

10-28-2004

Adapting the Green and Ampt Model to Account for Air Compression and Counterflow

Darwiche Sabeih
University of South Florida

Follow this and additional works at: <https://scholarcommons.usf.edu/etd>

 Part of the [American Studies Commons](#)

Scholar Commons Citation

Sabeih, Darwiche, "Adapting the Green and Ampt Model to Account for Air Compression and Counterflow" (2004). *Graduate Theses and Dissertations*.

<https://scholarcommons.usf.edu/etd/1230>

This Thesis is brought to you for free and open access by the Graduate School at Scholar Commons. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Scholar Commons. For more information, please contact scholarcommons@usf.edu.

Adapting the Green and Ampt Model to Account for Air Compression and Counterflow

by

Darwiche Sabeh

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: Mahmood Nachabe, Ph.D.
Mark Ross, Ph.D.
Paul Zandbergen, Ph.D.

Date of Approval:
October 28, 2004

Keywords: rainfall, infiltration, sharp wetting front, water table depth

© Copyright 2004, Darwiche Sabeh

DEDICATION

I dedicate this work to my parents, my siblings, Nabil and Amale Sabeh, and to my brothers and sisters. Thank you for all the support you have given me throughout my life, your care, and for the invaluable education I have acquired from you. I could not do it without you. Choukran.

ACKNOWLEDGEMENTS

I would like to thank the CMHAS personnel for making my stay at USF memorable. I extend special gratitude to Jeffrey Vomacka for his helpful assistance in this research. Thank you to Dr. Mahmood Nachabe for his constant guidance and commitment to quality research. Thank you also to Dr. Mark Ross and Dr. Paul Zandbergen for meeting with me and providing helpful insights. I would also like to recognize my cousins for their helpful support to my visit to the USA.

TABLE OF CONTENTS

LIST OF TABLES.....	iv
LIST OF FIGURES	v
ABSTRACT.....	viii
CHAPTER 1: INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objectives and Scope.....	2
1.3 Bridging Two Runoff Mechanisms	4
1.3.1 Traditional Separation of the Runoff Mechanisms	4
1.3.2 Air Phase Effect on Infiltration.....	6
1.4 Literature Review	9
1.4.1 Runoff Mechanisms	9
1.4.2 Green and Ampt Equation	11
1.4.3 Air Phase Effect on Infiltration.....	13
1.5 Contribution of This Study	21
CHAPTER 2: METHODOLOGY	23
2.1 Empirical vs. Theoretical Approach.....	23
2.2 Methodology Briefing.....	24
2.3 Air Compression using Boyle’s Law.....	24

2.4 Modified Green and Ampt Approach (MODGA)	25
2.5 Finite Difference Approach	27
2.6 Air Pressure Quantification	27
2.7 Air Mass Flux	28
2.8 Algorithm for the Modified Green and Ampt Model (MODGA)	30
2.8.1 MODGA's Assumptions.....	31
2.8.2 MODGA's Description	31
2.8.2.1 Ponding Time Calculation	32
2.8.2.2 Infiltration Capacity Calculation.....	33
2.8.3 Flow Chart	34
2.9 MODGA's Sensitivity to Time Step.....	35
CHAPTER 3: RESULTS AND DISCUSSION.....	40
3.1 Introduction.....	40
3.2 Comparison of Three Infiltration Modeling Approaches	40
3.2.1 Shallow Water Table Environment (SWT).....	41
3.2.1.1 Modeling Air Pressure Ahead of the Wetting Front.....	41
3.2.1.2 Modeling Wetting Front Depth and Cumulative Infiltration.....	43
3.2.1.3 Modeling the Infiltration Rate	45
3.2.2 Deep Water Table Environment (DWT).....	47
3.3 Impact of Depth-to-Water Table.....	50
3.4 Impact of Initial Soil Moisture Content.....	53
3.5 Impact of Rainfall Intensity	57
3.6 Impact of Saturated Hydraulic Conductivity	60

3.7 Impact of Soil Type	63
CHAPTER 4: CONCLUSION	67
4.1 Comparison of Three Infiltration Approaches.....	67
4.2 MODGA Sensitivity to Different Parameters.....	68
REFERENCES	70
APPENDICES	73
Appendix A. MODGA Programmed with Visual Basic®.....	74
Appendix B. Air and Water Physical Properties at 20°C	84

