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Modeling Soil Infiltration under Variables of Application Rate and Number of Irrigation

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Abstract. The effect of variable sprinkler water application rates on bare soil and the response of the soil infiltration after exposure to a sequence of irrigation events were investigated. A simple empirical model based on the Kostiakov equation was presented. This model will predict soil infiltration rate under soil type and soil characteristics and a sequence of irrigation events. The validity of the model was tested and supported by the results of laboratory experiments. In addition, the values of the constant k and n in the Kostiakov equation were computed by the model and compared and validated with the measured k and n values.

Introduction

Water is an important vector of socio-economic development the world over. It is, however, a limited resource. There is a distinct need to economize in the use of water. It is known that agriculture is the largest water user. It is also known that agriculture is the largest traditional wasting of water. Any reduction in this waste will substantially contribute to water saving in water-deficit areas. As the necessity for conservation of water resources increases, a shift in focus is required from the development of additional irrigation resources. This will increase the irrigation efficiency of use of the already developed water resources. Therefore, more attention should be given towards more precise knowledge of irrigation application efficiencies of sprinkler systems and the relation between application rate and soil infiltration rate during the season. The assessment of soil infiltration, which varies with time in irrigated areas, is very important in order to apply the suitable application rate and to minimize the surface runoff from each irrigation during the season. As long as the application rate is greater than the soil infiltration rate then water will become available for surface runoff. So, the rate at which infiltration can be maintained in a particular soil is an extremely important parameter in the selection and the design of the irrigation system.

Quantifying infiltration is necessary to predict irrigation system performance and the hydrologic responses of watersheds to precipitation. Knowledge of water infiltration in the field is an important prerequisite for successful design and management of an irrigation system. For sprinkler irrigation systems the soil infiltration rate determines the design application rate to avoid or minimize surface runoff, particularly in areas where water conservation is essentially required. In irrigation, runoff is a serious problem that

Constitute severe losses in water, soils and energy, in addition to poor production. This problem exists clearly with mobile sprinkler irrigation systems, such as center pivot systems. This is because the application rates of these systems can exceed greatly the soil infiltration rate. The type of irrigation system which may be applied at a given site is often governed by the infiltration characteristics of the soil. It is difficult to evaluate water management practices without good estimates of infiltration during the irrigation season.

Soil infiltration rate affects the rate of surface runoff, which is important in the prediction of water loss under irrigation and soil erosion. Infiltration is affected by properties of irrigation water and soil type and characteristics. The infiltration response to irrigation depth and application rate has been investigated by many researchers such as[1-11]. Soil infiltration varies both with loaction and time and the variation of infiltration through a field at any given time is in the range of 20 to 50% [12-14]. While a field's average infiltration rate may vary between 30 to 50% through an irrigation season it can also vary from season to season [15-17]. Infiltration variation results from many causes such as surface sealing due to water drop impact, overland flow, and changes at the soil surface and plant growth. Von Bernuth and Gilley [18] estimated that the potential runoff from a water application of 25 mm from center pivot irrigation systems could vary from 0-20% on loamy sand soils to as much as 30-55% on clays.

Many investigators have acknowledged the runoff problems with moving sprinkler irrigation systems, particularly with low-pressure center pivot systems. Therefore, the understanding and predicting the response of a soil profile to a given rainfall event, in terms of infiltration and runoff characteristics are of vital importance in irrigation. One should minimize the amount of runoff during irrigation by selecting the proper combination of nozzle size and application rate. In practical application to system design and water management, the decrease in infiltration with the increase of irrigation events is normally ignored. Recent agricultural development in the Kingdom of Saudi Arabia has led to the increase of the number of center pivot systems and this has led to higher water application rates and hence the increase of potential runoff in a country of limited water supply. Therefore there is a need to establish a more appropriate design method which takes into account the application rate, soil infiltration rate and its reduction with the increase of irrigation numbers. This method is very useful in developing general design parameters for sprinkler system and can be helpful to reduce runoff and select the optimum application rate pattern and center pivot speed.

