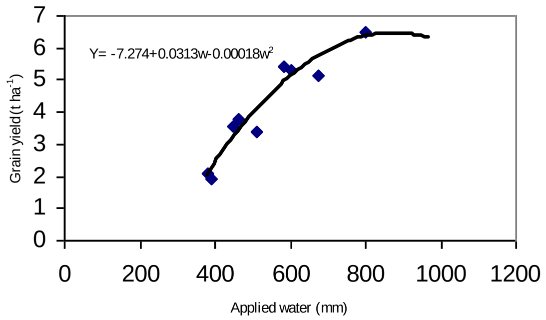


**Figure 1- Relationship between grain yield and applied water**

## Results and Discussion

### Seasonal approach

Ghasemi (1999) has established a second order polynomial regression between measured yields Y (t $ha^{-1}$) and applied seasonal irrigation water W (mm) in the form of:

$$Y=-7.274+0.0313W-0.000018W^2 \quad (8)$$

For which $R^2=0.93$, Standard error (SE)=0.5, and Significance probability $p<0.0004$.

This production function was obtained for short furrow irrigation with application efficiency of about 90% which is attainable in short furrows with precise determination of irrigation water requirements. The regression coefficients ($a_1$, $b_1$, and $c_1$) are statistically significant at probability levels of 0.03, 0.04 and 0.04, respectively. Furthermore, the high $R^2$ and low SE and p values of the multiple regression indicated that using the amounts of irrigation water from different furrow irrigations and irrigation intervals resulted in a statistically significant multiple regression equation. Therefore, this production function is applicable for the study area using surface irrigation (Ghasemi, 1999). However, different production functions may be obtained for different irrigation methods such as sprinkler or trickle irrigation. A similar equation for the production function of Sorghum was obtained in another area located 75 km north of Bajgah area (Ghasemi, 1999) and High Plain of Kansas (USA) (Stone et al., 1996). Furthermore, the obtained production function was somewhat similar to that reported by Sharma and Alonso Neto (1986) in northeastern Brazil. Therefore, it may be applicable to similar areas in the region.

On the other hand, total variable cost (C, Rls $ha^{-1}$) of production may be represented as follows:

$$C=a_2+b_2W \quad (9)$$

where $a_2$ is the fixed cost and $b_2$ is the slope of line. Where the applied water W is variable, the total cost C is also variable. Ghasemi (1999) has calculated C as 779621 Rls $ha^{-1}$ (8000 Rls is one US Dollar).
A local survey showed that the price of Sorghum is in the order of 430 Rls $kg^{-1}$. With definite functions of Sorghum yield and cost, optimal amounts of water for maximum yield ($W_m$) (6.333 t $ha^{-1}$), and maximum benefit for water-limiting condition ($W_w$) would be as follows:

$$W_m=-b_1/(2c_1) \quad (10)$$

$$W_w=\{(P_c.a_1-a_2)/(P_c.c_1)\}^{1/2} \quad (11)$$

Where $b_1$ and $c_1$ are the second and third coefficients of yield-water production function (Eq. 8), $a_1$ is the first coefficient of yield-water production function (Eq. 8), $a_2$ is the fixed cost of production or the first coefficient of cost function (Eq. 9), $P_c$ is the price per unit weight of crop, and $c_1$ is the third coefficient of yield-water production function (Eq. 8). Equation. (10) was obtained by maximizing Eq. (8). Equation (11) was obtained by substituting derivatives of Eqs. (8) and (9) in Eq. (1).

The maximum benefit for water-non limiting condition ($W_l$) would be as follows:

$$W_l=\{(b_2-P_c.b_1)/(2P_c.c_1)\} \quad (12)$$

Where $b_2$ is the slope of cost function (Eq. 9) and $P_c$ and $c_1$ were described previously. Equation (12) was obtained by substituting Eqs. (8) and (9) and their derivatives in Eqn. (2).

The values of $W_m$, $W_w$, and $W_l$ were computed as 869, 710.5 and 837.3 mm (with water price of 50 Rls $m^{-3}$), respectively. This means that under limited water supply, 18% reduction in the amount of applied water is an optimum policy especially when the price of water is very low as is the case in Iran. Furthermore, when the water is limiting, the $W_w$ is reduced about 15% as compared with $W_l$. It is interesting to note that for furrow irrigation neither $W_m$ nor $W_w$ (Eqs. 10 and 11, respectively) depend on the cost of water and irrigation application efficiency. This might be due to the fact that performance of irrigation has not been taken into account in economic analysis. Figure 2 shows the mutual effect of water cost and applied water depth in the farm net benefit. It appears that corresponding to every water cost, there is a unique optimal water depth to maximize farm income. The variation pattern is however somewhat identical for all water prices. Figure 2 also shows that, with the seasonal approach (Eq. 2), for a specific net benefit, more irrigation water is required as the unit water cost raises. With a water cost of 250 Rls $m^{-3}$ and higher there will be virtually no farm benefit.

