A Graphical Solution to Estimate Potential Runoff in Center-Pivot Irrigation

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Abstract. *This article describes a mathematical model for computing the potential runoff (RUNp) in center-pivot irrigation based on curvilinear regression analysis. The RUNp is related to the water depth application (WDP) and to the maximum water depth (WDPmx) that can be applied to the soil before runoff occurs. Furthermore, using a simple three-axis graphical tool, the RUNp-WDP-WDPmx relationship was also attained. The WDPmx was determined by solving an equation incorporating the peak water application rate (a center-pivot design parameter) and two physical parameters associated with the Green-Ampt infiltration model: the effective matric potential and the saturated hydraulic conductivity. From this study, using field data from irrigation events of several center pivots, selected with different lengths and sprinkler configurations, it was concluded that the proposed graphical solution is a reasonable and easy way to estimate potential runoff. The model reliability in predicting runoff was confirmed by calculating the basic model performance statistics.*

Keywords. *Center-pivot irrigation, Graphical solution, Green-Ampt parameters, Model efficiency, Potential runoff.*

The effectiveness of on-farm irrigation may be evaluated through the performance parameters of uniformity and efficiency of water application. Irrigation effectiveness is an important objective of research in order to assist farmers to adopt good practices for sustainable use of soil and water resources. Many irrigation technology developments focus on increasing water application efficiency. However, to conserve energy and reduce costs, center-pivot systems may not be properly designed and ensure reliable operation (Keller and Bliesner, 1990). For example, sprinkler packages with low-pressure nozzles, generating high application rates, are used to save energy; however, their use is a common cause of surface runoff on low-infiltration soils and sloping topography. On the other hand, one water management goal for a sprinkler system may be to apply as much water as possible during each irrigation event, but without causing runoff (Kranz et al., 1996). Thus, poor designs can result in lower water application efficiency of the installation and may lead to severe problems of soil erosion.

Potential runoff (RUNp) occurs when the rate of rainfall, or irrigation, exceeds the infiltration rate of the soil. The infiltration of water into soil may be described by the Richards equation, which is valid for different surface conditions. Smith and Woolhiser (1971) solved numerically the one-dimensional form and found that the theoretical predictions of infiltration and runoff from rainfall or ponding surface conditions were in good agreement with the results of both laboratory and field experiments. Heermann and Duke (1983) used the Richards equation to provide a basis for comparing techniques to predict runoff in center-pivot irrigation (related to time-varying water application conditions).

In center-pivot irrigation, potential runoff is a function of the peak water application rate, the irrigation depth, and the soil infiltration rate (Gilley, 1984). The soil infiltration rate may be estimated by the Kostiakov equation (Kincaid et al., 1969; Gilley, 1984; Wilmes et al., 1993) or by the Green-Ampt equation (Slack, 1980; von Bernuth, 1982; Kincaid, 2002). Gilley (1984) developed center-pivot sprinkler selection criteria using an analysis that combined the effects of water application rate and soil intake family curves to determine the maximum depth of water that can be applied per irrigation event without causing runoff. With reasonable success, Kincaid (2002) used the WEPP model, incorporating the Green-Ampt equation as described by Mein and Larson (1973), to predict runoff occurrence. He found that effective hydraulic conductivity is the main soil parameter affecting infiltration and runoff prediction. The results indicate that reliable estimation of both the soil effective hydraulic conductivity and the water application pattern, as determined by the type of sprinkler and the operating pressure, is critical in predicting runoff. Considering the negative impact of high application rates on runoff occurrence, Kincaid (2005) developed a method to predict the average and peak application rates. The method can then be incorporated with infiltration and center-pivot design models to predict when runoff might occur. Partsch et al. (1993), using the Green-Ampt equation as modified by Mein and Larson (1971), considered that the time to the start of runoff could be related to when the cumulative precipitation equaled the accumulated infiltration. Therefore, with proper use of relationships between the potential runoff and water depth, soil water (irrigation management parameters), peak application rate (center-pivot design parameter), and saturated hydraulic conductivity (soil parameter), irrigation options can be prechecked and used to predict runoff and erosion problems.

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Luz and Martins (2007) developed a new center-pivot irrigation model, $PIVOT\_ESC_0$, to predict runoff based on water depth application (WDP) and maximum application related to the initiation of runoff (WDPmx) using a curvilinear regression equation. An equation to determine the WDPmx was developed from a relationship involving a geometric water application pattern and the Green-Ampt equation, referred to the center-pivot design and to the soil characterization, respectively. As the soil infiltration process could be accurately described by the Richards equation, a numerical solution, GNFLUX (Smith, 1990), was used as a tool to evaluate the proposed procedures. Considering a wide scenario of soil and irrigation conditions, this numerical solution provided RUNp and WDPmx predictions.

The basic objectives of this study were to (1) validate the $PIVOT\_ESC_0$ model for potential runoff prediction, and (2) present a graphical solution to estimate the potential runoff from any typical center-pivot irrigation scenario (based on data obtained from the mathematical model). The graphical procedure to solve the mathematical model has the potential to decrease predictive accuracy, but it is an easy-to-apply solution. In addition, while a graphical tool cannot be taken as a substitute for mathematical models, its role as an aid in the design and management of on-farm irrigation systems is immense, since it presents a compact solution to a relatively complex problem (Zerihun et al., 1993). For example, it avoids an iterative technique, which is sometimes required to solve mathematical models. Regarding the runoff problem, this study aimed to develop innovative tools to help farmers, agriculture technicians, and other stakeholders select adequate center-pivot sprinkler configurations and irrigation scheduling.

Theory and Procedures

Richards Equation

The infiltration process may be characterized using the Richards equation. One-dimensional vertical infiltration is described by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial \Psi}{\partial z}\right) - \frac{\partial K}{\partial z} \tag{1}$$

where θ is water content, t is time, K is hydraulic conductivity, ψ is soil capillary potential, and z is depth from soil surface. In the absence of analytical solutions to the Richards equation, there is a need for a numerical solution to solve infiltration at any time. A computer program, GNFLUX (Smith, 1990), was used for this propose. Moreover, the program can be used for: (1) estimating RUNp considering soil conditions with or without crust sealing, (2) determining the water application and soil parameters that are related to a RUNp value, and (3) comparative procedures with other RUNp models. To run the program, it is necessary to set the initial soil water content for a specific soil depth, the peak application rate, and the water application time. The two water application parameters are needed to define the water application depth with an assumed water application pattern (elliptical, parabolic, or triangular). The scenarios of soil input data involve several hydraulic parameters, which may be attained from field plots or by using the Rawls and Brakensiek (1989) regression equations.

Maximum Water Depth Application to Avoid Runoff (WDPmx)

This section presents a review of a methodology developed by Luz and Silva (2007) to determine the WDPmx. A solution containing the soil parameters of the Green-Ampt infiltration equation and a design parameter of the irrigation system can be expressed as:

$$\text{WDPmx} = \frac{2NK_s}{(P_k - K_s)} \tag{2}$$

where

WDPmx = maximum water depth application to avoid runoff (mm)
N = effective matric potential (mm)
K_s = saturated hydraulic conductivity (mm h^{-1})
Pk = peak rate of water application (mm h^{-1}).

