# GREEN-AMPT INFILTRATION IN LAYERED SOILS WITH POSITIVE SOIL WATER POTENTIALS

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## INTRODUCTION

Infiltration, the process whereby water enters the soil profile, is a critical factor in numerous hydrologic modeling studies. Hydrologic modeling of watersheds and groundwater typically includes infiltration as a major component. Moreover, accurate estimates of infiltration are needed for agricultural purposes such as irrigation scheduling. It follows that accurate simulation of the physics of the process is crucial in providing good estimates of infiltration.

Many decades of research have been dedicated to studying the physics of the infiltration process. These studies have their foundations in the work conducted by Darcy in the late 18th century. Darcy's Law established the framework for the understanding of water movement within the soil. Since that time, Darcy's Law has been widely used and modified by researchers to provide the basis for modeling the infiltration process. However, the current models used to estimate infiltration do not adequately describe the infiltration process during the occurrence of positive soil water potentials.

Positive soil water potentials can develop in layered soils during infiltration. The soil profile in which this phenomena occurs consists of a coarse textured soil overlaying a fine textured soil. An example would be a soil profile with a sand layer over a clay layer. When infiltrating water from the sand layer reaches the clay, it begins to accumulate at the layer interface due to the differences in the hydraulic conductivity of the two materials. The sand layer, with a much greater hydraulic conductivity than the clay, will deliver water at a rate greater than the clay can accept. This initially results in increasing the water content in the soil above the interface. Subsequently, subsurface layer ponding, free water, and a positive soil water potential will develop. The development of the positive pressure potentials corresponds to the development of hydrostatic heads in the sand layer. This effect has been observed to occur in fields with similar soil profiles. The occurrence of free water and positive soil water potentials is documented in the literature regarding hillslope stability (Sidle et al. 1985).

In an effort to further document positive soil water potentials, laboratory and field research was conducted at the Texas A&M University Agricultural Engineering Department in 1991. This research involved field experiments with double ring infiltrometers and laboratory experiments with soil columns. The field experiments and laboratory columns provided a data base that documented the occurrence of positive soil water potentials. The data base was used to test the feasibility of using an existing infiltration model to estimate infiltration during subsurface layer ponding.

The Green-Ampt infiltration model was selected as the model to use for the study and is one of the most widely used approximate theory-based infiltration models. It was chosen because of the physical basis of the Green-Ampt equation parameters, the ease of use, and the wide acceptability of the model. Two versions of the Green-Ampt model were tested: a version for uniform soils and a version for layered soils. The version of the model for uniform soils was tested using independent data from a uniform sand column and accurately predicted infiltration into the uniform soil (Rawls 1992). The Green-Ampt layered model was tested using an independent data set collected from a soil column consisting of a sand over clay layer. The model accurately predicted infiltration for 200 minutes of the simulation, then under-predicted the observed data for the remainder of the experiment. This discrepancy corresponded to the development of positive soil water potential, indicated by hydrostatic heads that developed in piezometer tubes at the interface. Furthermore, the model failed to predict the time at which the wetting front moved into the clay layer. It was therefore concluded that the Green-Ampt model will give reasonable estimates of infiltration until hydrostatic heads develop throughout the sand layer. At such a time, the model will fail to yield acceptable estimates of infiltration.

An infiltration model capable of accounting for positive pressure potentials was developed. Traditionally, the approach to infiltration modeling has not focused on the effects of hydrostatic heads in layered soils on the infiltration process. However, since this has been documented to have an effect on the process, it should be included as an infiltration modeling component. Thus, the need for a model capable of accounting for the occurrence of positive pressure potentials in layered soils as they relate to infiltration motivated this research.

## OBJECTIVE

This research applies to infiltration occurring under the influence of positive soil water potentials. The scenario investigated was the occurrence of positive soil water potentials in layered soil columns, specifically, columns which have a coarse textured soil over a fine textured soil. Only data collected from controlled laboratory experiments were utilized, thus enabling better control of variation and better parameter estimation for the research.

The overall objective of this study was to develop a method that will provide an accurate estimate of cumulative infiltration during the occurrence of positive soil water potentials in layered soils. Part of that objective involved modeling the movement of the wetting front through the layered soil. An existing wetting front model, the Green-Ampt model, was modified to allow for the occurrence of positive soil water potentials. Using the modified Green-Ampt model, a wetting front model was developed to accomplish the overall objective.

The objectives of this research were to:

1. Test the hypothesis that current layered Green-Ampt models fail to accurately describe infiltration into layered soils in the presence of positive soil water potentials.

2. Develop a modeling technique (modified Green-Ampt model) to allow for prediction of infiltration into soil columns under the influence of positive soil water potentials.

3. Validate the modified Green-Ampt model with an independent data set and compare results to previous layered Green-Ampt methodologies.

