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AN APPROACH ON ECONOMICS TO ASSESS OPTIMAL TIME OF WATER SUPPLY IN FREE-DRAINAGE FURROW IRRIGATION

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ABSTRACT: Criteria based on economics are essential to rationalize water use from the highest investment payback perspective in irrigated agricultural systems decision support. The central goal of this work is to provide theoretical basis for calculating the optimal time of water supply in free-drainage furrow irrigation systems. The purposed methodology might be generalized to different situations, being basically explained by: a) yield function (total applied water versus yield); b) duration of each phenological stages followed by their corresponding crop coefficients; c) parameters regarding to advance and infiltration equations; and d) information related to price of marketable products, costs of water and the other production factors. The specific values of parameters and attributes should be provided or suggested from users. The outputs to be achieved should denote a time of water supply regarding to maximum mean net income, which is obtained from different scenarios of water deficits that are corresponding to different fractions of required water to be infiltrated at the end of the furrow.
Keywords: infiltration, maximum net income, crop response to water, deficit irrigation

ABORDAGEM ECONÔMICA PARA AVALIAR O TEMPO ÓTIMO DE APLICAÇÃO DE ÁGUA EM IRRIGAÇÃO POR SULCOS

RESUMO. Os critérios econômicos na tomada de decisão em sistemas agrícolas irrigados são fundamentais para a racionalização do uso da água com o máximo retorno do investimento. Este trabalho visa apresentar um modelo para determinar o tempo ótimo de aplicação de água em irrigação por sulcos de tamanho definido e com drenagem livre na extremidade. O desenvolvimento do modelo está basicamente alicerçado em: a) função de produção (lâmina total vs. produção); b) duração da fase fenológica, com o respectivo coeficiente de cultura (Kc); c) parâmetros inerentes à equação de avanço e às infiltrações em cada trecho; e d) informações sobre preços do produto comercializável e custos da água (se esta for cobrada) e dos demais envolvidos. Por se tratar de um modelo genérico, os valores específicos dos parâmetros e dos atributos apresentados deverão ser sugeridos pelo usuário. O resultado deverá mostrar um tempo de aplicação referente ao máximo lucro médio, o qual é obtido dos diferentes cenários de déficit provocados, correspondentes a diferentes frações da lâmina requerida que deve infiltrar na extremidade final do sulco.
Palavras-chave: infiltração, lucro médio máximo, função de produção, irrigação com déficit

INTRODUCTION

The classic concept about time of water supply in furrow irrigation systems highlights that a reposition period should last the necessary time to infiltrate the required water at the end portion of furrow (Criddle et al., 1956). Nevertheless, the approach contemplating traditional economics emphasizes that water supply should last while increments on benefits surpass increments on costs or, in order to maximize net return, crops does not need to be fully supplied in water even if necessary to reduce productivity until an acceptable level that assures the highest net return (Frizzone, 2005).

By using a yield-water function, it is possible to verify which water depth can be that one that addresses maximum yield. In furrow irrigation, if the infiltration patterns throughout furrow assume normal distribution, it would be sufficient to differentiate net income function and find the maximum point afterwards. However, as the infiltration distribution generally assumes power-type (Frizzone, 2000), it will be a specific yield for each portion of the furrow, which will result in different incomes and costs along it. If different situations are simulated in terms of water deficit being infiltrated at the end of the furrow, there will be different gross margins and costs throughout furrow for each scenario, mathematically saying, it is originated a matrix in which one of the outcomes is related to the maximum mean net income of the contemplated agricultural system. Therefore, it is essential to deduct and present, for academic exercises applicable to practice, an algorithm capable to detect the maximum mean net income. The central goal of this work is to provide the theoretical basis of a generic model to set optimal time of water supply for free-drainage furrow irrigation systems, in which criteria based on economics and furrow irrigation sciences are took in account.

DEVELOPMENT

The current work is based on the organization of a list of equations and functional relationships regarding to practical aspects of furrow irrigation management and theoretical approaches of economy and soil physics, leading to a model development.

The estimation of a crop yield can be derived from a yield-response curve to total water supply throughout length cycle, assuming the condition that the rest of variable are kept inelastic and under suitable levels. Either excess or scarcity of water leads to yield losses, although the latter is more evident. Holzapfel et al. (2000) has shown, not mathematically, the shapes and standards of some yield-water functions; for example, it can be such a “x-root function”. These premises carry to the following yield-water function representation (Haxem and Heady, 1978):

$$Y = a \cdot W^{0.5} + b \cdot W + c \qquad (1)$$

where Y is the crop yield (kg ha^{-1}); W the water depth (mm) necessary to achieve that yield; and a, b and c the empirical parameters.