Water Application

The water application rate at any point within a center-pivot irrigation system varies during the irrigation event and is determined by the sprinkler characteristics (nozzle size, nozzle pressure, sprinkler spacing, and sprinkler types) associated with the system length and flow. Considering that the individual patterns of two or more sprinklers overlap and assuming some geometric shape to represent the application rate, it is possible to estimate the water applied at any time as a function of the peak rate. The peak rate has a fixed value for each lateral location and is independent of the system's speed of travel. Considering a given wetted diameter for a specific sprinkler, the travel speed establishes the time the system takes to deliver water at a given point and determines the water application depth. Figure 1 shows an elliptical application shape. Notice the increase of water application depth (proportional to larger geometric areas) related to high speed, average speed, and low speed as well as the constant peak water application rate.

Thus, it is advantageous to use expressions involving the peak rate of a geometric shape to estimate the water application rate and depth at a given time. In figure 2, three water application rate-time distribution patterns are shown for elliptical, parabolic, and triangular shapes.

The geometric shapes of water application and the resulting areas may be determined by familiar analytical solutions. The derived expressions found by establishing equivalent relationships among the parameters Pk, WDP, and T are the following:

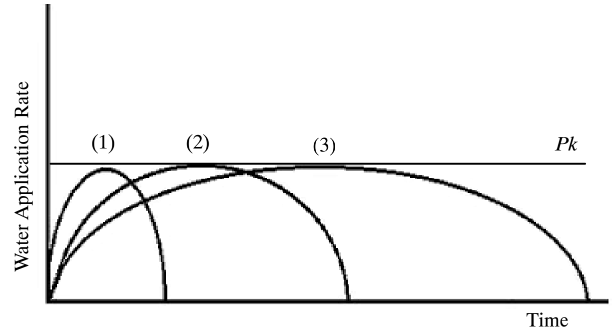

Figure 1. Water application patterns with decreasing speed at the same irrigation point: (1) high speed, (2) average speed (2), and (3) low speed.

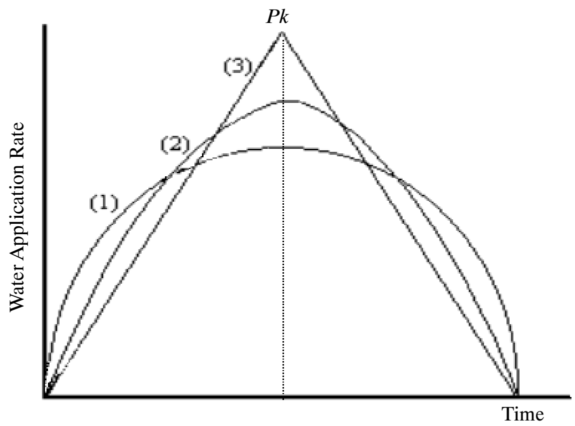

Figure 2. Center-pivot irrigation application patterns with the same water application depth: (1) elliptical, (2) parabolic, and (3) triangular.

$$\text{Elliptical shape: } Pk = \frac{4\text{WDP}}{\pi T} \quad (3)$$

$$\text{Parabolic shape: } Pk = \frac{1.5\text{WDP}}{T} \quad (4)$$

$$\text{Triangular shape: } Pk = \frac{2\text{WDP}}{T} \quad (5)$$

where

Pk = peak rate of water application (mm h^{-1})
WDP = water depth application (mm)
T = time period to the correspondent water depth application (h).

There is often a lack of field experimental data concerning the parameters of physically based models, and an option is to use an estimation procedure. However, estimation of input parameters will contribute to model error. Consequently, the likelihood of failure to predict the WDPmx (or potential runoff) because of a poor-fitting water application pattern is greatly increased. Two of the most common patterns to represent the center-pivot water application rates are the elliptical and triangular shapes (Gilley, 1984). However, the parabolic shape was found to be better fitting to most center-pivot water application measurements available in this study, thus increasing the accuracy of the parameters (*Pk*, WDP, and *T*) and the model feasibility. This pattern also gives intermediate values between the triangular and elliptical shapes. Therefore, it is possible to avoid the poorest predictions, as in the case where field data follow an elliptical pattern but the triangular approach is considered, or vice versa.

Green-Ampt Infiltration Equation

The Green-Ampt equation is a simplified solution to describe vertical downward movement of water into soil, relating the infiltration rate to the cumulative infiltration depth. This equation is becoming more widely used, partly as a result of the Mein and Larson (1971) interpretation and WEPP model development (Stone et al., 1994). According to Kincaid (2002), this model can be used to predict when runoff might occur under center pivots for different conditions and to determine limits on application depths and rates. The equation for infiltration rate (i) is (Rawls and Brakensiek, 1989):

$$i = K_s\left(1 + \frac{N}{I}\right) \quad (6)$$

where

i = infiltration rate (mm h^{-1})
K_s = saturated hydraulic conductivity (mm h^{-1})
N = effective matric potential (mm)
I = cumulative infiltration (mm)

In equation 6, the effective matric potential (N) is computed using:

$$N = n\psi_f \quad (7)$$

$$n = (\phi_e - \theta_i) \quad (8)$$

$$\phi_e = \phi - \theta_r \quad (9)$$

where

n = available pore space (mm^3 mm^{-3})
ψ_f = wetting front suction (mm)
ϕ_e = effective porosity (mm^3 mm^{-3})
θ_i = initial water content (mm^3 mm^{-3})
ϕ = total porosity (mm^3 mm^{-3})
θ_r = residual water content (mm^3 mm^{-3}).

The Green-Ampt equation has an inherent advantage over the approximate equations that specify infiltration rates in terms of time in that a single curve (infiltration capacity versus cumulative infiltration) can be used for all application rates. Another advantage of the Green-Ampt approach is that the equation parameters have physical significance, although the definition of N has caused some difficulty (Skaggs et al, 1983). Parameter values may be obtained using functions derived from soil properties, such as texture, and based on data and analysis from experimental work (Rawls and Brakensiek, 1989).

Precipitation-Infiltration Relationship (solving WDPmx)

The procedure to determine the WDPmx accounts for fundamental relationships behind the analytic theory for physically based infiltration models (Richards, Green-Ampt, among others). This theory indicates that, at time of ponding, the amount of cumulative infiltration (I_1) is equal to the cumulative water application (P_1), as shown in figure 3, and the infiltration rate (i_1) is equal to the water application rate (p_1) (Smith, 1982; Stone et al., 1994; Partsch et al, 1993). Equivalently, for given initial water content, there is a unique rela–

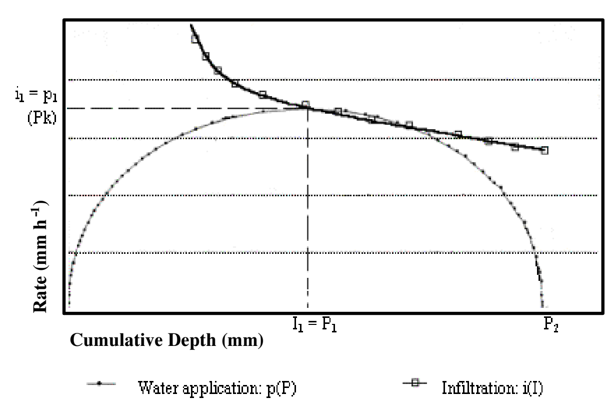

Figure 3. Infiltration and water application rates versus cumulative depths.

tionship between the water application rate and cumulative infiltration depth at time of ponding (Smith, 1982).