## INFILTRATION INTO LAYERED SOILS

Considering infiltration into layered soils, numerous approaches have been applied in an effort to accurately predict infiltration rates. One such approach involves the extension of the Green-Ampt equations for homogeneous soils. The Green-Ampt equations have been widely used and accepted for infiltration into homogenous soils. Extensions to heterogeneous soils were made by utilizing the differences in the hydraulic conductivity of multiple soil layers.

Childs and Bybordi (1969) and Hachum and Alfaro (1980) detailed the use of the Green-Ampt equations for infiltration into layered soils columns in which the hydraulic conductivity decreases with depth. The approach involves monitoring the movement of the wetting front through the soil column. As long as the wetting front remains in the top soil layer, the Green-Ampt equations remain unchanged. However, once the front reaches the second soil layer, the hydraulic conductivity value is changed to the harmonic mean of the two layers. The harmonic mean is given in equation (1) as

$$K_h = \sqrt{K_1 K_2} \qquad \textbf{(1)}$$

where

$K_h$ = harmonic mean ($Lt^{-1}$), and
$K_1$ and $K_2$ = the hydraulic conductivity of layers 1 and 2 ($Lt^{-1}$).

Upon the arrival of the wetting front into the second layer, the hydraulic conductivity is set equal to the harmonic mean for the wetted depths and the capillary head is set equal to the suction front of the second layer. For soil columns with more than two layers, the procedure is applied in the same manner utilizing the harmonic mean of the next two layers. Incorporating this method increases the estimated hydraulic conductivity of the underlying soil layers and thus increases the predicted infiltration rate. This procedure can be applied only when the hydraulic conductivity is decreasing with depth. In cases where the hydraulic conductivity is increasing with depth, another approach can be applied. The infiltration through the higher conductivity soil layer can be governed by the harmonic mean of the upper layers (Moore and Eigel 1981). Typically, hydraulic conductivity values decrease with the depth; however, surface crusting can result in a soil layer with a low over high conductivity layer.

Wolfe et al. (1988) approached infiltration into layered soils in a similar manner. Basically, the same procedure described above is applied with the exception of using the harmonic mean. When the wetting front reaches the second layer, the hydraulic conductivity is changed to that of the second layer. Therefore, this method uses a lower infiltration rate than the previously described method. Hill (1992) tested simulation models based on these two approaches. Using data collected from laboratory soil column experiments, it was shown that these simulation models under-predicted cumulative infiltration. Thus, the current layered Green-Ampt models are not able to accurately predict cumulative infiltration.

## MODEL FORMULATION

In evaluating infiltration into a soil column influenced by positive soil water potentials, it is necessary to characterize and model the location of the wetting front, to know the cumulative infiltration into the column, and to quantify the effects of the positive pressures within the column. Thus, the increase in cumulative infiltration into soil columns associated with positive soil water potentials must be established. It follows that the description of the flow of water into the column during positive soil water potentials must also be developed. The problem involves determining the location of the wetting front, monitoring the saturation of the sand layer, and utilizing the proper conductivities during the modeling stages. This was accomplished by modification of the existing Green-Ampt equation.

The Green-Ampt model was originally developed to predict infiltration into a deep homogeneous dry soil with an initial water content and ponded water surface (Rawls et al. 1992). An assumption that is used in the Green-Ampt model is that water enters the soil profile as a sharply defined wetting front that separates the wet soil from the dry. This has been referred to as slug flow. The model is a direct derivation of Darcy's law and is widely used and accepted. Several modifications have been made to the original Green-Ampt equation to meet the demands for infiltration models for other conditions.

The Green-Ampt equation for infiltration from a ponded water surface into a deep homogeneous soil profile when the depth of infiltration is assumed to be shallow can be written as

$$K_s t = F - S_f M \ln\left(1 + \frac{F}{MS_f}\right) \qquad \mathbf{(2)}$$

where

$K_s$ = the hydraulic conductivity of transmission zone ($Lt^{-1}$),
$t$ = time ($t$),
$F$ = cumulative infiltration ($L$),
$S_f$ = the effective suction at the wetting front ($L$), and
$M$ = moisture difference ($L^3L^{-3}$).

The cumulative infiltration can then be calculated through numerical integration of equation (2). Following numerical integration of equation (2), a Green-Ampt model can be developed to predict both cumulative infiltration and infiltration rate into a soil. The relationship of cumulative infiltration to wetting front and moisture deficit can then be used to determine the location of the wetting front.

The modified Green-Ampt model is based on equation (2). The model has been divided into three stages based on the development of positive soil water potentials. The steps are given below.

1. *Run the single layer Green-Ampt model until the wetting front reaches the second soil layer.* The Green-Ampt model is applied as it would be for a homogeneous soil layer. The direct application is used until such time as the wetting front reaches the second soil layer. When the wetting front reaches the second soil layer, step 2 is initiated.

2. *Conduct a water balance on the first layer and continue single layer Green-Ampt until the first layer reaches saturation.* Infiltration into the second soil layer will not occur before the layer above reaches saturation. The saturation level can be detected by performing a water balance within the soil layer. Step three is initiated when the top layer reaches saturation. It should be noted that saturation of the first soil layer occurs when the entire layer is under the influence of positive soil water potentials as indicated by free water in piezometer tubes at intervals in the sand layer.