The objective of this study is to present an empirical model based on the Kostiakov equation capable of predicting infiltration rate under variable application rates with different number of irrigation during the season. Also, this approach can be used to predict runoff.

The Model

Numerous equations have been developed to represent the infiltration phenomena. They can be classified into three general categories of models: empirical, physical-based and numerical. In each category, different approaches are made to calculate infiltration rate, and each method has advantages and disadvantages. Most of these equations are empirical in nature and have been developed to match observed data sets. The empirical technique is used extensively more than the other techniques in irrigation system design. The mean reason for this is that it can be used practically in the field. The most widely used empirical equation is the Kostiakov equation [19], which is a simple powerful one. It takes the form:

$$I = kt^{n} \qquad (1)$$

Where:

I = infiltration rate (mm/hr)
t = time of infiltration (hr)
k,n = empirical constants

This equation is very popular in irrigation engineering and it is relatively easy to determine the values of the two constants k and n. These empirical constants k and n are dependent of soil properties and initial water content of the soil [20]. This equation has been found to fit field measured infiltration data, which makes it particularly adaptable to irrigation system design.

The infiltration model used in this study was based on the Kostiakov's equation. In developing the model the author look into consideration that the application rate (Ra) and the number of applications or irrigation event (N) influence the soil infiltration rate (I). Also, the infiltration rate value is affected by the constant values for the kostiakov equation. There is a functional relation between these constants and the application rate and number of irrigation, because of their effect on the soil conditions. To determine this relationship a nonlinear regression analysis was performed to select the suitable equation for each constant. The values of k and n can be calculated by the following:

$$k=b_I+b_2\ln N+b_3\ln Ra \quad (2)$$

$$n = C_1 + C_2 N + C_3 R_a \quad (3)$$

Values of the constants $b_{I,}$, b_2, b_3 , C_1 , C_2 *and* C_3 *were determined using the ordinary least squares method.* Substitution of Eqs. (2) and (3) into Eq. (1) results in:

$$I = (b_1 + b_2 \ln N + b_3 \ln Ra)\, t^{(c_1 + c_2 N + c_3 Ra)} \quad (4)$$

Equation (4) can be used to compute the infiltration rate under different application rates and different number of applications during the season. This equation is suitably modified to determine the soil infiltration rate at any given irrigation number during the season. Once the infiltration rate has been determined each application it is a simple matter to determine the suitable application rate and hence the surface runoff.

Model Validation

To validate the mathematical model a laboratory experiment was conducted. A plane sloping soil surface with two application rates and different irrigation depths of sandy loam soils were used. The soil consists of 63% sand, 20% silt and 17% clay and it was air dried, and then sieved through a 12.5-mm mesh sieve. To expose the soil to irrigation, three soil metal boxes were constructed with dimensions of 1.25m long, 0.75m wide and 0.25m deep. Many small holes were drilled into the bottom of each box to allow infiltrated water to drain freely and filter cloth was placed over the holes to prevent soil loss and any blockage of the small holes. Soil was then placed and uniformly compacted by a metal rod until each box was full and the soil surface was made as smooth as practicable to try to eliminate surface storage. The average bulk density was 1.45 gm/cm^3. The three soil boxes were placed at appropriate slopes under a uniform stationary water spray system. Runoff from each soil surface was collected and measured at intervals until the runoff rate became constant. Runoff collectors were designed and attached to the soil boxes and a flexible hose was connected to each collector to convey the surface runoff to a container for measurement. The soil moisture tension was measured by using tensiometers; the measurements were taken at different depths from the middle and sides of the irrigated area. Then a calibration between the soil moisture tensions by the tensiometrs and soil moisture contents were made. It was found that the average soil moisture contents were nearly constant (8- 9 % weight) before each run as indicated by tensiometers. The time between successive runs for each water application rate was not constant due to the variable climatic conditions during the study.