The simulation program GNFLUX (Smith, 1990) was run, using a parabolic water application pattern, to estimate the potential runoff, combining soil conditions (K_s ranged from 4 to 15 mm h^{-1}) and center-pivot water application conditions (Pk ranged from 55 to 110 mm h^{-1} and WDP ranged from 6 to 17 mm). It was found that if no runoff occurred at the time the peak application rate crossed the location, then the possibility of runoff occurrence during the following water application period was greatly reduced. Following the peak application rate, the water application rate drops much faster than the infiltration rate. When runoff begins in such conditions, the estimated amounts are very low, with a maximum of 3.5% of the water application (Luz and Silva, 2007). Let us consider a field under irrigation, where the peak rate is observed at the time of ponding. With a good approximation, the applied water application depth (WDP) may be considered as the maximum water application to avoid runoff (WDPmx). If soil infiltration is described by the Green-Ampt solution, then P_2 is the WDPmx and Pk is a design parameter of the center pivot (fig. 3). According to equation 6 and considering the intersection point in figure 3 (where $i_1 = Pk$ and $I_1 = P_1$), one obtains:

$$P_k = K_s\left(1+\frac{N}{P_1}\right) \tag{10}$$

and as $2P_1 = P_2$ = WDPmx, equation 2 is rewritten as:

$$P_1 = \frac{N K_s}{\left(P_k - K_s\right)} \tag{11}$$

The model efficiency applied to validation, comparing the WDPmx results attained with this equation and with GNFLUX, with same soil and center-pivot parameters, was 99% (Luz and Silva, 2007). Values of N and K_s, which are needed in this method for a specific site, can be determined from graphical forms of the Brooks-Corey water retention parameters (Brooks and Corey, 1966) based mainly on soil texture properties (Rawls and Brakensiek, 1989).

Approaches to Runoff Occurrence

To predict surface runoff at a given location, or to predict the time at which runoff starts, Slack (1980) and Von Bernuth (1982) proposed complex iterative procedures relating an infiltration function and the water application rate distribution over time. These procedures, considering several of the equations referred to at the beginning of this article, have been greatly facilitated through the development of computational tools. On the other hand, some researchers are using graphical solutions to provide an easy tool for stakeholder use. For example, the program CPNOZZLE (Kranz, 2000) determines runoff information, based on input parameters including system length, system capacity, wetted diameter, water application depth, soil intake family, field slope, and residue cover percentage to determine the surface storage, that may then be provided through a series of figures, considering several defined relationships. This study presents a new graphical solution to predict potential runoff, which is conceptualized through a relationship involving the parameters used by the PIVOT_ESC$_0$ model, which is described in the next section. A graphical solution proposed by Gilley (1984) is also presented in order to carry out a comparative analysis.

PIVOT_ESC$_0$ Model

The PIVOT_ESC$_0$ model, developed by Luz and Martins (2007) to estimate runoff, is based on a relationship between two composed parameters, W_w and R_w, corresponding to WDPmx/WDP and RUNp/WDP, respectively. This semi-analytical solution is expressed by an approximate equation describing that relationship and involving a fitting procedure. The curve fitting procedure used SPSS (SPSS for Windows, release 12.0.1, Chicago, Ill.: SPSS, Inc.), and a nonlinear regression model was chosen: $y = a[(x + b)^{-c} - d]$. This relationship was established using field data. In order to define the model, table 1 shows the WDPmx, RUNp, W_w, and R_w results related to data acquired from 12 field tests (Luz and Martins, 2007). The WDP values varied from 9 to 21 mm, and the results of WDPmx, obtained with equation 2, varied from 0.5 to 9.3 mm. The RUNp values, estimated with GNFLUX, ranged from 1.3 to 12.8 mm.

The equation describing the relationship between W_w and R_w, defining the basic PIVOT_ESC$_0$ model, is:

Table 1. Parameters required for the curve fitting procedure.

	Field Site	WDP[a] (mm)	Pk[a] (mm h^{-1})	N[a] (mm)	K_s[a] (mm h^{-1})	WDPmx[b] (mm)	RUNp[c] (mm)	W_w[d] (mm mm^{-1})	R_w[d] (mm mm^{-1})
1	M. Alhos	17	70	31.5	9.0	9.3	2.3	0.55	0.14
2	Lampreia	14	55	28.2	6.0	6.9	2.7	0.49	0.19
3	M. Alhos	10	100	25.1	8.0	4.4	2.4	0.44	0.24
4	Évora	10	100	38.1	8.0	6.6	1.3	0.66	0.13
5	Roxo	10	60	27.1	4.0	3.9	2.7	0.39	0.27
6	Odivelas	9	80	33.5	5.0	4.5	1.8	0.50	0.20
7	M. Velhos	15	45	52.8	1.5	3.6	5.7	0.24	0.38
8	Idanha	19	72	47.1	4.6	6.4	5.7	0.34	0.30
9	Guiomar	15	100	51.7	2.5	2.7	7.1	0.18	0.47
10	Guiomar	21	115	44.0	2.5	2.0	12.8	0.09	0.61
11	Jungeiros	10	125	4.8	6.0	0.5	7.0	0.05	0.70
12	Jungeiros	10	60	19.2	2.5	1.7	5.0	0.17	0.50

[a] Based on field tests conducted by several researchers (Luz and Martins, 2007). Information and procedures as in table 3, reference 2 (WDP = water depth application, Pk = peak rate of water application, N = effective matric potential, and K_s = saturated hydraulic conductivity).
[b] Obtained with equation 2.
[c] Estimated with GNFLUX (Smith, 1990).
[d] W_w = WDPmx/WDP; R_w = RUNp/WDP.

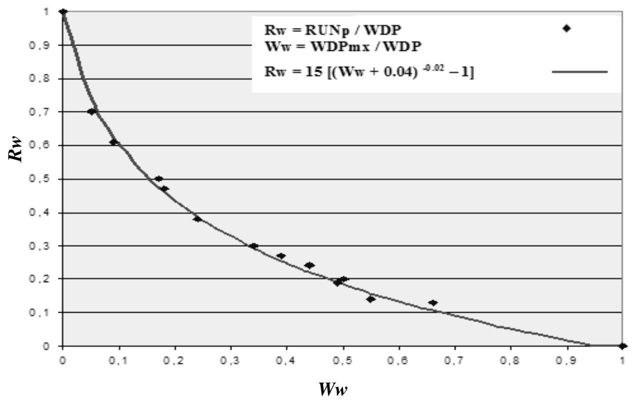

Figure 4. Curvilinear regression equation fitting points of the relationship W_w-R_w.

$$Rw = 15\left[(Ww + 0.04)^{-0.02} - 0.9992\right] \quad (12)$$

The coefficient of determination value (r^2) for the fitting procedure was 99%, exhibiting a strong correlation between parameters.