LIST OF TABLES

Table 1 – Infiltration Rates (cm/h) Impacted by Air (Constantz et al., 1988).....	18
Table 2 – Comparison of Three Infiltration Models (Wilson et al., 1982).....	20
Table 3 – Parameters Used for the Reference Simulation	35
Table 4 - Ponding Time Sensitivity to Time Step (MODGA).....	39
Table 5 – Air Effect on Ponding and Saturation Times (SWT).....	45
Table 6 – Impact of Depth-to-Water Table on Ponding Time.....	53
Table 7 – Impact of Initial Water Content on Ponding Time	56
Table 8 – Impact of Rainfall Intensity on Ponding Time	59
Table 9 – Impact of Saturated Hydraulic Conductivity on Ponding Time	62
Table 10 – Parameters Used for the Impact of Soil Type Simulation	63
Table 11 – Impact of Soil Type on Ponding Time.....	66
Table 12 – Air and Water Physical Properties at 20°C.....	84

LIST OF FIGURES

Figure 1 – Runoff Mechanisms (Freeze, 1980)	5
Figure 2 – Air Compression Effect on Water Table Elevation on 2/22/02	8
Figure 3 – Rain Event on 2/22/02	8
Figure 4 – Factors Influencing Runoff Mechanisms (Dunne, 1983)	10
Figure 5 – Green and Ampt Infiltration Model (Chow et al., 1988).....	12
Figure 6 – Air Effect on Water Content Profiles (Vachaud et al., 1974)	14
Figure 7 – Air Effect on Cumulative Infiltration (Vachaud et al., 1974)	15
Figure 8 – Air Effect on Infiltration Rate (Vachaud et al. 1974).....	15
Figure 9 – Modified Green and Ampt Model (MODGA) Algorithm.....	34
Figure 10 – Air Pressure Sensitivity to Time Step	35
Figure 11 – Air Pressure Sensitivity to Time Step (Zoom)	36
Figure 12 – Wetting Front Depth Sensitivity to Time Step	36
Figure 13 – Infiltration Sensitivity to Time Step	37
Figure 14 – Infiltration Rate Sensitivity to Time Step.....	37
Figure 15 – Infiltration Rate Sensitivity to Time Step (Zoom)	38
Figure 16 – Air Pressure Ahead of the Wetting Front (SWT).....	41
Figure 17 – Air Pressure Ahead of the Wetting Front (SWT) (Zoom).....	42
Figure 18 – Wetting Front Depth (SWT).....	43

Figure 19 – Cumulative Infiltration (SWT).....	44
Figure 20 – Infiltration Rate Modeling (SWT).....	45
Figure 21 – Infiltration Capacity at Saturation	46
Figure 22 – Air Pressure at Saturation.....	47
Figure 23 – Air Pressure Ahead of the Wetting Front (DWT)	48
Figure 24 – Wetting Front Depth (DWT).....	48
Figure 25 – Cumulative Infiltration (SWT).....	49
Figure 26 – Infiltration Rate Modeling (DWT).....	49
Figure 27 – Impact of Depth-to-Water Table on Air Pressure	51
Figure 28 – Impact of Depth-to-Water Table on Wetting Front.....	51
Figure 29 – Impact of Depth-to-Water Table on Cumulative Infiltration	52
Figure 30 – Impact of Depth-to-Water Table on Cumulative Infiltration Rate.....	52
Figure 31 – Impact of Initial Soil Moisture Content on Air Pressure.....	54
Figure 32 – Impact of Initial Water Content on Wetting Front	54
Figure 33 – Impact of Initial Water Content on Cumulative Infiltration.....	55
Figure 34 – Impact of Initial Water Content on Infiltration Rate.....	55
Figure 35 – Infiltration when Soil is Near Saturation.....	56
Figure 36 – Impact of Rainfall Intensity on Air Pressure.....	57
Figure 37 – Impact of Rainfall Intensity on Wetting Front	58
Figure 38 – Impact of Rainfall Intensity on Cumulative Infiltration.....	58
Figure 39 – Impact Rainfall Intensity on Infiltration Rate	59
Figure 40 – Impact of Saturated Hydraulic Conductivity on Air Pressure.....	60
Figure 41 – Impact of Saturated Hydraulic Conductivity on Wetting Front	61