Differentiating eq. 1 and equaling it to zero gives the maximum point of the function:

$$W_{T_{disp}} = 0.25 \cdot a^2 \cdot b^{-2} \qquad (2)$$

where $W_{T_{disp}}$ refers to seasonal water depth (mm) available to be spent during the whole crop cycle; one could call it as the optimal water depth from the technical view point.

The value of $W_{T_{disp}}$ should be share in smaller depths in order to supply the water requirements of the different phenological stages according to following management assumption:

$$W_{FF_k} = 0.001 \cdot \frac{Kc_k}{Kc_{máx}} \cdot \frac{D_{FF_k}}{DT_C} \cdot \left(W_{Tdisp} + F_{PW}\right) \quad (3)$$

where W_{FF_k} refers to available water depth (m) for irrigation of k^{th} phenological stage; Kc_k to crop coefficient of k^{th} stage and D_{FF_k} the corresponding duration (days) of that stage; Kc_{max} to the highest value of all Kc; DT_C to total length (days) of crop cycle; and F_{PW} is an algorithm (dimension: mm) that shares remnant values of water depths after the value of $W_{T_{disp}}$ be shared according to Kc_k and D_{FF_k} criteria, as discussed in Detomini et al (2005).

In order to share W_{FF_k}, it might be assumed as a practical criterion of irrigation management:

$$N_{irr_k} = \frac{W_{FF_k}}{W_{n0k}}; \quad N_{irr_k} \in I \quad (4)$$

where N_{irr_k} refers to the number of irrigation events applicable to k^{th} phenological stage; W_{n0k} to the water depth (m) that should be infiltrated at the end of furrow after water has completed the advance time, considering a initial condition in which there is no water deficit on the k^{th} phenological stage.

Moreover, the following conditions regarding to water management applicable to phenological stages can be assumed:

$$\begin{aligned} &\text{if } k=1;\ W_{n0k} \le 0.020 \\ &\text{if } k=2;\ 0.020 \le W_{n0k} \le 0.030 \\ &\text{if } k=3;\ 0.030 \le W_{n0k} \le 0.040 \\ &\text{if } k=4;\ 0.040 \le W_{n0k} \le 0.050 \end{aligned} \quad (5)$$

From the beginning of furrow, the time intervals that water takes to reach the end portion are estimated from power equations likely to be created from simple field tests (data of length traveled by water throughout furrow versus their corresponding times). According to Valiantzas (2000), the advance time (t_{av}, min) can be expressed by a simple power equation:

$$t_{av} = u \cdot X^v \quad (6)$$

Consequently, the time required by the water advance to reach the i^{th} furrow portion (t_i, min) is:

$$t_i = u \cdot X_i^v \quad (6a)$$

where X is the length (m) of the furrow; X_i the distance (m) from derivation siphon to the i^{th} portion in which water infiltrates after advance time has been completed; u and v are the empirical parameters.

As suggested by Bernardo et al. (2006; p.44), the water infiltration rate may be expressed according to Kostiakov-Lewis' derivation:

$$V_I = f \cdot t^g + f_0 \quad (7)$$

where V_I refers to the infiltration rate (m min^{-1}); t to the time (min) that water takes to travel along furrow; f_0 is basic infiltration rate (m min^{-1}); and f and g the empirical parameters set by regression analysis treated after data field has been sampled.

The real value of f_0 can be actually obtained from field tests (i.e. inflow-outflow method associated with the use of WSC flume A devices located on two furrow extremities). When the value corresponding to the difference between two measured flows becomes constant (i.e. after five observations), this value is presumably f_0. If this parameter is considered, later analyses are likely to become hard-working due to the necessity of using numerical methods to solve eq. 7 in its integrated form. Other infiltration models could be used instead of eq. 8. However, Kostiakov equation is simpler to solve and is friendly adjustable for a number of soils, especially for small intervals of time (Libardi, 2005). Then the parameter f_0 will be suppressed into this current approach.

Thus, the opportunity time to infiltrate the “technically optimal” water depth is given by the empiric model postulated by Kostiakov (1932):

$$T_{n0k} = \left(\frac{W_{n0k}}{\beta} \right)^{1/\alpha} \quad (8)$$

where T_{n0k} refers to required time (min) to infiltrate W_{n0k}; β and α are the empirical parameters, being α related to soil textural class and varying from 0 to 1 (clay conditions lessen the value of α).