From figure 4, it is possible to determine that RUNp/WDP decreases when WDPmx/WDP increases. On the other hand, WDPmx may be equal for different soil and system irrigation conditions, and each WDPmx value will define a unique WDP-RUNp relationship independent of any soil type. This relationship may be assumed due to the excellent result in curve fitting. In addition, an equation may be established to predict RUNp.

Rewriting equation 12 in order to determine RUNp, where the value -1.0 does not change the results significantly and considering that all parameters have the same dimension (L), the following direct solution is defined:

$$\text{RUNp} = 15\text{WDP}\left[\left(\frac{\text{WDPmx}}{\text{WDP}} + 0.04\right)^{-0.02} - 1.0\right] \quad (13)$$

Next, combining equations 2 and 13 and including the surface storage (S_s) gives the possibility to determine the actual runoff (RUNa) as follows:

$$\text{RUNa} = 15\text{WDP}\left[\left(\frac{2NK_s}{\text{WDP}(Pk - K_s)} + 0.04\right)^{-0.02} - 1.0\right] - S_s \quad (14)$$

where

RUNa = actual runoff (mm)
WDP = water depth application (mm)
N = effective matric potential (mm)
K_s = saturated hydraulic conductivity (mm h^{-1})
Pk = peak rate of water application (mm h^{-1})
S_s = surface storage (mm).

Graphical Solution

Determining the WDP required to avoid RUNa with S_s would require an iterative method to solve equation 14. Another option is a graphical procedure, involving a relationship among the WDP-WDPmx-RUNp parameters (fig. 5). At a particular location, any WDP exceeding the WDPmx will cause RUNp. However, if the RUNp value is lower than or equal to S_s, then RUNa will be avoided. Therefore, considering these assumptions, the graphical procedure will generate a quick result of the WDP required to avoid RUNa and may be a substitute for equation 14. In addition, with regard to a selected center pivot, information on the WDP-RUNp relationship is sometimes available. Thus, this graphical solution gives the value of WDPmx directly, avoiding the need of solving equation 2. Consequently, for different events with several WDP values, considering that the respective lines will cross the graph at the same WDPmx value, it is possible to determine each associated RUNp. The S_s value, which is a function of slope, residue/mulch management, soil surface roughness, or tillage practices (including basins and reservoirs) (Silva, 2010), will then determine if RUNa may be avoided.

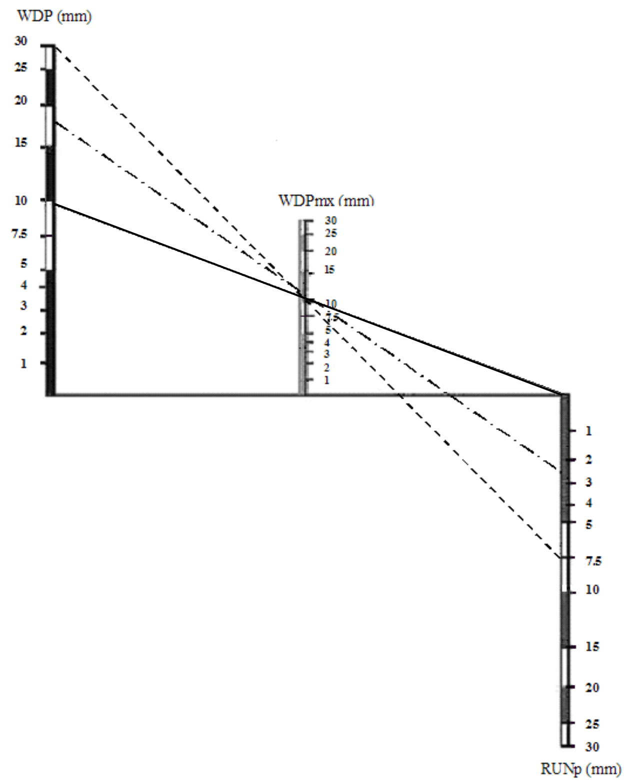

Figure 5. Graphical solution to the WDP-WDPmx-RUNp relationship.

The graphical solution scale was obtained by a trial-and-error approach by applying $PIVOT\_ESC_0$ to a representative range of soil and design data to match the three-axis (WDP, WDPmx, and RUNp) results. Inherent in the WDPmx concept is that an appropriate scale should be consistent with two basic considerations: (1) when WDP and RUNp exhibit equal values, then the line drawn between them must cross the WDPmx axis at the zero point; and (2) any line intersecting the RUNp axis at the zero point must cross the WDP and WDPmx axes at the same value. The diagonal lines in figure 5 are an example of a graphical solution. Assuming that the soil and design conditions define a WDPmx of 10 mm, applying water depths (WDP) of 18 or 30 mm will result in potential runoff (RUNp) of 2.5 and 7.5 mm, respectively. Furthermore, if the RUNp results are equal to the S_s values, then RUNa will be avoided.

Gilley Methodology

The analysis proposed by Gilley (1984), through the use of figures, allows the prediction of runoff and WDPmx for various types of soils and sprinkler packages. The potential runoff is determined by a technique given by Kincaid et al. (1969) that involves a modified flooded intake function of Kostiakov and an elliptical pattern to represent the water application rate-time distribution (an iterative process is needed). This technique uses an infiltration-time function, which accounts for the surface unsaturated conditions for center-pivot systems (Gilley, 1984). This accounts for the assumptions of infiltration theory in the Richards and Green-Ampt equations. The allowable surface storage is taken from Dillon et al. (1972). Then, through simulation analysis, several figures are built, related to soil intake family (0.1, 0.3, 0.5, and 1.0), where it is possible to observe the water depth that may be applied by a particular system (characterized by the peak application rate) in order to avoid runoff, considering the amount of soil surface storage. This information is useful to determine guidelines for proper selection of center-pivot systems. From the adapted Gilley (1984) figures, it is also possible to observe an interesting fact: considering a certain water application related to no runoff (such as 10 mm in the soil families in fig. 6), the potential runoff related to the surface storage (2.5, 7.6, or 12.7 mm) will be reported to nearly equal application depths (approximately 18, 30, or 40 mm, respectively), independent of the soil family. Only the peak application rate will change according the soil family. Therefore, for any particular set of soil and irrigation system conditions, if the same WDPmx (zero potential runoff) is determined, then, for approximation purposes, a unique relationship may be assumed between water application depth and potential runoff (or allowable surface storage) values. Such observations and results are consistent with the PIVOT_ESC$_0$ model and the graphical solution explanations. The presented example is helpful in clarifying those conclusions.

