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Modeling of Infiltration from An Artificial Recharge Basin with a Decreasing Ponded Depth

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Abstract. The first important physical process in basin recharge is the infiltration of water from the basin's bed to the water table below. The Green and Ampt approach was applied to model infiltration from an artificial recharge basin with a decreasing ponded depth. Several field experiments were carried out. Results of one experiment were used to calibrate the model. The suggested approach was then used to predict infiltration for the other experiments and its results were compared to field values.

Introduction

Artificial recharge in arid and semi-arid regions plays an important role in conservation of water and the avoidance of depletion of existing aquifers. An important method of artificial recharge is basin recharge; where excess surface water is spread over the area of a basin (or basins) and the water is allowed to infiltrate to the water table below. A good description of spreading methods of artificial recharge (like the basin method) can be found in Todd [1].

The first step in recharge from a basin (or any other similar spreading facility) is infiltration from the surface of the basin after ponding of water in it. **Infiltration** can be defined as **"the physical process of water entry into the soil".** Such a process involves the displacement of air into the soil matrix by water.

Due to the importance of infiltration in many hydrological and engineering problems, many researches have been devoted to its study since the beginning of the century. Many equations, empirical as well as physically-based have been proposed to estimate infiltration of water as a function of time. Empirical equations were developed using infiltrometer test data and the resulting relations were applied to describe a rate of infiltration decreasing from an initial maximum to a final minimum rate. The most famous empirical equations of infiltration include those proposed by Kostiakov [2] and Horton [3,4]. Empirical equations have serious limitations. Their parameters have little or no physical meaning and they can not usually be determined or estimated from data available on the soil. The most important physically-based equations of infiltration are those due to Philip [5] and Green and Ampt [6]. Both equations, and especially the Green and Ampt equation, utilize parameters some of which can be evaluated from physical properties on the soil. Fok [7] gives a summary on development and limitations of different infiltration equations.

The Green and Ampt model has been the subject of considerable development in recent years because of its simplicity and its satisfactory performance in many hydrological problems. For instance, it has been extended to soils of non-uniform initial moisture content [8], to layered soils [9] and to crust-topped soils [10]. It has also been used to model infiltration into homogeneous soils from constant [11] as well as from unsteady rainfall [12].

The main objective of this work was to use the Green and Ampt model to study the infiltration process in an artificial recharge basin with a decreasing ponded depth. Several infiltration experiments were conducted in the basin. Using the results of one of these experiments, the model was first calibrated. It was then used to predict infiltration for the other runs and its results were compared to field values.

Data

The data utilized in this paper are obtained from five infiltration experimental runs conducted in an artificial recharge basin. The dimensions of the basin are 24.76 × 14.47 × 0.4 m deep, with a total surface area of 358.28 m^2. The walls of the basin were constructed with cement blocks. The inside faces of the walls were covered by a heavy duty plastic sheet to prevent lateral leakage of water. To measure the drop in water level in the basin, two stilling wells equipped with pointer gages were installed along the two long walls, one along each. The daily evaporation rate values in the site were obtained from Class A pan installed near the basin. The daily values of evaporation rate from the surface of the basin were obtained by multiplying the measured values of evaporation by a pan-to-lake coefficient.

The groundwater levels in the vicinity of the basin were obtained from an observation well located at about 40 m downstream to the basin. Depth of water table in the observation well was recorded before the start of each of the five runs.

Soil samples were also taken from different locations and depths in the basin. The initial moisture content of the soil was then calculated as the average of all the samples. Water was then pumped into the basin until a depth of 20-30 cm is ponded. Table 1 shows the particulars of the five experimental runs.

Table 1. Particulars of the Infiltration Runs

Run No.	Initial Depth (cm)	Initial moisture content (% by volume)	Depth of water table (m)	Duration (hr)
1	23.24	0.504	8.06	43.00
2	22.85	2.856	3.69	53.15
3	20.76	3.912	8.98	46.13
4	21.45	2.892	13.11	45.50
5	27.04	9.468	1.60	53.52

After the pumping was stopped, the depths of water at different points in the basin were meausred to determine the average depth of water at that time. The installed pointer gages were then used to determine the drops in water level in the basin. The monitoring of water levels at the gages continued for 43 to 53 hours. Because of the high variability of infiltration rate during the beginning of each run, readings were taken at short intervals. As time proceeded, the interval between readings was increased. Druing each interval, the drop in water level was estimated as an average of the measured drops at both gages.