Integrating eq. 7 provides α as a function of parameter g and β from f and g, (Frizzone, 2000):

$$\alpha = g + 1 \quad (9)$$

$$\beta = \frac{f}{g+1} \quad (9a)$$

It is possible to calculate the i^th gross income for the i^th portion of furrow for whatever scenario (j^th scenario) of water deficit:

$$RB_{ij} = Y_{ij} \cdot Pr_{pd} \quad (10)$$

where RB_{ij} is gross return (R$ ha^{-1}) verified on i^th portion and on j^th water deficit scenario; Y_{ij} refers to the corresponding crop yield (kg ha^{-1}); and Pr_{pd} to the deflationed price of selling product (R$ kg^{-1}).

When product selling prices dataset is available (i.e. over 20 years), it can be generated a probability normal distribution (if there is adherence) and then a random simulation, although it is firstly crucial to level price data in the same basis in order to compare values for preventing the effect of different inflation rates corresponding to different times (Assaf Neto, 2009). The process of prices deflation may be obtained from:

$$Pr_{pd} = Pr_{psh} \cdot \frac{D_a}{D_{Pr_{psh}}} \quad (11)$$

where Pr_{psh} refers to the product nominal price (R$ kg^{-1}); D_a to the actual deflator (regarding to the actual month); and $D_{Pr_{psh}}$ to deflator of an interest month.

By substituting eq. 1 into eq. 10 besides considering the water management conditions of eq. 5:

$$RB_{ij} = \left[a \cdot \left(\sum_{k=1}^{n} W_{ijk} \right)^2 + b \cdot \left(\sum_{k=1}^{n} W_{ijk} \right) + c \right] \cdot Pr_{pd} \quad (12)$$

where $\sum_{k=1}^{n} W_{ijk}$ is the sum of water depths (mm) required from all phenological stages, which shall be infiltrated on i^th portion of furrow of a j^th water deficit scenario. The sum is then given by:

$$\left(\sum_{k=1}^{n} W_{ijk} \right) = N_{irr_1} \cdot W_{ij1} + N_{irr_2} \cdot W_{ij2} + \ldots + N_{irr_n} \cdot W_{ijn} \quad (13)$$

where N_{irr_1}, N_{irr_2} and N_{irr_3} are related to the number of irrigation events on first, second and n^th (k = n) phenological stage, respectively; and W_{ij1}, W_{ij2} and W_{ij3} the water depths (mm) that infiltrate on i^th portion of furrow, on j^th water deficit scenario, and on 1^st, 2^nd and n^th phenological stage, respectively.

Whereas each water depth (W_{ijk}, mm) is calculated from:

$$W_{ijk} = 1000 \cdot \beta \cdot \left[t_{av} - t_{X_i} + \left(\frac{\delta_j \cdot W_{n0k}}{\beta} \right)^{1/\alpha} \right]^{\alpha} \quad (14)$$

where t_{av} is the advance time (min); δ_j the water deficit scenario, which is, indeed, a fraction of the required water depth that infiltrates at the end of the furrow:

$$\delta_j = \frac{X - j}{X} \quad (15)$$

where X is length (m) of furrow; and j is the ordinary number of scenario.

The water depth that infiltrates in each portion plus the water depth that runs off at to the end of the furrow both consist the total water depth that shall be computed on costs. The latter is obtained by multiplying total averaged water depth ($\overline{Wa}_{jk}$, mm) per run off dimensionless water volume ($\forall e_{jk}$). The total cost (CT_{ij}, R\$ ha^{-1}) in the i^{th} portion of a j^{th} water deficit scenario will be then given by:

$$CT_{ij} = 10 \cdot \left\{ \left[\Pr_W \cdot \sum_{k=1}^{n} \left(W_{ijk} + \overline{W}a_{jk} \cdot \forall e_{jk} \right) \right] + \left(CW \cdot \sum_{k=1}^{n} W_{ijk} \right) \right\} + CO \quad (16)$$

where Pr_W is the price of pumped water (R\$ m^{-3}) if is the case; CW is the cost (R\$ m^{-3}) regarding to all aspects related to irrigation except pumped water volumes (includes the selected pump, energy, etc.; given that all of these will vary as the pumped water varies); CO the other costs not related to irrigation (R\$ ha^{-1}); and n (denominator) is the amount of discretized furrow portions.