Measured and Estimated Parameters Data

A comparative analysis of RUNp solutions, involving data from 47 available field tests from published studies, was related to the most typical operating conditions of center pivots combined with several different soil conditions. Table 2 presents the input data needed to apply the RUNp solutions. Table 2 includes soil conditions with very low infiltration (related to an effective K_s equal to 0.8 mm h^{-1}) and very high infiltration (K_s equal to 65 mm h^{-1}). Field tests labeled with a "c" had crust sealing development. The range of *Pk* values was also very wide (40 to 200 mm h^{-1}), and the WDP varied from 9 to 25 mm. The WDPmx, a key parameter of the new methodologies and dependent on the soil and system design conditions, was calculated with equation 2. The results ranged from 0.5 to 22.5 mm. The calculations showed a high percentage of low WDPmx values or, equivalently, of excessive RUNp. This fact illustrates the magnitude of the runoff problem with respect to center-pivot irrigation in Portugal. The problem is generally due to conditions that combine soils with low infiltrability (many with surface seal formation) and low-pressure irrigation systems with peak rates that are too high (meaning that the

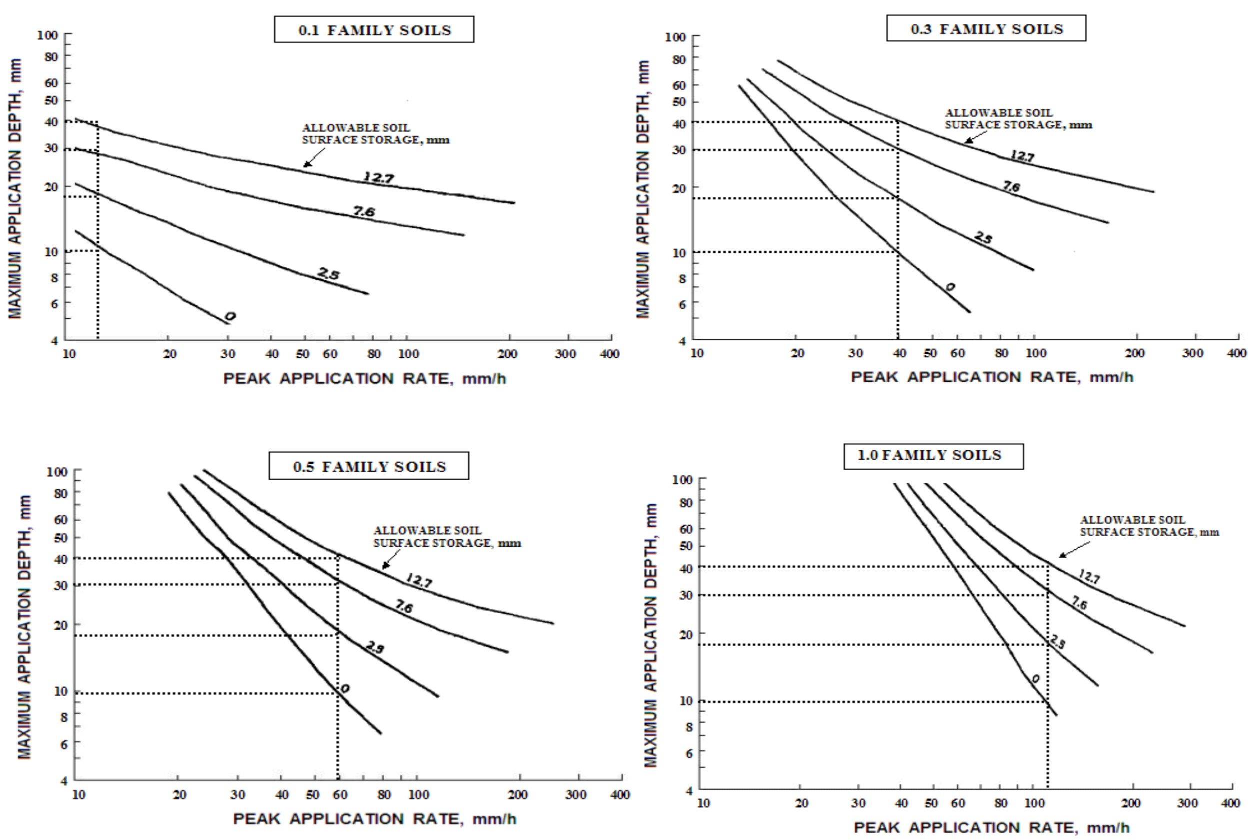

Figure 6. Conditions of maximum application depth to avoid runoff for different soil families (adapted from Gilley, 1984).

Table 2. Database of input parameters needed to evaluate RUNp solutions.

	Field Test	N (mm)	K_s (mm h-1)	Pk (mm h-1)	WDP (mm)	WDPmx[a] (mm)	Ref.[b]
1	S.Dak1_82-85	11.4	65.0	200	25	11.0	1
2	S.Dak2_82-85	15.9	25.0	90	25	12.2	1
3	S.Dak3_82-85	18.7	18.0	60	25	16.0	1
4	S.Dak4_82-85	23.0	11.0	40	25	17.5	1
5	M.A.1_I8-98	26.9	8.8	55	10	10.3	2
6	M.A.2_I8-98	28.3	8.8	55	17	10.8	2
7	M.A.3_I16-98	34.9	9.0	70	10	10.3	2
8	M.A.4_I16-98	34.9	9.0	70	17	10.3	2
9	M.A.5_I4-98c	36.7	1.3	40	10	2.5	2
10	M.A.6_I4-98c	35.4	1.3	40	17	2.4	2
11	M.A.7_I14-98c	29.9	1.2	70	10	1.0	2
12	M.A.8_I14-98c	30.3	1.2	70	17	1.1	2
13	M.A.9_II12-98c	88.7	0.8	70	10	2.1	2
14	M.A.10_II12-98c	86.0	0.8	70	17	2.0	2
15	M.A.11_II4-98c	84.8	0.8	40	10	3.5	2
16	M.A.12_II4-98c	84.0	0.8	40	17	3.4	2
17	M.A.13_96-98c	29.7	1.3	70	10	1.1	2
18	M.A.14_96-98c	29.7	1.3	70	17	1.1	2
19	M.A.15_96-98c	29.7	1.3	70	23	1.1	2
20	M.A.17_02-04c	34.1	1.5	100	17	1.0	2
21	M.A.18_02-04c	27.6	1.5	100	10	0.8	2
22	M.A.19_02-04c	35.8	1.5	100	10	1.1	2
23	M.A.20_02-04c	35.8	1.5	100	14	1.1	2
24	CP1_19001	52.8	1.5	45	15	3.6	3
25	CP2_21501	28.2	6.0	55	14	6.9	3
26	CP3_25001	52.8	1.5	60	10	2.7	3
27	CP4_25001c	22.0	1.5	84	10	0.8	3
28	CP6_30001	25.1	8.0	100	10	4.4	3
29	CP6_30001c	25.1	1.2	100	10	0.6	3
30	CP7_35001	52.8	1.5	90	10	1.8	3
31	CP10_45001	24.4	8.0	115	10	3.6	3
32	IDA1_03	52.2	1.4	96	10	1.5	4
33	IDA3_03	59.4	2.3	84	9	3.3	4
34	IDA4_03	47.1	4.6	72	19	6.4	4
35	EVO4_01	38.1	8.0	100	10	6.6	5
36	R1_250M03	27.1	4.0	60	10	3.9	6
37	R2_350M03	27.1	5.0	90	10	3.2	6
38	R3_450M03	12.8	6.0	125	10	1.3	6
39	O1_255M03	28.7	5.0	80	10	3.8	6
40	O2_275M03	33.5	5.0	80	9	4.5	6
41	R1_250M04	19.2	2.5	60	10	1.7	6
42	R1_250E04	27.1	2.5	60	9	2.4	6
43	R2_350M04	27.1	5.0	90	10	3.2	6
44	R2_350E04	27.1	5.0	90	10	3.2	6
45	R3_450M04	4.8	6.0	125	10	0.5	6
46	I1_320B04	51.7	2.5	100	15	2.7	6
47	I2_350M04	44.0	2.5	115	21	2.0	6

[a] Obtained with equation 2.
[b] Input data (N, K_s, Pk, and WDP) from: 1 = DeBoer et al. (1992),; 2 = Luz et al. (2007), 3 = EAN/INIA (2002), 4 = Moreira (2002), 5 = Silva (2001), and 6 = EAN/INIA (2007).

wetted diameters are too small). Increasing surface storage through the use of small dikes is a common tillage practice adopted by Portuguese farmers to avoid RUNa.