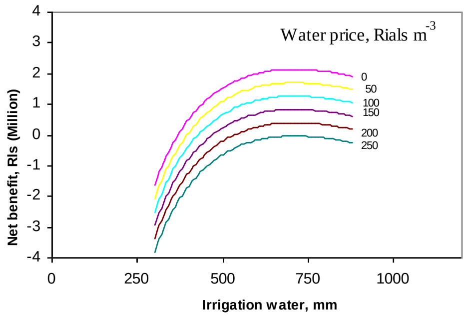


**Figure 2- Farm net benefit as a function of irrigation water amount and water cost for Sorghum at the Bajgah under a water–limiting condition obtained from seasonal approach**

## Intra-seasonal approach

Figure 3 shows the maximized relative grain yield (Ya/Yp) for Sorghum as a function of irrigation water reduction (x), obtained from the intra-seasonal approach (Eqs. 3-5). There is negligible reduction in relative yield up to a water reduction of about 10%. Afterwards, a slightly ascending trend is established between water reduction and the corresponding Sorghum yield reduction. This implies that Sorghum is a relatively insensitive crop. Field data (Ghasemi, 1999) are also included in this Figure. It was concluded that, although field trials were not planned for a maximum yield at a specific water supply level, there was a good agreement between maximized curve and field data. Due to the defined constraints, the maximized curve has not been extended at water reductions higher than 50%. (c.f. Doorenbos & Kassam, 1979).

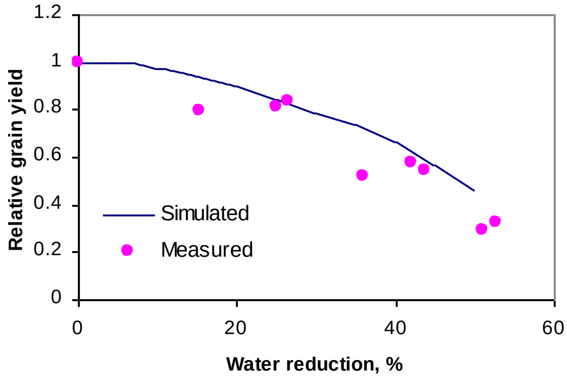


**Figure 3- Relative grain yield of Sorghum at different water reductions.**

The relationship between the values of Z (the relative net benefit) and the values of x (fraction of water reduction) at different values of benefit to cost ratio (B/C) are calculated based on Eq. (7). The results are shown in Fig. 4. The range of B/C (1.1 to 2.4)used in this analysis corresponds to the values that may occur in case of seasonal analysis with different amounts of applied irrigation water. In this analysis, the production cost was assumed to be independent of the method and intervals of irrigation as shown in Eq. (9). In Iran more than 50% of irrigation water is supplied by private pumping wells. Furthermore, the labor cost for irrigation is not a considerable amount. Therefore, the most significant exogenous variables influencing B/C ratio are the fixed production cost and benefit (revenue) per unit area. Figure 4 indicates that deficit irrigation is valid through a range of water reduction rates starting at 0% (full irrigation) and terminating at 50% in this study. There is a unique point in this range, however, that maximizes the relative net benefit. In this study, 8% water reduction can maximize relative net benefit irrespective of B/C ratio (except for B/C=1.1 which needs 7% water reduction). Generally this is also dependent on B/C (e.g. Ghahraman & Sepaskhah, 1997). This discrepancy may be due to less sensitivity of Sorghum to water deficit at various growth stages (Table 1) compared to those for other crops. As B/C ratio increases, there will be a higher range of water reduction and also a higher relative net benefit (Fig. 4). The relationship between values of Z and x for Sorghum is quite different from that obtained for Corn (Ghahraman et al., 2001) in which the similar values of Z were obtained for much higher values of B/C.