In order to estimate the infiltration depth during each interval, it was necessary to account for evaporation. The evaporation depth druing each time interval was estimated by distributing the daily evaporation rate from the surface of the basin over the time intervals based on the hourly variation of evaporation during the day which were taken from the data of an evaporation balance. That instrument records the evaporation on hourly basis.

The actual infiltration depth during each time interval was then calculated by subtracting the estimated evaporation depth for that interval from the total drop in water level during the same interval. The resulting depth was then divided by the length of the interval to obtain an average infiltration rate during that interval.

The Model

The Green and Ampt model can be derived by applying Darcy's law between the soil surface and the location of the wetting front. The first assumption made in a derivation is that at the wetting front, the water presure head remains constant. The second assumption is that behind the wetting front, the soil is uniformally wet with a consant hydraulic conductivity corresponding to the conductivity at natural saturation.

The Green and Ampt infiltration rate equation can be written as [13, pp. 35-65]:

$$I = \frac{dw}{dt} = K\left(\frac{S_f + W}{W}\right) \tag{1}$$

where

I	is the infiltration rate, (LT^{-1})
W	is the cumulative infiltration depth of water, (L)
t	is the time, (T)
K	is the hydraulic conductivity of the wetted zone, (Lt^{-1})
S_f	is the storage-suction factor, (L)

The storage-suction factor can be expressed by the following equation [13, pp. 35-65]:

$$S_f = (\theta_f - \theta_i)(H_f + H) \tag{2}$$

where

θ_f	is the final water content behind the wetting front, fraction
θ_i	is the initial water content for the soil profile, fraction
H_f	is the effective capillary drive or suction at the wetting front, (L)
H	is the ponded depth of water, (L)

There are two problems in using equations (1) and (2) to estimate the infiltration rates from basin with variable depth of water. The first is that both I and W are unknowns in equation (1), while the second is that in equation (2), H is normally assumed to be constant during the infiltration process.

Integration of equation (1) between the limits (t_{j-1}, W_{j-1}) and (t_j, W_j) will result in the following expression (14).

$$K(t_j - t_{j-1}) = W_j - W_{j-1} - S_{fj} \ln\left(\frac{S_{fj} + W_j}{S_{fj} + W_{j-1}}\right) \tag{3}$$

where

t_j	is the time at the end of j^{th} period
t_{j-1}	is the time at the end of j-1 period
W_j	is the cumulative infiltration depth of water at the end of the j^{th} period
W_{j-1}	is the cumulative infiltration depth of water at the end of the j-1 period
S_{fj}	is the variable storage- suction factor for the j^{th} period

The variable storage suction, S_{fj} can be estimated as:

$$S_{fj} = (\theta_f - \theta_i)(H_f + H_j) \tag{4}$$

where H_j is the ponded depth of water at the beginning of the j^{th} period.

The distance the wetting front advances to below the basin can be calculated using the equation:

$$z_{fj} = \frac{W_j}{\theta_f - \theta_i} \tag{5}$$

where z_{fj} is the distance from the bottom of the basin to the wetting front at the end of the j^{th} period.

The average ifiltration rate during the j^{th} period can be calculated as:

$$I_j = \frac{W_j - W_{j-1}}{t_j - t_{j-1}} \tag{6}$$

Computational Procedure

The procedure starts by first estimating the parameters θ_f, θ_i, H_f and K as will be described in the next section.

The purpose of the model is to predict the infiltration rates from a basin given the values of the above parameters and the initial ponded depth of water in the basin.

Let H_l represent the initial ponded depth at the beginning of the first period. Let E_j represent the evaporation depth during the j^{th} period.

The steps of computation for any period are as follows:

1. Calculate

$$ET_{j-1} = ET_{j-2} + E_{j-1}$$

where

ET_{j-1} is the cumulative evaporation depth at the end of the j-1 period

ET_{j-2} is the cumulative evaporation depth at the end of the j-2 period

2. Calculate the ponded depth of water at the beginning of the period

$$H_j = H_l - ET_{j-1} - W_{j-1}$$

Note that during each period W_{j-1} is known from the previous calculation.