The WDP values were generally determined through the travel speed based on design information provided by the irrigation system manufacturer. However, the great majority of the data presented by the studies were collected in the field or were obtained in the laboratory. The different procedures and devices used to determine the required parameters are listed in table 3. Several soil parameters referred to in this table were also attained through methodologies used at our location and are described by Ramos et al. (2006).

Estimation tools were applied in cases where needed data were missing. For example, similar to the proposed procedure in OPUS (Smith, 1992), this study took advantage of the extensive data assembly and analysis by Rawls and Brakensiek (1989) to give the user a survey of the expected Brooks-Corey parameters values. This procedure, involving the use of regressions, provides a way to estimate reasonable parameters in most cases from the user's knowledge of the soil texture (Brakensiek et al., 1984). Initial soil moisture and Brooks-Corey parameters data are not reported here, but table 3 provides an example showing the procedure needed to determine the effective matric potential, N (defined in the Green-Ampt Infiltration Equation section). Table 3 also summarizes the runoff measurement systems and soil surface conditions. The information on factors for estimating surface storage (S_s) is useful in predicting RUNp from RUNa. The allowable surface storage is primarily a function of the roughness of the soil surface and the topography of the given site, primarily slope (Gilley, 1984). Values of soil surface storage related to slope may be taken from Dillon et al. (1972). Rawls and Brakensiek (1989) developed equations to describe soil management effects on infiltration parameters. The attained information indicates that there were several tests without any surface storage (related to slope greater than 5%), crop residue, or plant canopy. Consequently, plot devices were adequate to collect potential runoff, and in such conditions RUNa was equal to RUNp. On the other hand, several authors (De Boer et al., 1992; Luz et al, 2007; EAN/INIA, 2007) confirmed the impact of one or more surface storage factors.

Model Performance Evaluation

The Nash and Sutcliffe (1970) model efficiency (EF) was applied to indicate the agreement between the observed and predicted values. This concept, which is similar to the correlation coefficient from linear regression (R^2), is defined as:

$$\mathrm{EF} = 1 - \frac{\sum_{t=1}^{N}\left(Y_t - P_t\right)^2}{\sum_{t=1}^{N}\left(Y_t - \overline{Y}\right)^2} \qquad (15)$$

where

Y_t and P_t = observed and predicted output for event t, respectively

$\overline{Y}$ = average of the observed values.

An important difference between the model efficiency and R^2 values is that the model efficiency compares the predicted values to the 1:1 line between measured and predicted values rather than the best regression line through the points. The EF will always be lower than the correlation coefficient, and the amount by which it is lower is indicative of bias in the model. When the EF is negative, it indicates that the average value of the output is a better estimate than the model prediction (Risse et al., 1994). According to common practice (Van

Table 3. Summary of information and procedures used for runoff and related parameter evaluation.

Reference (Field Tests)	Parameter				Runoff Measurement System (and Soil Surface Conditions)
	θ_i	N[a]	K_s[b]	Pk	
1 (tests 1-4)	Neutron probe	Functions from soil properties (Rawls and Brakensiek, 1989) (related also to given K_s)	Field data and Moshref-Javadi approach (De Boer, 1992)	Tipping-bucket rain gauges	Calibrated flumes (corn canopy, 3% slope, 30% residue cover, soil crusting)
2 (tests 5-19)	Soil samples, neutron probe	Disturbed and undisturbed samples (laboratory methods); functions from soil properties (Rawls and Brakensiek, 1989)	Double-ring infiltrometer in field testing	Catch cans with stationary lateral (Dillon et al., 1972)	Circular plot frame, accumulator tank (corn canopy, soil crusting in tests 9-19)
2 (tests 20-23)	Soil samples, TDR-Trime	Disturbed and undisturbed samples (laboratory methods); functions from soil properties (Rawls and Brakensiek, 1989)	Tension-disk infiltrometer in field testing	Tipping-bucket rain gauges	Rectangular plot frame, accumulator tank (corn canopy, 2% to 5% slope, soil crusting)
3 (tests 24-31)	Soil samples	Disturbed and undisturbed samples (laboratory methods); functions from soil properties (Rawls and Brakensiek, 1989)	Field data and Rawls and Brakensiek (1989) approach; laboratory constant-head method (Stolte, 1997)	Tipping-bucket rain gauges	Circular plot frame, accumulator tank, (potential runoff, soil crusting in tests 27 and 29)
4 (tests 32-34)	Gypsum block	Disturbed and undisturbed samples (laboratory methods); functions from soil properties (Rawls and Brakensiek, 1989)	Laboratory, hydraulic conductivity curve: K (h)	Tipping-bucket rain gauges	Circular plot frame, accumulator tank (tobacco canopy)
5 (test 35)	Theta probe ML2	Functions from soil properties (Rawls and Brakensiek, 1989)	Tension-disk infiltrometer in field testing	Catch cans with moving lateral; volume and time measurements	Circular plot frame, accumulator tank (potential runoff)
6 (tests 36-47)	TDR-Trime	Disturbed and undisturbed samples (laboratory methods); functions from soil properties (Rawls and Brakensiek, 1989)	Tension-disk infiltrometer in field testing; laboratory constant-head method (Stolte, 1997)	Tipping-bucket rain gauges	Rectangular plot frame, accumulator tank (potential runoff)

[a] Includes Brooks-Corey water retention parameters (ψ_f, ϕ, and θ_r). For example, for N calculation (eq. 7) related to a given K_s (e.g., 6.5 mm h^{-1} in field test 1), loam soil texture, average θ_i of 20%, and Brooks-Corey parameters considering the Rawls and Brakensiek (1989) approach (ψ_f = 81.25, ϕ = 0.39, θ_r = 0.05), N = 11.4 mm.

[b] Based on field tests (with crusted or uncrusted soil) and laboratory samples.

Liew and Garbrecht, 2003), simulation results are classified as good (EF ≥ 0.75), satisfactory (0.75 > EF > 0.36), and unsatisfactory (EF < 0.36).