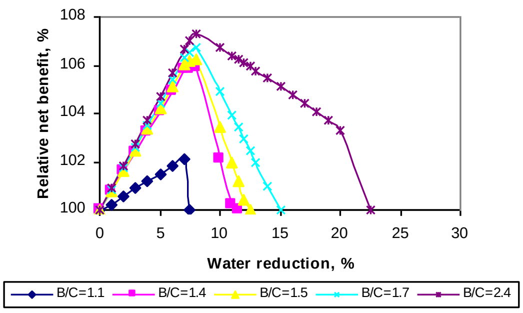


**Figure 4- Simulated relative net benefit for Sorghum at different water reduction and B/C ratios**

**Comparison of the Methods**

Table 2 compares the results of relative Sorghum grain yield and the net benefit between seasonal and intra-seasonal methods at different depths of applied water, irrigation application efficiency, and the cost of water. The results clearly indicate that for the applied water depths less than 500 and 600 mm with water prices lower than 200 and 100 Rls m $^{-3}$ , respectively, the intra-seasonal approach results in a more economical yield. This might be due to the approximation of $(ET_a/ET_p)_i$ by $(W_a/W_p)_i$ which is valid only when deep percolation is almost negligible. For applied water depths greater than 600 mm the corresponding deep percolation may not be negligible. In theory, the intra-seasonal approach shows better results if irrigation application efficiency is considered in the economic analysis. Due to the applied restrictions for this study (%50 max of supply reduction), the results are not presented for water depths less than 400 mm. The seasonal model does not have this restriction in its structure.

The results revealed that for water reduction of about 31% (1-600/869) and higher, the intra-seasonal approach results in a higher net benefit. However, the irrigation application efficiency and uniformity are not included in the intra-seasonal approach.The seasonal approach was analyzed under a high application efficiency of about 90%. In general, the seasonal approach is more reliable since it considers the sensitivity of the crop stage to water deficit and crop production. Furthermore, for water reduction of 20% (1-700/869), it is preferable to apply water for each irrigation according to the sensitivity of crop growth stage to water (intra-seasonal approach) which will result in a higher relative grain yield (Table 2).

Table 3 shows the optimum water reductions of Sorghum under seasonal approach. Results are presented for water limiting and water-non limiting conditions at different water costs. The maximum allowable water deficit under intra-seasonal approach at different B/C ratios are also printed. In general, the allowable amounts of water reduction for Sorghum are higher than those for Corn as reported by Ghahraman et al. (2001). Table 3 shows that in the seasonal approach Sorghum is completely insensitive to water cost changes. The optimal water reduction for Sorghum is 18% while the optimum water reduction for Corn varied between 4.8 to 3.1% for water prices between 15.55 to 200 Rls m$^{-3}$. However, this was not the case for the intra-seasonal approach and an optimal water reduction of 25% was obtained for the higher value of B/C (2.4). The value of water reduction was decreased to 11% as the B/C value reduced to 1.4. No water reduction is allowed when the B/C value is smaller than 1.0 (Table 3). Due to the assumptions considered in the theory of seasonal approachs (English, 1990), the reduction in applied water was not dependent on the water price (Eq. 11). However, for water-non limiting condition, the optimum reduction in applied water was dependent on the water price (Eq. 12). Furthermore, the denominator of the B/C ratio (i.e., C) was dependent on water price according to Eq. (9). Therefore, the optimum water reduction was dependent on the water price for intra-seasonal approach. For seasonal approach this happens for water-non limiting condition. As the water price increased the allowable water reduction increased and an optimum water reduction of 14.2% resulted for a water price of 200 Rls m$^{-3}$.

In fact, the intra-seasonal approach showed a high degree of sensitivity to water cost. This is more rational, while it was not obtained for the seasonal approach.

The results showed that there was a remarkable difference between the results of allowable water reduction obtained by these two scenarios for Sorghum. Between these two approaches the intra-seasonal approach seemed more realistic under field conditions. Sorghum is not a highly water sensitive crop (Table 1), therefore, the allowable water reductions for both methods are considerable (Table 3).