3. *Change the hydraulic conductivity and capillary head values in the Green-Ampt model to those of the second soil layer.* After the saturation of the first soil layer, the infiltration will be governed by the physical properties of the second soil layer. The parameters of the Green-Ampt model are changed to reflect the decrease in the infiltration rate. Once again, a mass balance is applied to the second layer. The mass balance allows for a total accounting of water infiltrating into the soil column. Thus, the effects of the water in the column can be better described.

## MODIFIED MODEL APPLICATION

Utilizing the described procedure and equation (2), a modified Green-Ampt model was developed. Inputs to the modified Green-Ampt model include saturated moisture contents $\Theta_s$, initial moisture contents $\Theta_i$, saturated hydraulic conductivities $K_s$, suction fronts $S_f$, depth of ponding H, time step DT, total simulation time TST, and the error criterion ERR. The depth of ponding for the model refers to the head of water maintained above the soil column. The output from the program includes infiltration rate, cumulative infiltration, and wetting front location for each time step specified by the user.

Data used to test the modified Green-Ampt model were taken from experiments conducted by Hill (1992). Soil used in the soil-water potential experiments was collected from Granada Farms, located in Robertson County, Texas. Soils at the site are representative of those belonging to the Crockett fine sandy loam series in the great group Reddish Prairie. These soil formations have a characteristic 1 to 3 percent slope. Covering the soil is a thick layer of thatch and organic matter ranging in thickness from 6 to 25 mm. The surface soil layer is a grayish-brown, slightly acid fine sandy loam ranging from 0 to 18 cm thick and characterized as 80 percent sand and 20 percent silt and clay. The soil is friable when moist and crusty and hard when dry. Below the sandy soil layer is a reddish-brown acidic clay mottled with yellowish-brown streaks. This layer has a low permeability. It is also stiff and sticky when wet and extremely hard when dry. It is characterized as having a thickness of 18 to 55 cm with 85 percent clay and 15 percent sand and gravel composition. Immediately below this layer is another clay layer which is a pale olive alkaline clay mottled with light yellowish-brown flecks. The composition is also 85 percent clay and 15 percent sand and gravel. The depth of this layer ranges from 55 to 144 cm and extends to the parent layer. The depth of the parent material ranges from 140 to 225 cm or greater in thickness.

A hand packed soil column was used in each experiment performed. The clear plexiglas columns utilized ports drilled into the sides for the insertion of tensiometers and piezometers. The columns had an inner diameter of 15.8 cm and an outside diameter of 16.5 cm. The approximate height of the columns was 80 cm. Rubber stoppers were placed in the port holes prior to the packing of the soil columns. The stoppers were fitted into the port holes in such a manner as to prevent intrusion into the column. Thus, the stoppers did not interfere with the packing process.

The experiments conducted by Hill (1992) included homogeneous columns of sand and clay and layered soil columns where the sand was packed above the clay layer. Cumulative infiltration and wetting front locations were recorded for all experiments. Hill (1992) conducted extensive experiments to document the soil physical properties and the saturated hydraulic conductivity of material collected from Grenada Farms using conventional methods (Klutz 1986). Soil column experiments were conducted using soil from the top two layers. Thus, the fine sandy loam and the clay soil types were examined. It was determined that the sandy loam soil consisted of 80 percent sand and 20 percent silt and clay with a saturated conductivity value of 0.91 cm $hr^{-1}$. The clay layer was comprised of 85 percent clay and 15 percent sand and gravel with a saturated hydraulic conductivity of 0.10 cm $hr^{-1}$. The bulk density measurements ranged from 1.40 to 1.60 g $cm^{-3}$ for the sandy loam and 1.60 to 2.00 g $cm^{-3}$ for the clay.

The calculated parameters for the soils were then used on independent data sets. The modified Green-Ampt model was first applied to the single layered soil columns as a check to ensure that it was operating properly. The model was applied to both the single layered sand and clay soil columns. After successfully modeling the single layered columns, the model was applied to a layered column. The modified Green-Ampt model output was compared to the methods developed by Wolfe et al. (1988), Childs and Bybordi (1969), and Hachum and Alfaro (1980).

## SIMULATION RESULTS

The Green-Ampt infiltration modeling schemes developed to handle infiltration into layered soil columns consisting of a high conductivity material over a lower one were examined. All of the inputs into the models were the same for each method, only the solution techniques were varied. The inputs were obtained from independent laboratory experiments. The layered columns tested consisted of a fine sandy loam over a clay soil. The observed cumulative infiltration values from the experiments were compared to the simulated ones.