In addition to EF, other indicators used for RUNp solution evaluation included mean absolute error (MAE), mean error bias (MBE), and root mean square error (RMSE):

$$\text{MAE} = \frac{\sum_{t=1}^{N} \left| P_t - Y_t \right|}{N} \quad (16)$$

$$\text{MBE} = \frac{\sum_{t=1}^{N} \left(P_t - Y_t \right)}{N} \quad (17)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{N} \left(P_t - Y_t \right)^2}{N}} \quad (18)$$

Results and Discussion

Table 4 shows the measured runoff values, reported by the studies listed in table 2, and the results of RUNp solutions involving the 47 field tests. The measured (field tests) and predicted (proposed solutions) runoff values were first compared through the model efficiency (EF) calculation. According to the suggested classification (Van Liew and Garbrecht, 2003), this quantitatively evaluation (fig. 7) shows that a good result (0.75) was obtained by the Richards equation. All other solutions achieved a satisfactory result (between 0.70 and 0.47).

Regarding the model efficiency results, it may be concluded that the proposed solutions were adequate to simulate the runoff events. However, the soil infiltration behavior, within the test plots, must be in accordance with the basic concepts behind the analytical theory for physically based infiltration models, as described by Smith (1982). In such cases, it may be assumed that the soil matrix is rigid and does not change with time, so that the soil water characteristics and saturated hydraulic conductivity relationships are not time variant. These assumptions do not always hold and may cause large errors in predicted results (Skaggs et al, 1983). The good performance of the Richards equation confirms its reliability to describe actual soil and irrigation conditions involving factor effects (such as the initial soil water content and application rates) on infiltration. This ensures its adequacy to determine parameters with the experimental data used in this study, which represented a wide variety of soil types and water applications. Furthermore, the Richards equation may also provide the

Table 4. Database of measured runoff values and potential runoff predicted results obtained by applying the proposed solutions.

		RUNp or RUNa[a]	RUNp			
	Field Test	Experimental (mm)	Richards Equation[b] (mm)	PIVOT_ESC$_0$[c] (mm)	Graphical Solution[d] (mm)	Gilley Solution[e] (mm)
1	S.Dak1_82-85	4.8	5.7	5.6	5.0	5.5
2	S.Dak2_82-85	5.0	4.6	4.8	4.5	4.5
3	S.Dak3_82-85	2.5	2.9	2.9	2.5	2.5
4	S.Dak4_82-85	2.0	2.4	2.3	1.5	2.0
5	M.A.1_I8-98	0.5	0	0	0	0
6	M.A.2_I8-98	1.6	2.2	2.0	2.0	2.5
7	M.A.3_I16-98	2.9	0.2	0	0	0
8	M.A.4_I16-98	4.0	2.3	2.2	2.5	2.5
9	M.A.5_I4-98c	3.5	4.1	3.8	4.5	5.0
10	M.A.6_I4-98c	7.3	7.8	8.9	9.0	9.0
11	M.A.7_I14-98c	5.8	6.8	5.9	7.5	7.5
12	M.A.8_I14-98c	10.1	11.9	11.9	13.5	12.5
13	M.A.9_II12-98c	6.4	5.4	4.3	5.0	6.0
14	M.A.10_II12-98c	10.4	9.8	9.6	10.5	10.5
15	M.A.11_II4-98c	5.3	4.1	2.9	3.5	3.5
16	M.A.12_II4-98c	8.3	7.7	7.3	7.5	7.5
17	M.A.13_96-98c	5.0	6.3	5.8	7.0	7.5
18	M.A.14_96-98c	9.3	11.1	11.7	13.5	12.5
19	M.A.15_96-98c	14.4	15.4	17.1	17.0	15.0
20	M.A.17_02-04c	7.8	11.6	12.0	13.5	12.5
21	M.A.18_02-04c	5.3	6.7	6.4	8.0	7.5
22	M.A.19_02-04c	4.6	6.5	5.8	7.0	7.5
23	M.A.20_02-04c	7.9	9.4	9.2	10.5	10.5
24	CP1_19001	5.4	5.7	5.8	6.5	6.0
25	CP2_21501	2.5	2.7	2.7	3.0	2.5
26	CP3_25001	6.3	3.7	3.5	4.0	4.5
27	CP4_25001c	4.6	6.3	6.5	8.0	7.5
28	CP6_30001	1.7	2.4	2.2	2.5	2.5
29	CP6_30001c	4.3	7.6	7.0	8.5	8.0
30	CP7_35001	6.3	4.7	4.6	6.0	6.0
31	CP10_45001	4.3	2.9	2.7	3.5	3.5
32	IDA1_03	5.0	5.1	5.0	6.0	6.5
33	IDA3_03	3.3	2.4	2.4	2.5	3.0
34	IDA4_03	6.8	5.7	5.6	5.5	5.0
35	EVO4_01	2.1	1.3	1.1	1.5	1.5
36	R1_250M03	2.6	2.7	2.6	3.0	3.0
37	R2_350M03	2.7	3.3	3.1	3.5	3.5
38	R3_450M03	4.0	5.5	5.4	6.5	6.5
39	O1_255M03	2.2	2.8	2.6	3.0	3.0
40	O2_275M03	1.8	1.8	1.7	2.0	2.0
41	R1_250M04	3.7	5	4.8	6.0	6.0
42	R1_250E04	2.7	3.5	3.3	4.0	4.0
43	R2_350M04	3.5	3.3	3.1	3.5	3.5
44	R2_350E04	2.2	3.3	3.1	3.5	3.5
45	R3_450M04	5.1	7	7.5	8.0	8.0
46	I1_320B04	6.5	7.1	7.0	8.0	7.5
47	I2_350M04	10.5	12.8	13.0	13.5	14.0

[a] RUNp and RUNa data obtained from experimental tests.
[b] Obtained with GNFLUX (Smith, 1990).
[c] Obtained with equation 13.
[d] Obtained with figure 5.
[e] Approximation/interpolation of figure 6 using WDPmx and WDP data (from Gilley, 1984).

basis for comparison with potential runoff results of other approximate solutions. A satisfactory EF result (70%) was obtained with the PIVOT_ESC$_0$ solution. In addition, its RUNp values are in excellent agreement with those predicted with the Richards equation, confirming the methodology (including the WDPmx parameter) and taking into account basic soil infiltration assumptions, even though it involves simplified procedures.

The graphical and Gilley solutions required only a pair of WDP-WDPmx values to predict the resulting RUNp (which may be related to the allowable surface storage). The results also indicate that, given the same WDPmx value, the RUNp