**Table 2- Simulated relative grain yield and net benefit for Sorghum at different depths and costs of water.**

| Depth of Water (mm) | S[a] | IS[b] | Unit water cost (Rls/m$^3$) | Net benefit (Rls*10$^6$) S[a] | IS[b] |
|---|---|---|---|---|---|
| 400 | 0.374 | 0.547 | 0 | 0.238 | 0.550 |
| 400 | 0.374 | 0.547 | 50 | 0.038 | 0.323 |
| 400 | 0.374 | 0.547 | 100 | ------ | 0.098 |
| 500 | 0.612 | 0.762 | 0 | 0.887 | 1.095 |
| 500 | 0.612 | 0.762 | 50 | 0.637 | 0.812 |
| 500 | 0.612 | 0.762 | 100 | 0.387 | 0.530 |
| 500 | 0.612 | 0.762 | 150 | 0.137 | 0.248 |
| 600 | 0.794 | 0.907 | 0 | 1.382 | 1.449 |
| 600 | 0.794 | 0.907 | 50 | 1.082 | 1.111 |
| 600 | 0.794 | 0.907 | 100 | 0.782 | 0.772 |
| 600 | 0.794 | 0.907 | 150 | 0.482 | 0.433 |
| 600 | 0.794 | 0.907 | 200 | 0.182 | 0.095 |
| 700 | 0.918 | 0.996 | 0 | 1.721 | 1.651 |
| 700 | 0.918 | 0.996 | 50 | 1.371 | 1.256 |
| 700 | 0.918 | 0.996 | 100 | 1.021 | 0.861 |
| 700 | 0.918 | 0.996 | 150 | 0.671 | 0.466 |
| 700 | 0.918 | 0.996 | 200 | 0.321 | 0.071 |
| 800 | 0.986 | 1 | 0 | 1.906 | 1.622 |
| 800 | 0.986 | 1 | 50 | 1.506 | 1.171 |
| 800 | 0.986 | 1 | 100 | 1.106 | 0.719 |
| 800 | 0.986 | 1 | 150 | 0.706 | 0.267 |
| 1000 | 0.952 | 1 | 0 | 1.812 | 1.622 |
| 1000 | 0.952 | 1 | 50 | 1.312 | 0.977 |
| 1000 | 0.952 | 1 | 100 | 0.812 | 0.413 |
| 1000 | 0.952 | 1 | 150 | 0.312 | ------ |

[a]: Seasonal approach
[b]: Intera- seasonal approach

**Table 3- Optimum and maximum allowable water reduction for seasonal and intra-seasonal approaches, respectively**

| Seasonal approach: Cost of water (Rl m$^{-3}$) | Water reduction (%): Water limiting | Water reduction (%): Water non-limiting | Intra-seasonal approach: Benefit to cost ratio (B/C) | Water reduction (%) |
|---|---|---|---|---|
| 0 | 18.2 | 0.0 | 2.4 | 25 |
| 10 | 18.2 | 3.7 | 2.1 | 23 |
| 50 | 18.2 | 7.4 | 1.7 | 15 |
| 100 | 18.2 | 11.1 | 1.4 | 11 |
| 200 | 18.2 | 14.9 | 0.9 | -- |

A similar research was conducted for Corn by Ghahraman et al. (2001). They concluded that although there was a noticeable difference between the outcomes of the two approaches, there was a narrow range for water reduction for Corn. The optimum water reduction for Corn in the seasonal approach with the present price of water is much lower than that of Sorghum, i.e., 5% vs. 18.2% (Ghahraman et al., 2001). The difference between optimum water reduction under seasonal and intra-seasonal approaches with the present price of water was lower for Sorghum compared to that of Corn, i.e., 1.25 to 2.0 (Ghahraman et al., 2001). The distinct difference between Corn and Sorghum in response to seasonal and intra-seasonal approaches is mainly due to the sensitivity of Corn to water deficit. Furthermore, Stone et al. (1996) indicated that Corn produced more grain than Sorghum when the total irrigation plus rainfall is more than 671 mm. Sorghum is a better choice when this decreases to less than 532 mm.

**Conclusions**

The results of this research again confirmed that seasonal and intra-seasonal approaches yield different outcomes for Sorghum (i.e., a less sensitive crop to water stress) compared to Corn (i.e., a sensitive crop to water stress). The allowable range for water reduction for Sorghum in an intra-seasonal approach is rather wide since it is not a water sensitive crop. In computing the optimal water reduction, the seasonal approach did not respond to either water cost or irrigation application efficiency, which shows its unrealistic assumptions are inherent in its theory. The results clearly showed that the intra-seasonal approach yielded more economical preferences for Sorghum with a low price of water. However, the results obtained in the intra-seasonal method are sensitive to the unit water cost and the allowable water reduction becomes lower than that of the seasonal approach at the higher cost per unit. It is also concluded that for Sorghum, in contrast to Corn, the difference between seasonal and intra-seasonal approaches with water price of about 25 Rls $m^{-3}$ is negligible and both methods result in similar optimum water reductions.