For each stage k, the total averaged water depth applied for each scenario j is:

$$\overline{W}a_{jk} = \frac{60 \cdot q \cdot ta_{jk}}{X \cdot Se} \quad (17)$$

where q is discharge (L s^{-1}) come from siphons; Se is the spacing (m) between furrows; and ta_{jk} is total time (min) for applying the total water depth ($\overline{Wa}_{jk}$, mm), being:

$$ta_{jk} = t_{av} + \left(\frac{\delta_j \cdot W_{n0k}}{1000 \cdot \beta} \right)^{1/\alpha} \quad (18)$$

The integration of all water depths infiltrated after the end of a single furrow, according to power distribution of probabilities, provides the total dimensionless volume of runoff water:

$$\forall_{e\,jk} = \int_{1}^{Fe_{jk}} \left(\mu_{jk} + \varphi_{jk} \cdot F_{jk}^{\,d_{jk}} \right) \cdot dF_{jk} \quad (19)$$

where μ_{jk}, φ_{jk} and d_{jk} are the parameters of power distribution of probabilities; and Fe_{jk} is the attribute regarding to the fraction of furrow in which is infiltrated at least the runoff water depth. It is possible to estimate all parameters (Frizzone, 2000):

$$\mu_{jk} = \frac{W_{0\,jk}}{\overline{W}_{jk}} \quad (20)$$

$$\varphi_{jk} = -\left(\mu_{jk} - \frac{W_{njk}}{\overline{W}_{jk}} \right) \quad (21)$$

$$d_{jk} = \frac{1 - \left(\frac{W_{njk}}{\overline{W}_{jk}} \right)}{\left(\mu_{jk} \right) - 1} \quad (22)$$

$$Fe_{jk} = \left(-\frac{\mu_{jk}}{\varphi_{jk}} \right)^{1/d_{jk}} \quad (23)$$

The parameter μ_{ij} regards to the maximum value of dimensionless water depth whereas φ_{jk} gives the slope of the curve. The term d_{jk} provides the function shape, which is concave if $0 < d_{jk} < 1$, that means, at least more than 50% of irrigated area is supplied by a depth lower than the averaged infiltrated depth, typically for highly permeable soils. On the other hand, $b > 1$ denotes more than 50% of the irrigated area receiving more water than the averaged infiltrated water depth.

The mean water depth ($\overline{W}_{jk}$, m) considering all portions of the j^{th} scenario for the k^{th} plant phenological development stage will be:

$$\overline{W}_{jk} = \frac{\beta}{n} \cdot \sum_{i=1}^{n} T_{ijk}^{\alpha} \quad (24)$$

Contemplating all development stages, the net income (π_{ij}, R\$ ha^{-1}) for the j^{th} portion of furrow in the j^{th} water deficit scenario is:

$$\pi_{ij} = RB_{ij} - CT_{ij} \qquad (25)$$

Consequently, the mean net income for the j[th] scenario of water deficit ($\bar{\pi}_j$, R$ ha^{-1}) of the whole furrow is expressed by:

$$\bar{\pi}_j = \frac{1}{n} \cdot \sum_{i=1}^{n} \pi_{ij} \qquad (26)$$

It may be finally suggested the functional form to denote δ_j versus $\bar{\pi}_j$:

$$\bar{\pi}_j = \xi \cdot \delta_j^{\,m} + \zeta \cdot \delta_j \qquad (27)$$

where ξ and ζ are empirical parameters of model; and m defines the exponent of the power equation.

If eq. 27 is differentiated and then equaled to zero, the water deficit scenario that matches to the maximized mean net income (δ_π) becomes visible:

$$\delta_\pi = \left(\frac{-m \cdot \zeta}{\xi} \right)^{\frac{1}{m-1}}; \; \delta_\pi \in I \qquad (28)$$

Therefore, for each phenological phase, the equation that denotes the optimal time to water supply in furrow irrigation is:

$$ta_{k_\pi} = t_{av} + \left(\frac{\delta_\pi \cdot W_{n0k}}{\beta} \right)^{1/\alpha} \qquad (29)$$

Therefore, the optimal time to water supply (ta_{k_π}, min) regarding to any phenological stage the sum of the advance time plus the opportunity time of a fraction of water depth that infiltrates at the end portion (i = n) of the fully irrigated scenario (j = 0) for the k[th] phenological stage. The opportunity time corrects, in fact, the water depth W_{n0k} through the factor δ_π deducted at eq. 28.