The volume of runoff and time were recorded at intervals during each treatment, and each treatment was repeated three times for each run by using three soil boxes, and the average was used in the calculations. Each soil was exposed to eight runs for each application rate before the soil in the box was changed. Two application rates (25mm/h and 100mm/h) were used, these were established by using two sizes of spray nozzles. This type of nozzle is currently used on low pressure center pivot sprinkler irrigation systems. Preliminary tests were conducted with each nozzle size to select a suitable nozzle height, and a nozzle spacing on the boom to give the required application rate and high uniformity.

The infiltration rate was defined in this study as the difference between the water application rate and the measured runoff rate. The surface detention storage was very small and was ignored. The results were then used to determine the constants in the Kostiakov Equation. The range of experimental conditions were chosen to represent typical field sprinkler situation as well as providing a wide range of conditions for model validations.

Comparison between Model and Experiment

The average measured infiltration rate results for bare soil as function of time under two application rates is presented in Fig. 1 and 2. All the curves displayed the same characteristics; first, a period of high infiltration followed by a gradual decrease in infiltration to a constant rate. Also, the results show that infiltration rate decreased rapidly following the first run, and then progressively declined as the number of runs increased as shown in the figures. Also it can be seen that the reduction in infiltration rate was greater with the 100 mm/hr application rate as a result of greater impact of water. This reduction in soil infiltration rate between the runs was attributed to the formation of a surface seal and clogging of soil pores, which greatly created by the mechanical action of the applied water.

The nonlinear regression model parameters were estimated from the experimental data by using the method of least squares. The results of least squares fittings of Eq. 4 to the experimental data are: $b_1 = 26.972$; $b2 = -2.994$; $b_3 = -3.865$; $C_1 = -8.39$; $C_2 = 0.023$ *and* $C_3 = 0.005$. Then the Eq. 4 was used to predict the infiltration rates under the two application rates and the eight runs used as shown in Figs. 3 and 4. Generally, there was good agreement between the model and the experimental results. These curves produced by the model were judged statistically to show how the model performs in comparison with measured values. The values of infiltration rate for each run (measured and predicted) were found to be not significantly different at the 1% level of probability. Also, an indication of how equations fit the measured data is given by the average of the R^2 (correlation coefficient) values for all runs which was ranging from 0.91 to 0.97. There is some variation from one run to another; part of this variation is due to initial soil water conditions or/and to the surface compaction and crusting.

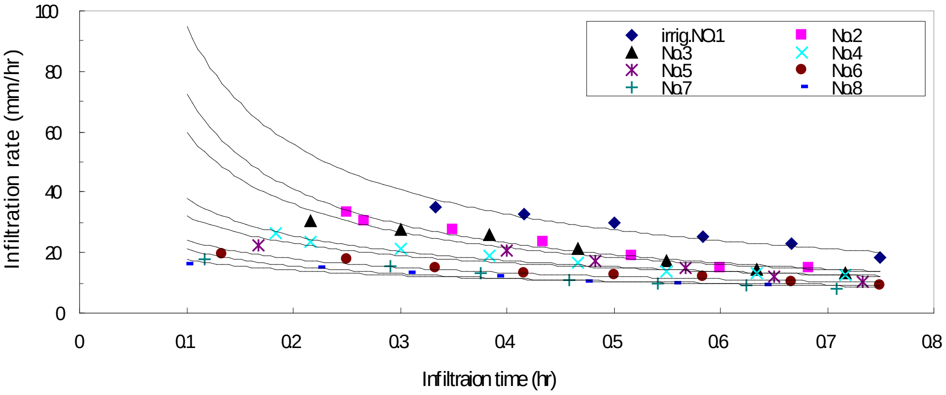

Fig. 1. Measured soil infiltration rates at different irrigation numbers under 25 mm/hr application rate.