3. Calculate the variable storage-suction (S_{fj}) by using equation (4).

4. The cumulative infiltration depth up to the end of the j[th] period (W_j) is then found by using equation (3) in a trial and error procedure.

5. Equation (5) is then used to check the position of the wetting front below the basin. If z_{fj} is equal to or greater than the distance from the bottom of the basin to the water table, the computations are stopped. Otherwise, the procedure is continued through the next period.

6. Based on the values of W_j and W_{j-1}, the infiltration rate through the jth period can be calculated using equation (6).

Parameter Estimation

To use the infiltration approach just described, it is necessary to estimate the parameters θ_i, θ_f, H_f and K.

The initial moisture content θ_i was estimated by taking four soil samples (one from each quarter of the basin) just before the beginning of each run, determining the moisture content for each sample in the laboratory, and taking the average value of the four moisture contents. The values of the initial moisture contents for each run shown in Table 1 represent these average θ_i values.

The parameter θ_f represents the maximum water content (as a fraction) behind the wetting front. It was approximated by the average porosity of the soil in the basin. That average porosity was calculated by taking the average of the porosities of four soil samples (one from each quarter of the basin). The value of θ_f used in the model was 0.3184. The approximation of θ_f by the average porosity is reasonable approximation becuase the model is applied under continuous application of water from above. This will prevent any drying in the soil profile. Had the model been applied under conditions where drying and wetting of the profile coccur, this approximation may be questionable.

The effective capillary drive H_f is a measure of the soil capillary pull, expressed as an equivalent depth of water. Almost all reported values in the literature for this parameter range between 5 and 40 cm [15,16]. This parameter can be neglected after few minutes in the infiltration process and its value becomes insignificant even at early times if the ponded head is in the order of 30 cm [17]. Since the durations of all the experiments used in this study were between two and three days and the ponded heads were between 20 and 30 cm, the choice of the value for H_f will not affect the results. The value of H_f which was used in both the calibration and the validation of the model was 35 cm.

The last parameter to be estimated is K; the hydraulic conductivity of the wetted zone (below the basin). The value that should be used is the average hydraulic conductivity for the soil layers below the basin. Due to the difficulty in establishing an average K value for the profile during infiltration, this parameter will be determined by calibration.

Calibration and Application of the Model

As stated previously the value of the hydraulic conductivity of the wetted zone K will be determined through calibration. Data of Run No. 1 were used for this purpose. To avoid the fluctuations in the values of the actual infiltration rate that resulted from field measurements, the total depth of water that infiltrated through the soil from the time of ponding until the end of the run was used as a criterion in the calibration. Different values of K were used in the model and the optimum value that gave the measured cumulative infiltrated depth (3.657 cm/day) was selected. Fig. 1 shows the actual and predicted cumulative infiltrated depths versus time for Run No. 1.