The production function may be different with various irrigation methods (i.e., surface irrigation, sprinkler or trickle irrigation) in the seasonal model. Therefore, appropriate function is required for the relevant irrigation methods. The production cost may be dependent on the irrigation methods for intra-seasonal models. Therefore, the B/C ratio may be dependent on the irrigation method. Furthermore, this model may be more appropriate for flexible schemes of irrigation such as private well for water supply.

**References**


Barrett, J.W.H., and Skogerboe, G.V., (1980), "Crop production functions and the allocation and use of irrigation water", *Agricultural Water Management*, 3, pp. 53-64.

Doorenbos, J., and Kassam, A.H., (1979), "Yield response to water", *Food and Agricultural Organization of the United Nations*, Pub. No, 33, 193p.

English, M.J., (1990), "Deficit irrigation. I: Analytical framework", *Journal of Irrigation and Drainage Engineering*, 116(3), pp. 399-412.

Ghahraman, B., (2000), "Optimal allocation of irrigation water for multiple cropping pattern through deterministic-stochastic programming from a single purpose reservoir", Ph.D. Dissertation, Irrigation Department, Shiraz University, I.R. of Iran, 322p.

Ghahraman, B., Parsa, Sh.Z., and Sepaskhah, A.R., (2001), "Deficit irrigation for Corn: A comparison of two methods", *Iran Agricultural Research*, 20, pp. 1-16.

Ghahraman, B., and Sepaskhah, A.R., (1997a), "Use of water deficit sensitivity index for partial irrigation scheduling of wheat and barley", *Irrigation Science*, 18, pp. 11-16.

Ghahraman, B., and Sepaskhah, A.R., (1997b), “Optimum deficit irrigation of cotton and potato fields in a semi-arid region”, *Iranian Journal of Science and Technology*, 21(4, A), pp. 395-405.

Ghahraman, B., and Sepaskhah, A.R., (1999), "Use of different irrigation water deficit schemes for economic operation of a reservoir", *Iranian Journal of Science and Technology*, 23, pp. 83-90.

Ghasemi, M.M., (1999), "The effect of every-other furrow irrigation with different irrigation intervals on Sorghum yield (*Sorghum durra* L.) in Bajgah and Kooshkak areas (Fars province)", M. Sc. Thesis, College of Agriculture, Shiraz University, I.R. Iran,182p,(in Farsi).

Jensen, M.E., (1968), "Water consumption by agricultural plants", In: Kozlowski, T.T. (Ed.), Water Deficit and Plant Growth. Academic Press, New York, pp:1-22.

Luenberger, D.G., (1984), *Linear and Nonlinear Programming*, 2nd Edn., Addison-Wesley, Reading, Mass., 491p.

Malek, E., (1981), "Water budget and climatic type at Bajgah area", *Iranian Journal of Agricultural Science*, 12, pp. 65-74, (in Farsi).

Meyer, S.J., Hubbard, K.G., and Wilhite, D.A., (1993), "A crop-specific drought index for Corn: I. Model development and validation", *Agronomy Journal*, 85, pp.388-395.

Nairizi, S., and Rydzewski, J.R., (1977), "Effects of dated soil moisture stress on crop yields", *Experimental Agriculture*, 13, pp. 51-59.

Rao, N.H., Sarma, P.B.S., Chander, S., (1988), "A simple dated water- production function for use in irrigated agriculture", *Agricultural Water Management*, 13, pp. 25-32.

Sepaskhah, A.R., and Ghahraman, B., (2004), "The effects of irrigation efficiency and uniformity coefficient on relative yield and profit for deficit irrigation", *Biosystems Engineering*, 87(4), pp. 495-507.

Sharma, P.N., and Alonso Neto, F.N., (1986), "Water production function of Sorghum for northeast of Brazil", *Agricultural Water Management*, 11, pp. 169-180.

Stone, L.R., Schlegel, A.J., Gwin, Jr. R.E., and Khan, A.H., (1996), "Response of Corn, grain Sorghum, and sunflower to irrigation in the high plain of Kansas", *Agricultural Water Management*, 30, pp. 251-259.

Zand-Parsa, Sh., Soltani, G.R., Sepaskhah, A.R., (2001), "Determination of optimum irrigation water depth for Corn in sprinkler irrigation", *Journal of Science and Technology for Agriculture and Natural Resources*, 5, pp. 1-7. (in Persian).

Submitted: December 5, 2004
Revised: July 8, 2006
Accepted: September 25, 2006