The layered soil columns consisted of a 14.9 cm depth of a fine loamy sand over 12.2 cm of clay. The properties used for the sand layer include an initial moisture content of 0.007 $cm^3$ $cm^{-3}$, a saturated moisture content of 0.66 $cm^3$ $cm^{-3}$, a suction front of 26.50 cm, and a saturated hydraulic conductivity of 0.91 cm $hr^{-1}$. The clay layer properties included an initial moisture content of 0.048 $cm^3$ $cm^{-3}$, a saturated moisture content of 0.62 $cm^3$ $cm^{-3}$, a suction front of 39.50 cm, and a saturated hydraulic conductivity of 0.10 cm $hr^{-1}$. These values were used for all of the simulations.

The first method examined was that proposed by Wolfe et al. (1988). The layered Green-Ampt infiltration model was programmed in two stages. The first stage consisted of running the model as a homogeneous layer throughout the sand. During the first stage, the location of the wetting front was monitored. When the wetting front reached the sand-clay interface, the model parameters were switched over to those of the clay. The results of the simulation are compared with observed values in figure (1). It can be interpreted from the figure that the method provides a sufficient estimate of cumulative infiltration until an elapsed time of approximately 170 minutes. Following this time, the model tends to under-predict cumulative infiltration. The failure of this model occurs at the same time as the development of positive pressure potentials within the sand soil layer. The simulated wetting front arrived at the clay layer at approximately 130 minutes, while the observed wetting front arrived in 120 minutes. A stepwise regression analysis of the predicted and observed cumulative infiltration values for this simulation resulted in a $R^2$ of 0.96.

The next method investigated was that presented by Rawls et al. (1992). This simulation procedure is similar to that presented by Wolfe et al. (1988). The main difference in the two methods is the procedure used when the wetting front reaches the clay layer. Like the first method, the Green-Ampt infiltration model is run using the inputs for the sand layer until the wetting front reaches the clay layer. Upon reaching the clay layer, all parameter values but the hydraulic conductivity are changed to that of the clay layer. Instead of using the hydraulic conductivity of the clay layer, the harmonic mean of the two layers is applied. The effect of using this method on cumulative infiltration is shown in figure (2). The simulation provided a sufficient estimate of cumulative infiltration for approximately 220 minutes into the simulation. This is slightly longer than the first method which only provided good estimates for 170 minutes. Furthermore, the cumulative infiltration predicted after the occurrence of positive pressure potentials is slightly greater than that obtained using the Wolfe et al. (1988) model. However, the procedure still under-predicts cumulative infiltration after this point.

Finally, the modified Green-Ampt infiltration model developed for the occurrence of positive pressure potentials in layered soils was tested. The first step in the simulation was to run the Green-Ampt single soil layer infiltration program until the wetting front reached the clay layer. Upon reaching the clay layer, Green-Ampt infiltration into the sand layer was continued until the soil became saturated ($\Theta_i=\Theta_s$). A water balance was applied to the sand layer to determine the time at which saturation occurred. Infiltration into the clay soil layer was initiated when the sand reached the saturation level. The parameters in the Green-Ampt infiltration program were updated to those of the clay layer at this time. The results from the modified Green-Ampt infiltration model are presented in figure (3). It can be seen from the figure that infiltration into the sand layer continues past the time the wetting front reaches the clay layer at 130 minutes. Because of this, the time at which the infiltration into the clay begins is delayed and the predicted cumulative infiltration values from the simulation increase at greater rate than the previous methods. Thus, the predicted cumulative infiltration into the layered soil column match the observed data better than the other methods. A $R^2$ value of 0.99 was calculated using a stepwise regression analysis of the observed and predicted cumulative infiltration values.

The results from the simulation methods proposed by Wolfe et al. (1988), Rawls et al. (1992), and the modified Green-Ampt are shown with the observed values in figure (4). All of the methods provide the same estimates for cumulative infiltration into the sand soil layer. However, the predicted values for the clay layers vary considerably for each method. The best estimate for cumulative infiltration during the occurrence of positive soil water potentials was achieved using the modified Green-Ampt model. Without the implementation of a water balance within the Green-Ampt model, the amount of water infiltrating into the sand layer will always be under predicted. Thus, the modified Green-Ampt model provides the best estimate of cumulative infiltration into layered soil columns during the occurrence of positive soil water potentials.

The output from the simulation methods proposed by Wolfe et al. (1988), Rawls et al. (1992), and the modified Green-Ampt were then compared against data from another independent data set. The data set was obtained from a soil column constructed in an identical manner to that used for the first dependent data set. The comparison between the simulations and the observed data set are shown in figure (5). The arrival of the wetting front to the clay layer occurred at approximately 130 minutes into the experiment. Other inflection points on the graph could be attributed to the release of entrapped air bubbles within the soil column. Although the modified Green-Ampt model slightly under-predicted cumulative infiltration during some time periods, it still provided the best estimate when compared to the other methods.