Figure 42 – Impact of Saturated Hydraulic Conductivity on Cumulative Infiltration.....	61
Figure 43 – Impact of Saturated Hydraulic Conductivity on Infiltration Rate	62
Figure 44 – Impact of Soil Type on Air Pressure	64
Figure 45 – Impact of Soil Type on Wetting Front	64
Figure 46 – Impact of Soil Type on Cumulative Infiltration	65
Figure 47 – Impact of Soil Type on Infiltration Rate	65
Figure 48 – MODGA’s Graphical Interface	74

ADAPTING THE GREEN AND AMPT MODEL TO ACCOUNT FOR AIR COMPRESSION AND COUNTERFLOW

Darwiche Sabeih

ABSTRACT

One of the earliest functions to express infiltration as a function of time was introduced by Green and Ampt. In this study their formula was modified to account for air compression and counterflow. Physically, infiltration, air compression, and counterflow occur simultaneously, while in this model they are decoupled within a time step. Counterflow is calculated as a mass flux and pressure is found using the perfect gas law. First, a comparison of three infiltration methods, the original Green and Ampt formulation, a modified version incorporating air compression only, and the third version including air compression and counterflow, was conducted. Then sensitivity of the model accounting for both air compression and counterflow was explored.

Results showed that accounting for both air compression and counterflow improves the predicted infiltration rate. Air effect on infiltration can be significant even for environments with an impervious layer as deep as 10m; while for very deep water table environments (100m) the three models give similar results. In shallow water table environments (0.5m), air effect on infiltration rate, cumulative infiltration, ponding time, and saturation time is substantial. The model accounting for air compression and counterflow was then tested for different parameters. It provided reasonable results

compared to the Green and Ampt model and the modified version accounting for air compression only. The advantages of this model are that no additional data is required other than what's needed for the original Green and Ampt formulation, and it can be applied for any environment. The assumption of uniform soil moisture content is a limitation for the model, especially for shallow water table environments where the variations in the soil moisture profile within the wetting front depth is substantial.

CHAPTER 1: INTRODUCTION

1.1 Background

Numerous formulations have been proposed to express infiltration as a function of time or of the total quantity of water infiltrated into the soil. One of the earliest was introduced by Green & Ampt in 1911 (Hillel, 1998), whose theory has been found to apply particularly to infiltration into uniform, initially dry and coarse-textured soils, which exhibit a sharp wetting front (Hillel and Gardner, 1970). The formula is best applied for infiltration excess runoff (Hortonian mechanism), where runoff occurs after rainfall intensity exceeds the infiltration capacity of the soil. In contrast, in shallow water table environments and soils with high hydraulic conductivity, it is believed that the dominating runoff mechanism is the saturation excess runoff (Dunne mechanism) where the soil storage capacity between a shallow water table and the ground surface is filled, and the remaining rainfall goes to runoff.

However, due to the effect of the air phase on the infiltration process, the classification of runoff into one of these two mechanisms is questionable. In fact, research has shown that air entrapment, compression, and counterflow in this kind of environment greatly reduce the soil storage capacity, as well as the infiltration rates (Vachaud et al., 1974; Morel-Seytoux and Khanji, 1975; Touma et al., 1984; Wang et al., 1997) – parameters that control the runoff process. Therefore, in environments where

saturation excess is likely to occur, i.e., Central and South Florida, the air phase movement and its effect on infiltration can reduce the infiltration capacity of the soil to a point where Hortonian runoff might occur. This reduction in the infiltration capacity of the soil can reach a value as low as zero and all the rain will go into runoff, which is the same as saturation excess runoff, but with a non-fully saturated soil. Thus, it is suggested that saturation excess runoff should be defined as the runoff that occurs when the infiltration rate reaches zero and not when the soil storage is filled. Observations suggest that encapsulated air below water table will always prevent complete saturation. Thus, in shallow water table environments and soils with high hydraulic conductivity, the traditional concept of saturation excess runoff may significantly underestimate the instantaneous and total volume of runoff. It is necessary to bridge between infiltration and saturation excess runoff based on the infiltration capacity of the soil as impacted by the air phase.

1.2 Objectives and Scope

The purpose of this research is to quantify the infiltration/runoff phenomenon to account for air encapsulation, air compression, and counterflow. In particular, the simple and widely used formula of Green and Ampt will be adjusted to account for the air phase effect on infiltration rate. Unlike the original Green and Ampt concept where the air is considered to be at atmospheric pressure during the infiltration and the flow of water is decoupled from the air flow, the infiltration process is approached as a two-phase flow (water-air). A model is formulated that provides coupling between air and water during the infiltration process by accounting for air pressure in the porous medium. The new

formula accounts for the possibility of a Hortonian type runoff occurring due to the air phase effect in areas where a saturation excess runoff is anticipated; thus, accounting for a runoff before the soil storage is completely filled.