APPLICATION AND DISCUSSION

It is worth to comment that if different discharges are imposed as a consequence of irrigation management, different conditions of infiltration rate immediately occur towards to modify the values of the empirical parameters of both advance and infiltration equations. As a result, new shapes of water infiltration through power distribution and water deficit scenarios are generated. Also, some useful indexes may be found after solving eq. 29 such as suitability index, water supply efficiency, water distribution uniformity and runoff losses, according to Detomini et al. (2005). Whereas in pressurized flow, the relationship between line pressure and lateral outflow through an emitter is relatively well known, the prediction of lateral outflow by soil infiltration is far more poorly grounded. Though the theory of infiltration is well established, the results are dependent on the physical and chemical characteristics of the soil, including the geometry of the soil particles and their configuration in the matrix and the ambient water content within. Besides, a varying depth of flow can influence the wetted area through which infiltration into the surrounding soil is affected. Characterizing all of these factors as they vary from place to place along the irrigation stream can be a formidable task, and major simplifying assumptions are commonly made (Strelkoff and Clemmens, 2007).

For application purposes, an example of the herein model is presented by considering no rain and the following data for bean production: conditions of eq. (5); Pr_{pd} = R$ 1.00 kg^{-1}; Pr_W = R$ 0.02 m^{-3}; CO = R$ 850.00 ha^{-1}; $t_{av} = 4.265 \cdot X^{0.689}$; $W = 0.0075116 \cdot T^{0.34}$; $Y = 628.07 \cdot W^{0.5} - 13.54 \cdot W - 5505.41$; CW = R$ 0.04 ha^{-1}; X = 100 m; Se = 1 m; Kc and development stage durations in Table 1.

Table 1 – Development stages of bean and the corresponding Kc and development stage duration.

Development stage	Kc	Duration (days)
Vegetative	0.75	55
Flowering	1.15	15
Grain filling	0.87	35
Maturity	0.62	15

Figure 1 reveals that irrigation management without deficit provides optimal water deficit along the whole furrow, which is the outcome of eq. (2) for the suggested particular data, that means, ~ 537 mm. By doing so, this management leads to excessive water depths at the beginning portions of furrow and to suboptimal productivities on these portions as a result, according to the premises of eq. (1), and to less excessive depths when irrigation management is set for 75% of water deficit, although this conditions also leads to productivity strikes after the mid part of furrow length. However, the greater is the irrigation deficit, the less will be the runoff water after the end of furrow, implying in lower costs of pumping energy, selected pump (due to size), water (if priced) and so forth.

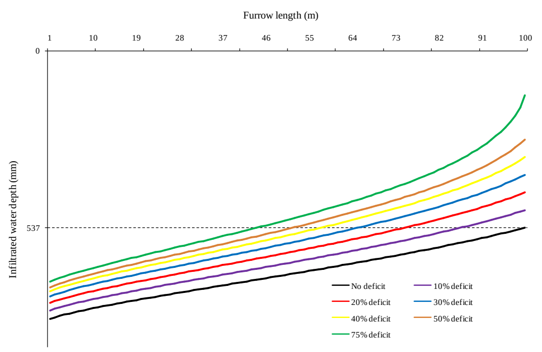

Figure 1 – Infiltrated water depths as a function of irrigation deficit management.

The technically optimal productivity occurs when 537 mm is substituted on the assumed yield-water function, resulting on about 1778 kg ha^{-1} (dry matter). If there is no irrigation deficit throughout furrow, yield tends to increase from the beginning until an optimal productivity verified at the end of furrow (Figure 2). Productivity is always lower before this point because there is excessive water. In this case, the adequacy index is 100% given that all plants of furrow is likely to receive at least the required water for achieving the highest yield.

If deficit conditions are provoked, upper values of yield (in comparison to the case without deficit) are then obtained for the initial parts of furrow due to less excessive water. These yields tend to achieve the optimal productivity as the opportunity time becomes longer, albeit tending to rapidly decrease from the intermediate portions of furrow as the greater is the deficit situation. Hence, it is visible a trade-off among variables such as water deficit conditions, yields and benefit-cost relations.

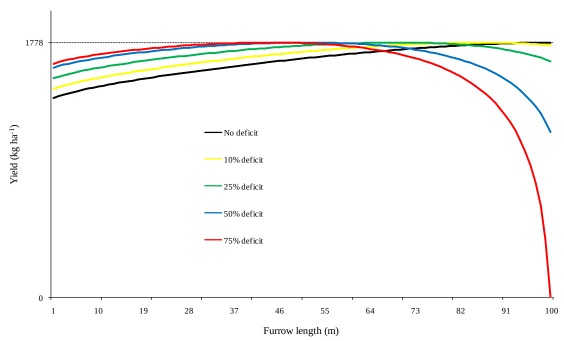

Figure 2 – Bean yield as function of infiltrated water depth.