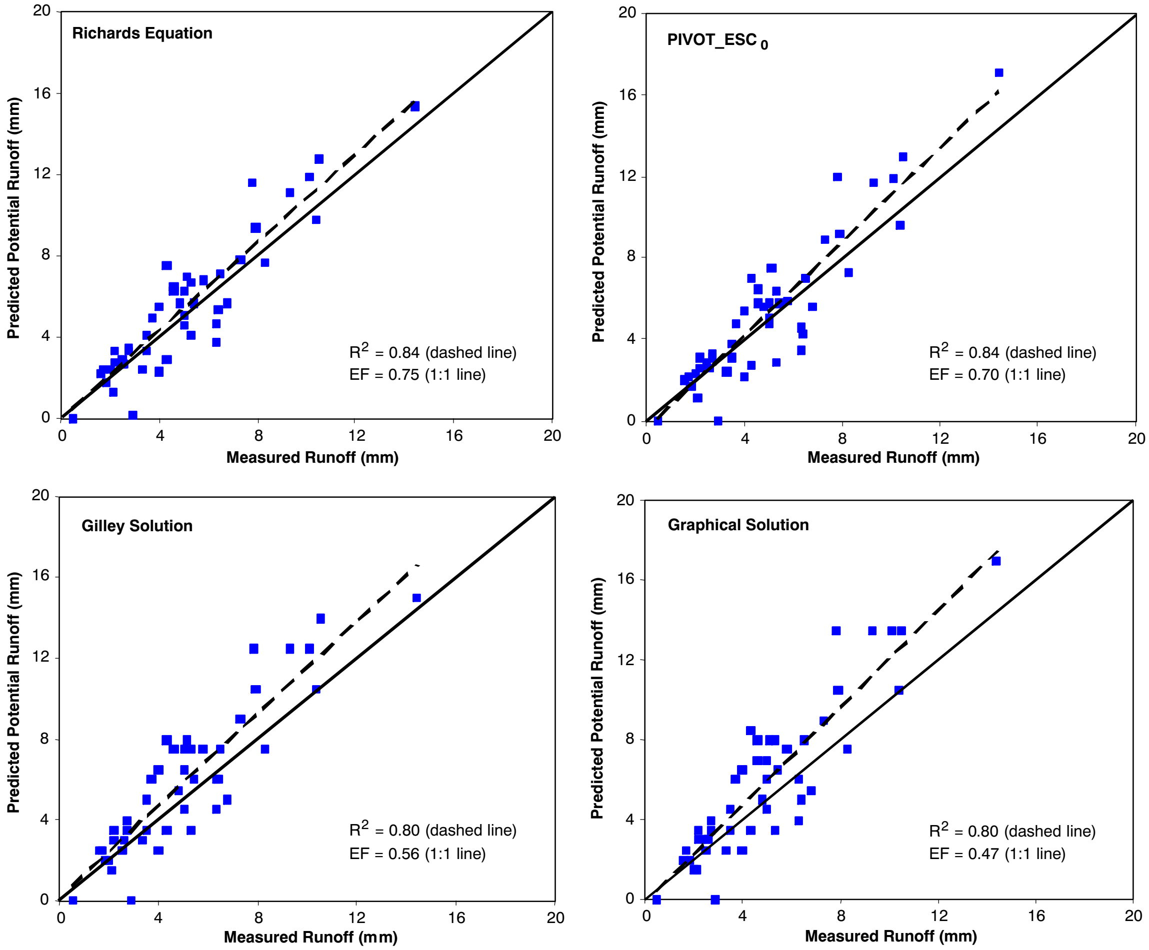

Figure 7. Measured versus predicted runoff for the four proposed solutions.

values obtained with the Gilley solution are not significantly influenced by the soil intake family, as previously shown. Nevertheless, each value was determined through a visual approximation, using available soil family charts in order to achieve a better evaluation. Note that the EF results of both solutions (graphical and Gilley) decrease due to approximation errors that are inherent in graphical development. However, the graphical solutions may avoid other errors resulting from uncertainties of input parameters that are required for iterative mathematical solutions.

All four solutions exhibited a general trend of runoff overprediction (fig. 7). It is possible that the surface storage factors, indicated in table 3 for several sites, might have contributed to this tendency. In fact, the impact of crop and soil conditions (reduced slope, residues, canopy) on runoff was not accounted for in the RUNp solutions and, generally, has resulted in lower measured values than predicted values (mainly in test plots related to the highest occurrences). Therefore, model performance may be improved by accounting for factors that increase soil water storage capacity. Table 5 shows the performance evaluation of the RUNp solutions using MAE, MBE, and RMSE statistical indicators.

Table 5. Results of statistical analysis between measured and simulated values for RUNp solutions.

Model	MAE	MBE	RMSE
Richards equation	1.13	0.40	1.40
PIVOT_ESC$_0$	1.21	0.30	1.54
Gilley solution	1.45	0.86	1.85
Graphical solution	1.59	0.91	2.03

The statistical analysis resulted in relatively low values of MAE, MBE, and RMSE for the Richards and PIVOT_ESC$_0$ solutions and higher values for the graphical and Gilley solutions. These differences were expected, considering the EF results, which are an indication that the goodness of fit between observed and predicted RUNp decreased from the Richards to the graphical solution. Accordingly, the MAE ranged from 1.13 to 1.59 mm (or 22.6% to 31.8% of measured runoff mean, equal to 5 mm), and the MBE $\pm$RMSE ranged from 0.30 $\pm$1.54 mm to 0.91 $\pm$2.03 mm (6.0% $\pm$30.8% to 18.2% $\pm$40.6% of measured runoff mean). These values confirmed the overprediction trend, but the performances achieved by all four solutions are consistent with relatively low prediction errors. In fact, we note a good general agreement of measured and estimated data, with the statistical results suggesting appropriate solutions and reasonable runoff predictions. However, it must be stressed that a degree of variability is always an important factor affecting the data of model parameters and field evaluations. Therefore, considering the use of the presented solutions, RUNp estimation will be reliable if the accuracy of the input data is ensured, by applying proper procedures and devices, and the influence of both spatial and temporal variability is limited.

Summary and Conclusions

Two methodologies were presented to determine the potential runoff (RUNp) using parameters representing maximum water application to avoid potential runoff (WDPmx) and total water application depth (WDP). The WDPmx parameter was obtained from a procedure involving the Green-Ampt infiltration equation and the water application pattern, considering the impact of the soil (including soil water) and center-pivot system conditions. This study showed that a relationship among RUNp, WDP, and WDPmx could be defined through a semi-analytical mathematical model, designated PIVOT_ESC$_0$. The procedure involved a curvilinear regression fitting, which achieved a coefficient of determination of 99%. Because of its simplicity, a graphical method relating these parameters was also proposed to present a solution in a compact manner. The graphical method is useful for WDP determination related to any given runoff value, avoiding the iterative procedures required with the PIVOT_ESC$_0$ model. When a WDPmx value is selected on the graph, through available data on WDP and RUNp, new sets of WDP and RUNp values may be determined by crossing lines at the WDPmx point.

Considering a wide scenario of field conditions, four proposed RUNp solutions were tested against field data to ensure their adequate behavior and robustness. This comparative analysis showed a general linear trend, and the model efficiency values ranged from 47% (satisfactory) to 75% (good). However, higher model performances could be expected if field test conditions avoided surface storage, which decreases runoff. Consequently, the RUNa could be assumed equal to RUNp, and the overprediction trend observed in the models would be reduced. The mathematical and graphical solutions based on the WDPmx parameter appeared suitable for runoff prediction. This approach was based on physically based infiltration models.

This study also showed that different soil and center-pivot peak application conditions could lead to the same WDPmx value. Then, for a particular WDP event, there is a unique and predictable RUNp value (equal to S_s if RUNa is avoided) independent of the soil family (fig. 6). Hence, the WDP-WDPmx-RUNp relationship is useful for designing center pivots to avoid runoff. Further work should investigate this approach, considering also fixed sprinkler irrigation systems, in order to pursue the important goal of agro-environmental protection.

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