## SUMMARY AND CONCLUSIONS

### Summary

Using the Green-Ampt infiltration model, a modification was made to account for the occurrence of positive pressure potentials. The modification involved three steps. The first step was to have single layer Green-Ampt infiltration into the first soil layer with no modification until the wetting front reached the second layer of lower conductivity. Next, incorporating a water balance, the development of positive pressure potentials within the sand layer was monitored. The water balance allowed for the determination of maximum soil water potentials within the column. The maximum value for positive pressure potentials occurred when the top soil layer became saturated. Upon reaching saturation, infiltration into the second layer of lower conductivity began. Finally, at this point, the soil parameters within the Green-Ampt equation were changed to those of the second layer and the model was run to completion.

The modified Green-Ampt model and other layered infiltration modeling schemes based on the Green-Ampt model were tested using laboratory soil column data. The parameters used in the simulation process were the same for all models; only the solution techniques were varied. The laboratory soil column data used in testing consisted of a fine loamy sand overlaying a clay soil. Simulations were run using this data and the outputs from the models were then compared to the observed data.

Results from the simulations revealed that only the modified Green-Ampt model developed in this research accurately predicted cumulative infiltration after the occurrence of positive soil water potentials. The other layered models based on the Green-Ampt equation produced suitable estimates of cumulative infiltration into the soil column until the development of the positive pressure potentials. After this event, these models under predicted the cumulative infiltration into the column. Thus, it was concluded that, although other layered infiltration models exist, only the modified Green-Ampt infiltration model is capable of accounting for the development of positive soil water potentials in soils in which a high conductivity material is overlaying a lower one. As a result, the modified Green-Ampt model provided the best estimates of cumulative infiltration into these columns.

There are several advantages realized with the development of the modified Green-Ampt model. A major advantage is better prediction of cumulative infiltration into layered soils. This will allow for a more efficient simulation of irrigation applications. Thus, a more realistic time for a soil to reach field capacity can be determined and optimal use of water can be made. Another benefit is a better physical representation of the infiltration process, a major component of most hydrodynamic models. Therefore, any improvement in this process would also improve these models. The improved hydrodynamic models could then be used to provide more accurate estimates for water quality simulations. The modified Green-Ampt model will provide improvements in research areas involving infiltration into a layered soil structure consisting of a high conductivity material over a lower one.

## Conclusions

The following conclusions can be drawn from this research:

1. The single layered Green-Ampt model will accurately predict infiltration into a homogeneous soil column of either sand or clay.

2. Existing layered Green-Ampt models do not account for the occurrence of positive pressure potentials in layered soil columns in which the top soil layer has a higher conductivity than the bottom layer.

3. The existing layered Green-Ampt models are capable of providing good estimates of cumulative infiltration into the layered soil columns until the development of the positive pressure potentials. This event corresponds to the arrival of the wetting front at the second soil layer.

4. After the occurrence of positive pressure potentials in a soil column, the existing layered Green-Ampt models under-predict cumulative infiltration.

5. A modified Green-Ampt model was developed to account for the occurrence of positive pressure potentials in layered soil columns.

6. The modified Green-Ampt model monitors the development of the positive pressure potentials by maintaining a water balance within the top soil layer. It was verified that maximum pressure potentials occur when the soil layer reaches the saturation point. At this point, infiltration into the second layer begins.

7. Predicted values of cumulative infiltration from the modified Green-Ampt model agreed with observed values from laboratory layered soil column experiments.

8. The modified Green-Ampt model provided the best estimates of cumulative infiltration when compared to other layered Green-Ampt modeling techniques.

## ACKNOWLEDGMENTS

Permission was granted by the U.S. Army Corps of Engineers to publish this information.