The measured k and n values were calculated using the experimental data. These values were compared to the values computed by the Eqs. 2 and 3 for k and n and presented in Figs. 5 and 6 as function of irrigation numbers (N) for each application rate. It can be seen that k values decreased with the increase of N values, where as n values are increasing with the increase of N values. Also, it was found that the measured and predicted values of k and n were not significantly different at the 1% level of probability.

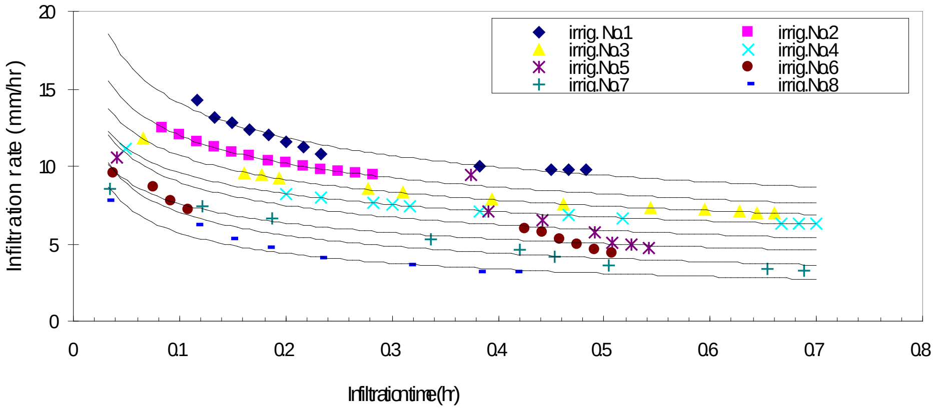

Fig. 2. Measured soil infiltration rates at different irrigation numbers under 100 mm/hr application rate.

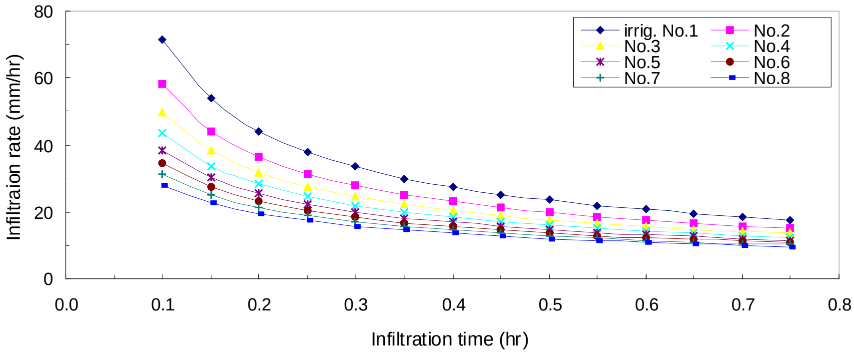

Fig. 3. Predicted soil infiltration rates at different irrigation numbers with application rate of 25 mm/hr.

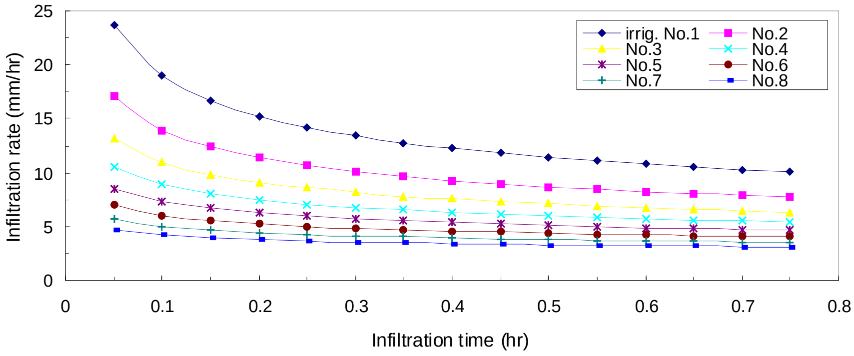

Fig. 4. Predicted soil infiltration rates at different irrigaiton numbers with application rate of 100 mm/hr.