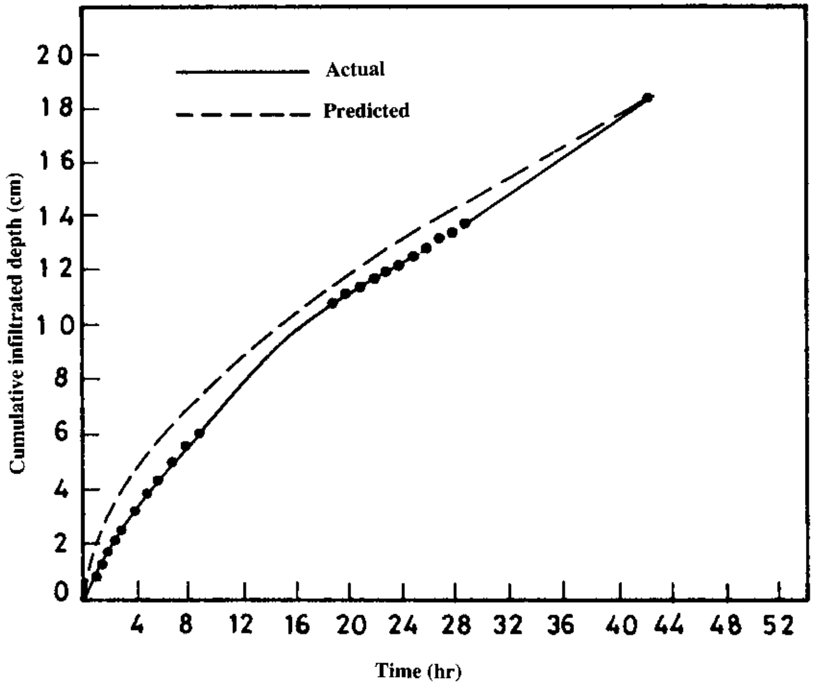

Fig. 1. Cumulative infiltrated depth versus time Run No. 1

To validate the model, the model with its estimated parameters was then applied to determine the variation of cumulative infiltrated depth with time for Runs No. 2,3,4, and 5. Figs. 2 to 5 show the results of the application. Table 2 shows the actual and predicted cumulative infiltrated depths by the end of the run for all the runs.