Results of this research will offer a modified form of the Green and Ampt formula to account for air phase impact on the infiltration rate. Also, it will be show that it is essential to account for both air compression and counterflow to accurately quantify the infiltration. Also, the Green and Ampt formula overestimates the infiltration capacity of the soil, and accounting for air compression only by using the Boyle's law underestimates it. Instead, coupling the two phase flow by applying the perfect gas law to the air phase in the porous medium after changing the volume occupied and mass every time step is a preferred approach. In addition, the impact of depth to water table, rainfall rate, initial soil moisture content, and soil properties on infiltration are explored and discussed. The application of this formula gives a better estimation of instantaneous and total runoff during a rainfall event. In fact, unlike the traditional concept of saturation excess runoff where all the rain infiltrates until the soil storage is completely filled when all additional rain becomes overland flow, this approach accounts for the possibility of having some runoff before saturation and reaching an infiltration rate of zero before the soil storage is completely filled.

This work is divided into four chapters. Chapter 1 is the introduction and contains general background on infiltration and saturation runoff mechanisms, the objective of this study, the need to bridge between the two mechanisms, and a literature review of previous work on two-phase flow. Chapter 2 is a description of the methodology used in this research. Chapter 3 represents the results of the modified Green and Ampt model.

Finally, Chapter 4 discusses the results of the proposed model and summarizes the findings of the study.

1.3 Bridging Two Runoff Mechanisms

This section contains a review of the traditional concept of infiltration excess and saturation excess runoff mechanisms and the effect of the air phase on total infiltration as well as infiltration rate.

1.3.1 Traditional Separation of the Runoff Mechanisms

Runoff generation has been considered to be either from infiltration excess (Hortonian) or saturation excess (Dunne). Hortonian runoff occurs when the rainfall rate exceeds the infiltration capacity of the soil and usually is observed in deep water table environments. Saturation excess runoff occurs when the soil is fully saturated, i.e., when the total infiltration depth exceeds the soil storage capacity. This mechanism occurs in highly conductive soils with shallow water table where the infiltration depth fills the soil storage before any overland flow starts to occur.