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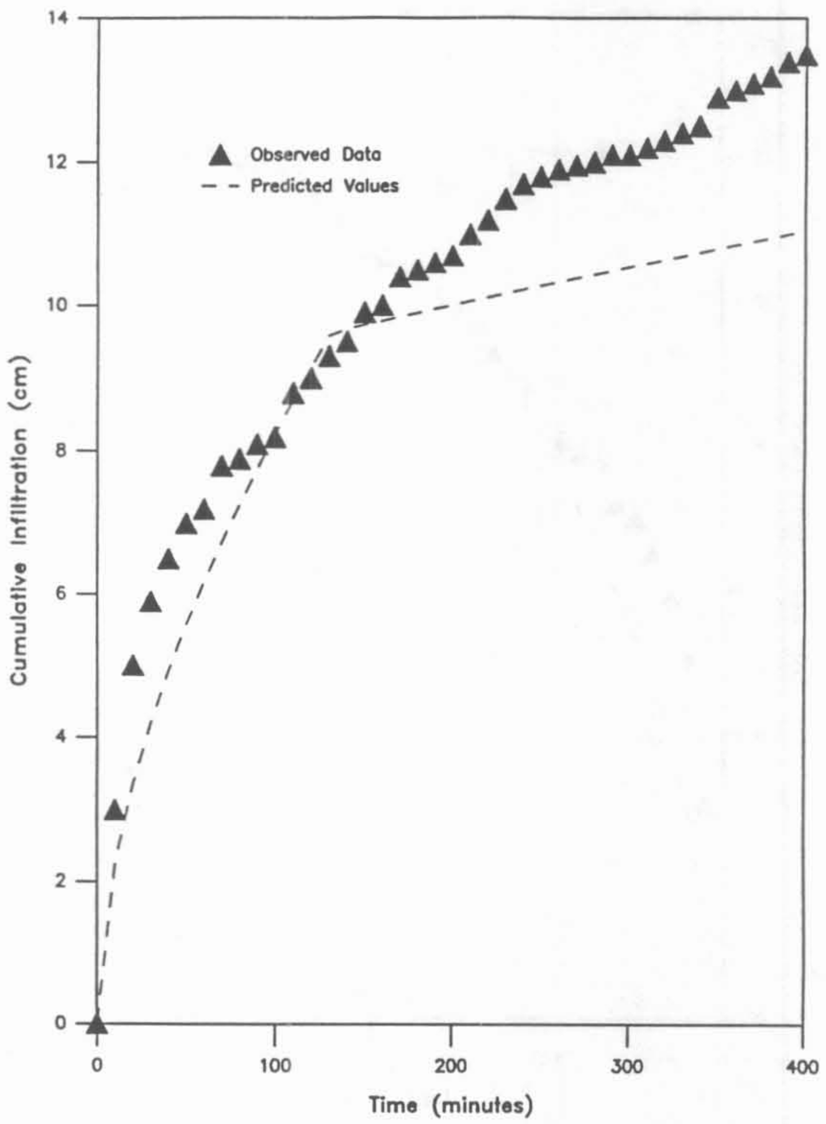


Figure 1. Simulated and observed values for cumulative infiltration into a layered soil column consisting of a sand over clay layer utilizing the two stage method proposed by Wolfe.

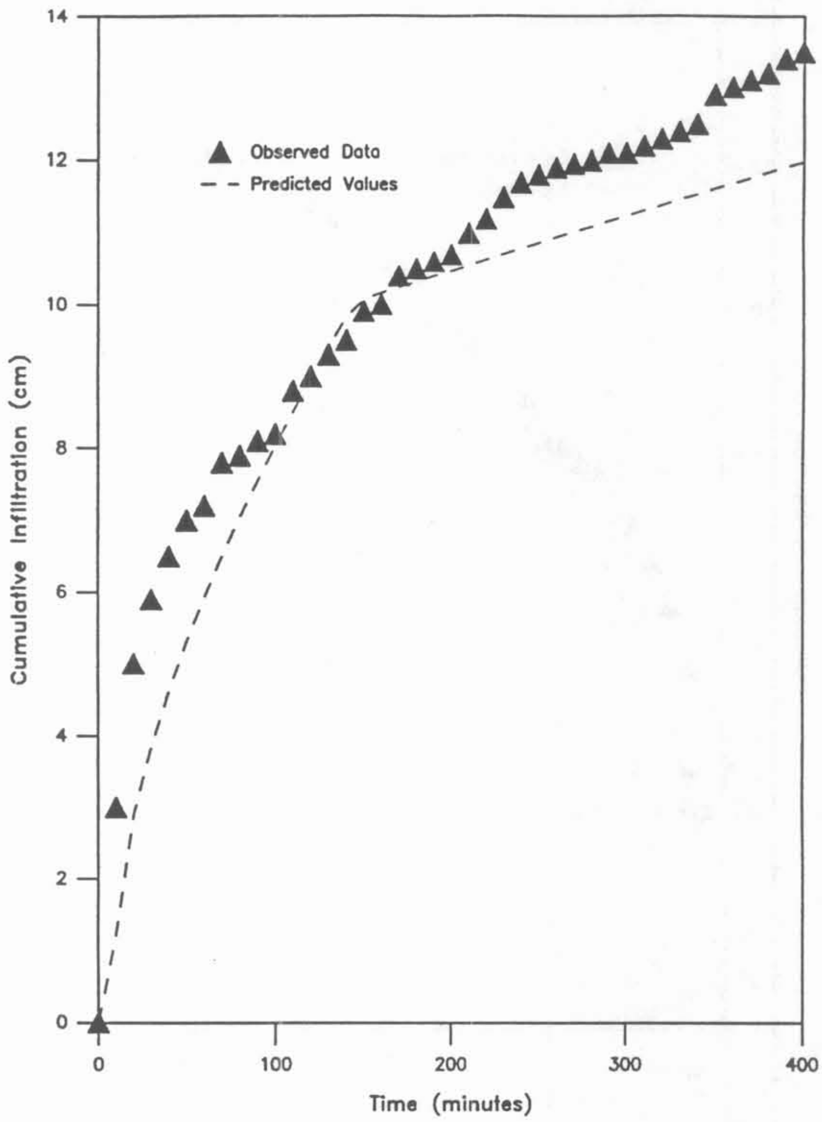


Figure 2. Simulated and observed values for cumulative infiltration into a layered soil column consisting of a sand over clay layer utilizing the Rawls method which incorporates the harmonic mean of the hydraulic conductivity values.