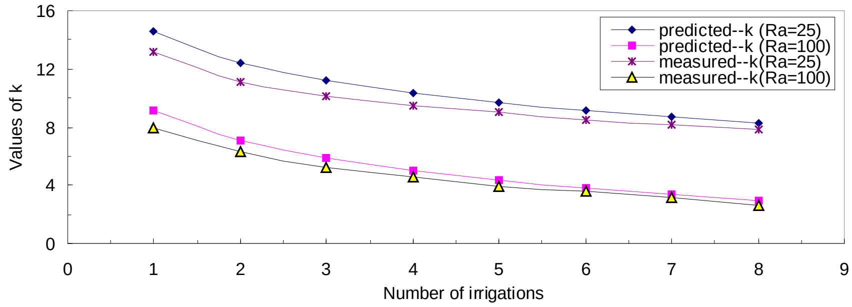

Fig. 5. Values of k at different numbers of irrigations and application rates.

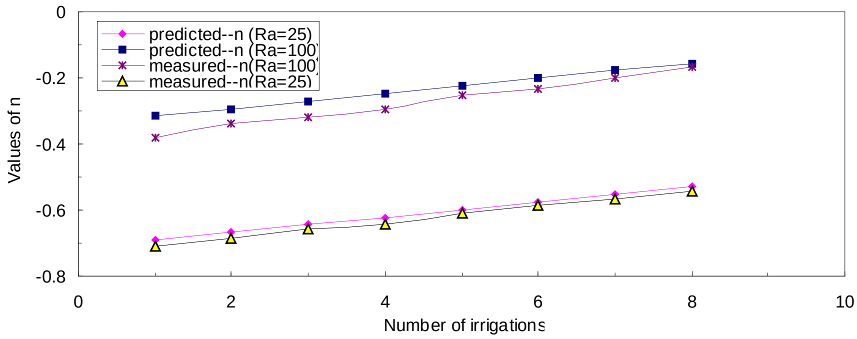

Fig. 6. Values of n at different numbers of irrigation and application rates.

Conclusion

The study has shown that the infiltration response of a soil after exposure to a sequence of irrigation events was dependent upon the number of runs and the rate of application. Also, the study has presented and demonstrated a simple empirical model capable of predicting the soil infiltration rates under two application rates and over a wide range of irrigation events. Also, the model was able to predict the values of k and n.

The model has been validated by experimental tests and could be used to generate data suitable for preliminary design purposes.

The results indicated that this model could provide valuable information for the effective design of sprinkler systems, particularly where runoff may be a potential problem. This is particularly the case with the center pivot systems. Further, managers of sprinkler irrigation systems can used the model to modify management practices such us speed rotation and application rate pattern during the season to reduce surface runoff and conserve water.

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إيجاد معدل تسرب التربة رياضيًا عند معدلات إضافة وعدد ريات مختلفة

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ملخص البحث. يهدف هذا البحث إلى دراسة تأثير عدد مرات الري ومعدلات الإضافة المتغيرة من نظام الري بالرش على خصائص معدل التسرب لتربة غير مزروعة. في هذه الدراسة تم استنباط معادلة تجريبية مبنية على معادلة كوستيكوف للتسرب لإيجاد معدل التسرب للتربة عند أي عدد من مرات الري وعند معدل الإضافة المستخدم على طول موسم الري. دقة المعادلة الرياضية المستنبطة تم اختبارها بواسطة نتائج تم الحصول عليها من تجارب عند قياس معدلات التسرب.

بالإضافة إلى ذلك تم إيجاد الثوابت k وn لمعادلة كوستيكوف بواسطة المعادلة المستنبطة وتم اختبارها ومقارنتها مع الثوابت المقاسة من التجارب.