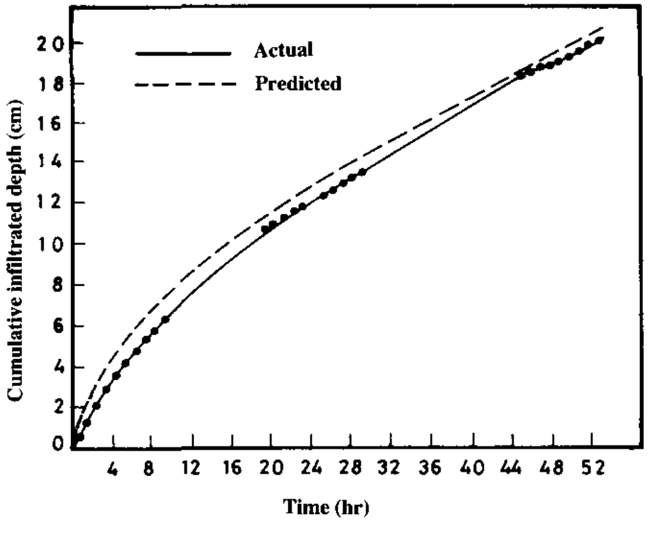

Fig. 2. Cumulative infiltrated depth versus time Run No. 2

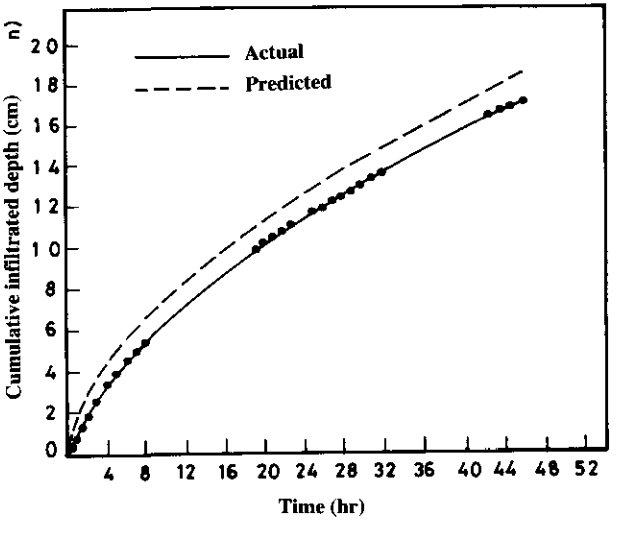

Fig. 3. Cumulative infiltrated depth versus time Run No. 3

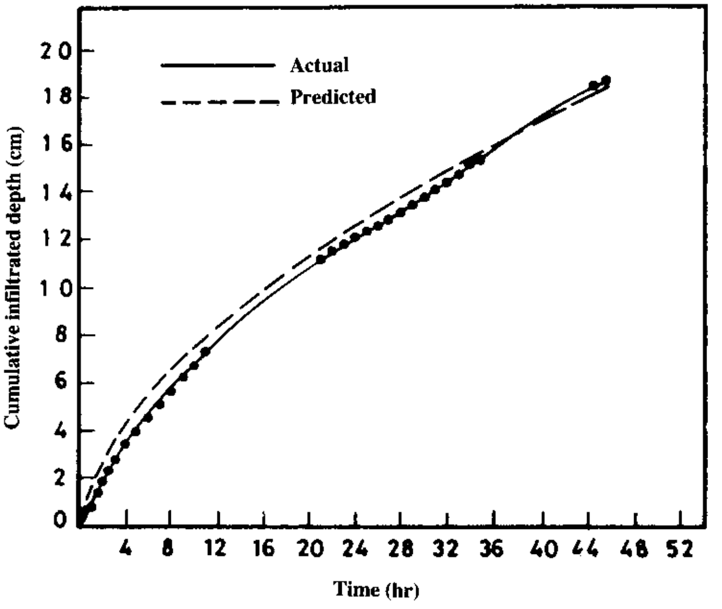

Fig. 4. Cumulative infiltrated depth versus time Run No. 4

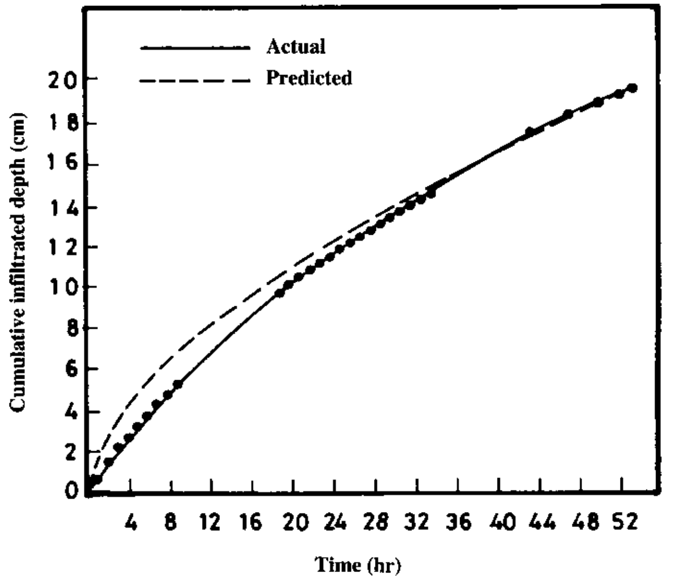

Fig. 5. Cumulative infiltrated depth versus time Run No. 5

Table 2. Actual and predicted cumulative infiltrated depths

Run No.	Cumulative infiltrated Depth (cm)		$\frac{\text{Actual-predicted}}{\text{Actual}} \times 100$
	Actual	Predicted	
1*	18.597	18.597	0
2	20.177	20.545	1.82
3	17.009	18.444	8.44
4	18.770	18.496	1.46
5	19.540	19.517	0.12

* Used in the Calibration

As can be seen from Table 2 the predicted cumulative infiltrated depths by the end of Runs No. 2,3,4 and 5 are in good agreement with the measured values. Figs. 1 to 5 show that the model resulted in an over-prediction of the cumulative infiltrated depths at the early stages of each run. This indicates that, the model is over-predicting the infiltration rates at the early times of each run. This over-prediction is attributed to the fact that, the model assumes that the infiltration process starts at the starting time of application of the model. In reality, the infiltration process in the basin started by the time when the pumping of water started in the basin. However, these figures show that as time passes, the predicted values of cumulative infiltrated depth become close to the actual values.

Concluding Remarks

The paper presents a method to model and predict the infiltration process through a recharge basin with decreasing ponded depth. The predicted values of cumulative infiltrated depths were compared with the actual values for four runs. The model overpredicted the cumulative infiltrated depths at the early stages of each run because the starting time of its application is different than the actual starting time of infiltration. However, the cumulative infiltrated depth by the end of each run is close to the actual value.

The technique used in this paper can be very helpful in designing recharge basins. One of the essential requirements of the design of a recharge basin (or basins) is to estimate infiltration rate from the bottom of the basin. The approach used in this work can be easily applied for that purpose.

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تمثيل التسرب من حوض استعاضة اصطناعي تحت عمق غمر متناقص

فؤاد فهد المطير وعبدالعزيز سليمان الطرباق

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ملخص البحث. إن أول عملية فيزيائية مهمة تحدث عند استعمال طريقة الاستعاضة بالأحواض هي تسرب المياه من قاع الحوض إلى المياه الجوفية. وقد استعملت طريقة جرين وآمبت في هذه الدراسة لتمثيل التسرب من حوض استعاضة اصطناعي تحت عمق غمر متناقص. وقد أجريت عدة تجارب على الحوض واستخدمت واحدة منها للمعايرة، ومن ثم استخدمت الطريقة المقترحة لحساب التسرب للتجارب الأخرى، كما قورنت نتائجها بالنتائج الحقلية.