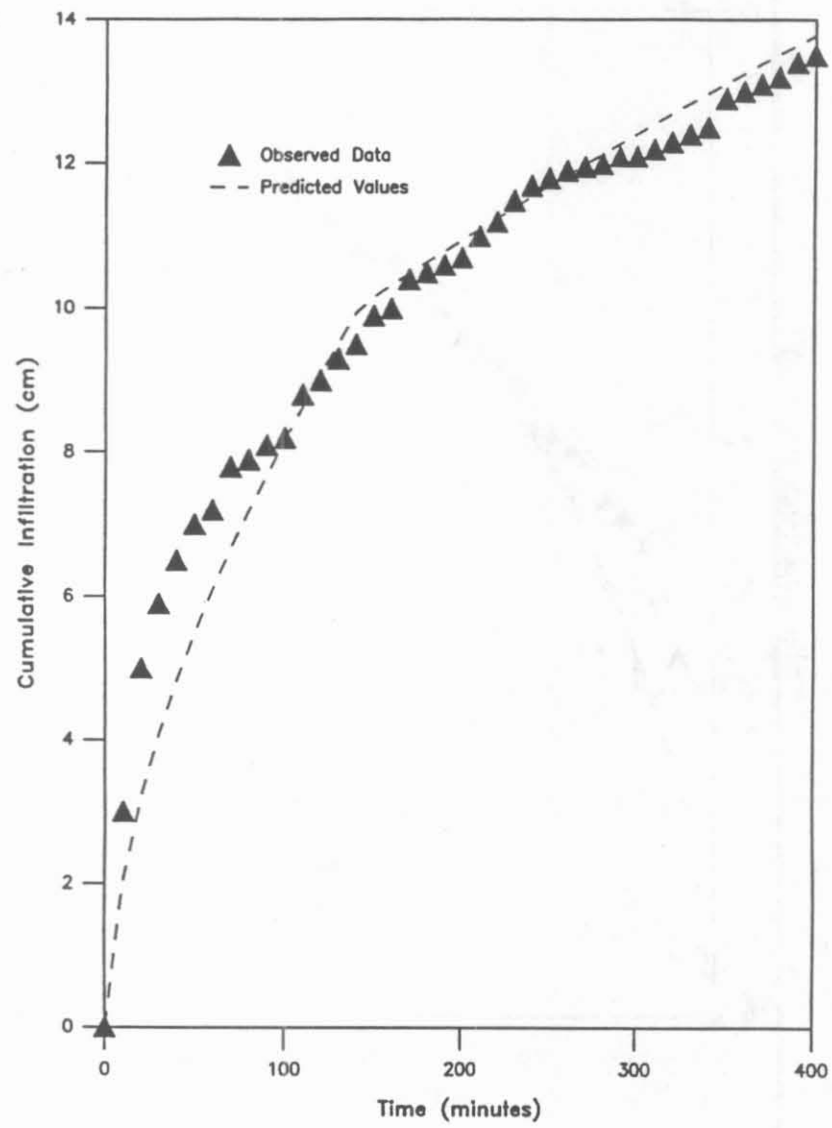


Figure 3. Simulated and observed values for cumulative infiltration into a layered soil column consisting of a sand over clay layer utilizing the proposed modified Green-Ampt model.