For the specific case of this simulation exercise, Figure 3 shows that the optimal productivity occurs when water deficit scenario is around 70% (or 30% in terms of irrigation deficit); while the optimal net return is found when somewhat around 60% in terms of scenario (or 40% in irrigation deficit) is set. The averaged yields in all deficit situations were obviously lower than the potential productivity (~ 1778 kg ha^{-1}), being the highest averaged yield equal to ~ 1711 kg ha^{-1}, whereas the greatest averaged net return was R$ 510.25 ha^{-1}. Once there is no coincidence for these two percentages, it can be concluded that not necessarily the best scenario for net return corresponds to the best scenario of yields (Frizzone, 2000). There could be a consonance for them as long as the water distribution throughout furrow followed Normal distribution instead of the Power distribution.

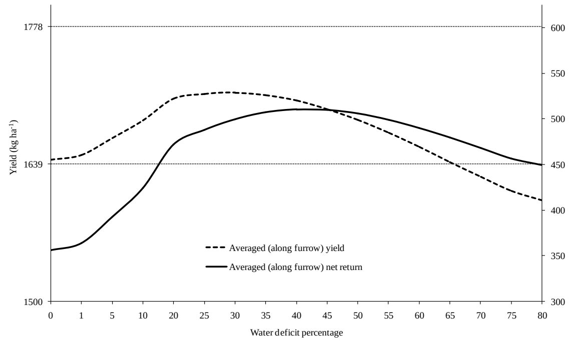

Figure 3 – Averaged yield and net return (both along furrow) as a function of water deficit percentage.

It is convenient for the instance to mention that the concepts of Economic Value Added (EVA) could be useful to introduce in economic approaches (Assaf Neto, 2009), regardless of simple return-cost analysis. Similar methodology of that one applied here for calculating furrow irrigation net return was used by Raghuwanshi and Wallender (1999), although these authors have adopted the optimization of costs prior to insert it on the net return equation, thus providing different and more sophisticated basis for the outcomes. In fact, the mean net income is maximized (δ_π) when δ_j equals to 0.6, which represents the situation of 40% of water deficit in terms of furrow irrigation management and, according to eq. (29), the optimal time to water supply (ta_{k_π}, min) for vegetative, flowering, grain filling and maturity stages would be, respectively, 105.81, 114.91, 132.30 and 160.56 minutes.

Considering the model assumptions and the deterministic feature of suggested data, the profitability of furrow irrigation could be assessed for all deficit scenarios anyhow. Scaloppi (2003) points that gravity-flow systems are generally not as costly as pressurized ones, in agreement with Letey et al. (1990), who indicated the same idea when no costs or restrictions are imposed, for example, on drainage water disposal. Towards this approach, if hidden costs of water wastage and of land degradation, as well as the increased environmental costs of drainage and land reclamation are taken into account, the relative costs of modern pressurized systems versus traditional irrigation methods can change radically (Oster and Wichelns, 2003).

Finally, economic issues play important roles on the analysis of irrigation sustainability. On the other hand, it is hard in practice to solve issues which are essentially political in nature (e.g. income distribution, environment, gender) with economics (i.e. economic instruments). Rather than solving these types of complex issues, economics helps us to better understand them. Economics provides very valuable analytical tools and is useful in tracing through the implications of various options for allocating scarce water resources. Economic analysis allows the introduction of criteria beyond simple profit and loss, but incorporation of criteria, such as income distribution and environmental concerns in the social welfare function requires weights and a common unit of measure, which are difficult to assess (Hellegers, 2006). Future works might be done in order to extend and make progresses on the herein model by inserting stochastic components and developing risk analysis in terms of simulation of both selling prices of product and rain events in phenological stages, as well as running sensitive analyses of important variables such as soil and water-yield function parameters on final outcomes.

CONSIDERATIONS

Different fractions of required water depth (that is regarding to maximum yield) being infiltrated at the end of furrow characterizes different water deficit situations, which implies a theoretical single net income for each discretized unit of portion throughout furrow. Hence there will be one scenario that will outline the best value for the mean net income. By being a generic model, it recommends the use of the presented tool for various situations since furrow is long defined and free-drained. Specific values of each variable and/or parameters should be suggested and/or set by users.

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