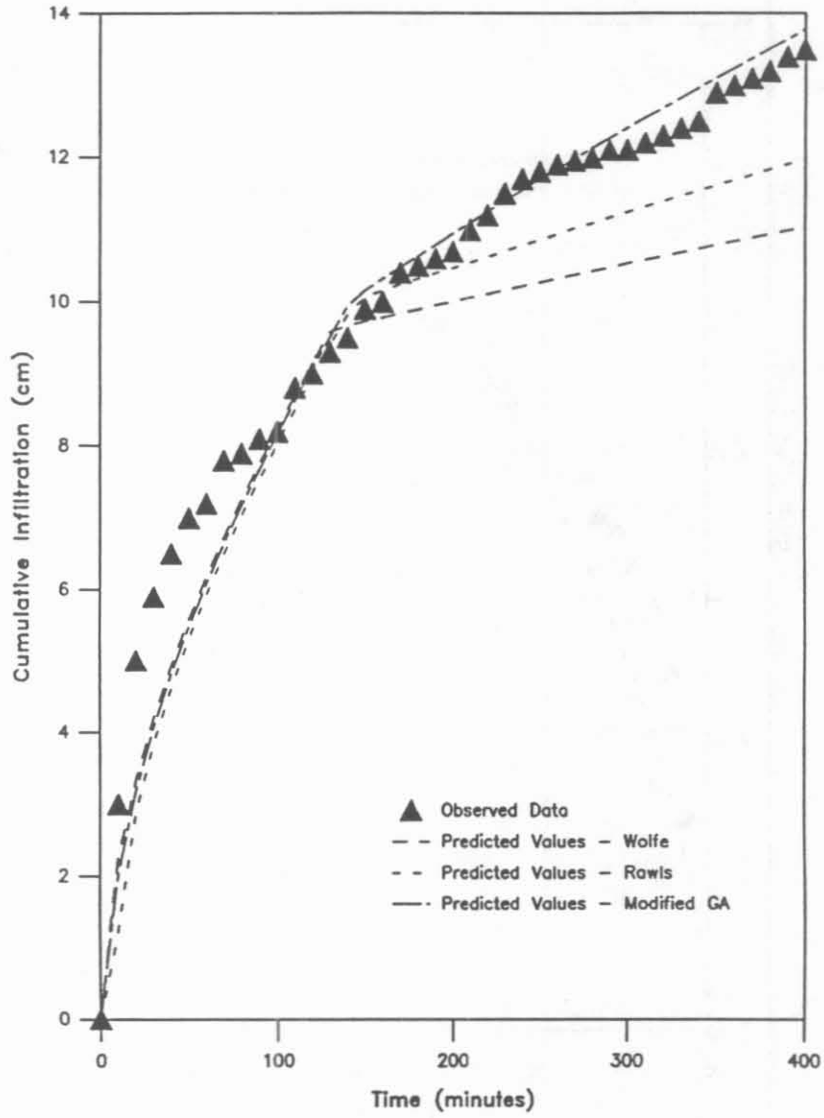


Figure 4. Simulated and observed values for cumulative infiltration into a layered soil column consisting of a sand over clay layer utilizing the methods proposed Wolfe, Rawls, and the modified Green-Ampt model.

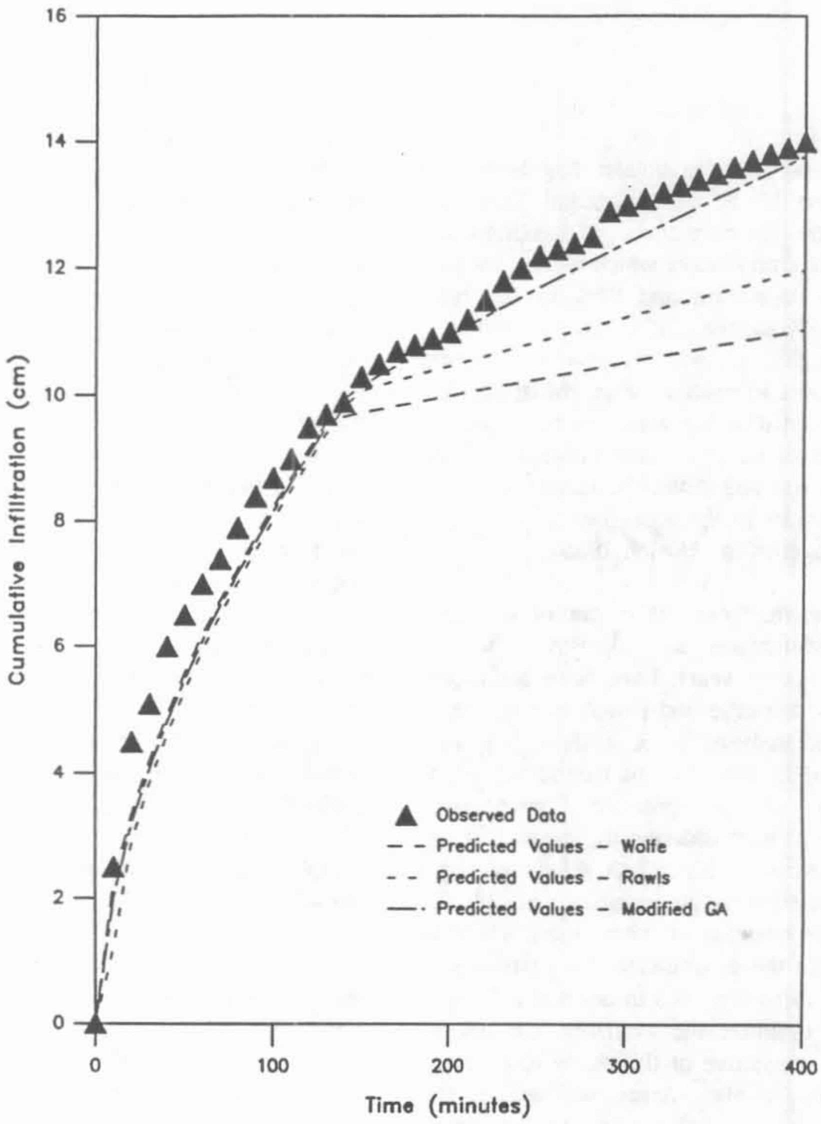


Figure 5. Simulated and observed values for cumulative infiltration into a layered soil column consisting of a sand over clay layer utilizing the methods proposed Wolfe, Rawls, and the modified Green-Ampt model utilizing second independent data set.