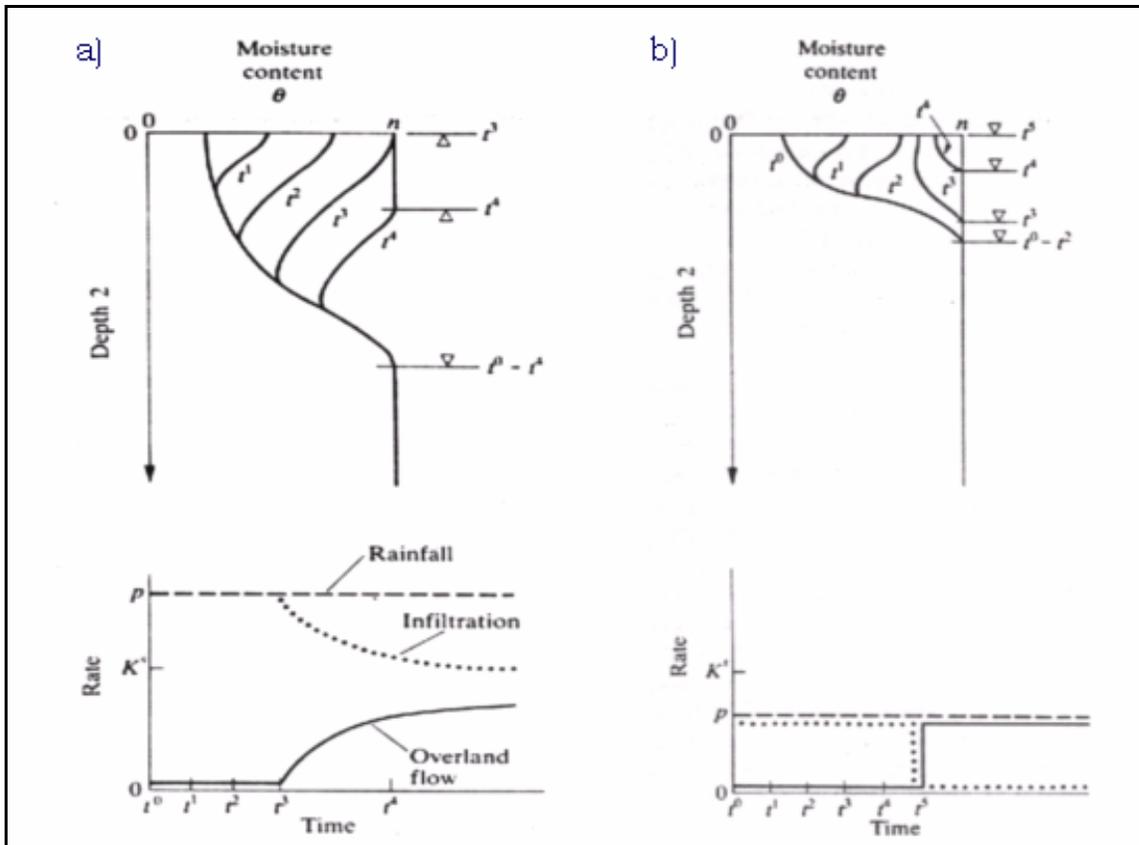


Figure 1 – Runoff Mechanisms (Freeze, 1980)

Figure 1 represents a comparison between these two mechanisms as described by Freeze (1980). For infiltration excess runoff, Figure 1 a), all the rainfall infiltrates into the soil increasing the soil moisture content before ponding time, t_p . After that time, infiltration proceeds at infiltration capacity of the soil and the excess rain goes into runoff. In contrast, for saturation excess runoff, Figure 1 b), all rain infiltrates into the soil until saturation is reached. After the soil storage is completely saturated, rainfall becomes runoff. A detailed literature review on this subject is presented in section 1.4.

It is suggested that presence of air affects runoff generation substantially, and a Hortonian type runoff might occur in shallow water table environments with highly conductive soils prior to saturation excess runoff.

1.3.2 Air Phase Effect on Infiltration

The vadose zone is a multiphase porous medium where the movement of one phase in the pore space is associated with a movement of the other. In particular, there are several mechanisms by which air affects the infiltration process: viscous resistance, compression effect, buoyancy effect, counterflow effect, hysteresis effect and several others (Morel-Seytoux and Khanji, 1975).

Because of air entrapment (or encapsulation in bubble or bypassed pores), the soil-water content does not attain total saturation but some maximal value lower than saturation, which has been called saturation (Hillel, 1998). This issue can be taken into account by considering that the maximum water content in a soil only reaches a value smaller than porosity known as natural saturation or effective porosity (Charbeneau, 2000).

During infiltration, air can be compressed in the vadose zone, especially if the water table is shallow and air can not escape to deeper layers. Research has shown that air compression can affect the infiltration process significantly. For instance, Culligan et al. (2000) found that even for a small increase in pressure relative to the case where the air was free to escape, e.g., < 1cm of water, there was a small but measurable reduction in infiltration.

Compressed air can still make its way out to the atmosphere through the wetting front. This process is counterflow of air. According to Morel-Seytoux and Khanji (1975), because air flows upward, the water content in the counterflow zone must decrease. They also stated that counterflow and hysteretic effects must be associated. However, they suggest that as long as the water content is high in the zone affected by counterflow and the gradient of water content low, this hysteretic effect will not be pronounced (Morel-Seytoux and Khanji, 1975).

Impact on the water table level is another interest for quantifying the air pressure. In fact, if water table level and soil moisture content are monitored at the same location, it is observed that rise in water table occurs prior to the wetting front propagation to the capillary zone (Charbeneau, 2000). Figure 2 is a representation of this effect from data collected by Vomacka et al. (2002) in Lithia, Florida. Figure 2 shows water table depth in a monitoring well (dashed lines) at several periods during a rainfall event, as well as soil water content (continuous lines) obtained from soil moisture probes. The change in water content has not reached the saturated zone; therefore, a change in water table elevation would not be expected. However, the monitoring well at that location shows a water table rise. Therefore, the rise in the monitoring well is only an “apparent rise” of water table as a result of pressure increase in the vadose zone. The water table well is open to the atmosphere. Simply, due to air compression a pressure gradient between the compressed air in the vadose zone and the air in the monitoring well causes a water level rise in the monitoring well. This water level rise in the well is a measurement of gage air pressure in the vadose zone. Figure 3 represents cumulative rainfall for this event and continuous

change in the depth-to-water table during this event period. A detailed literature review of air phase effect on infiltration will be presented in section 1.4.3.

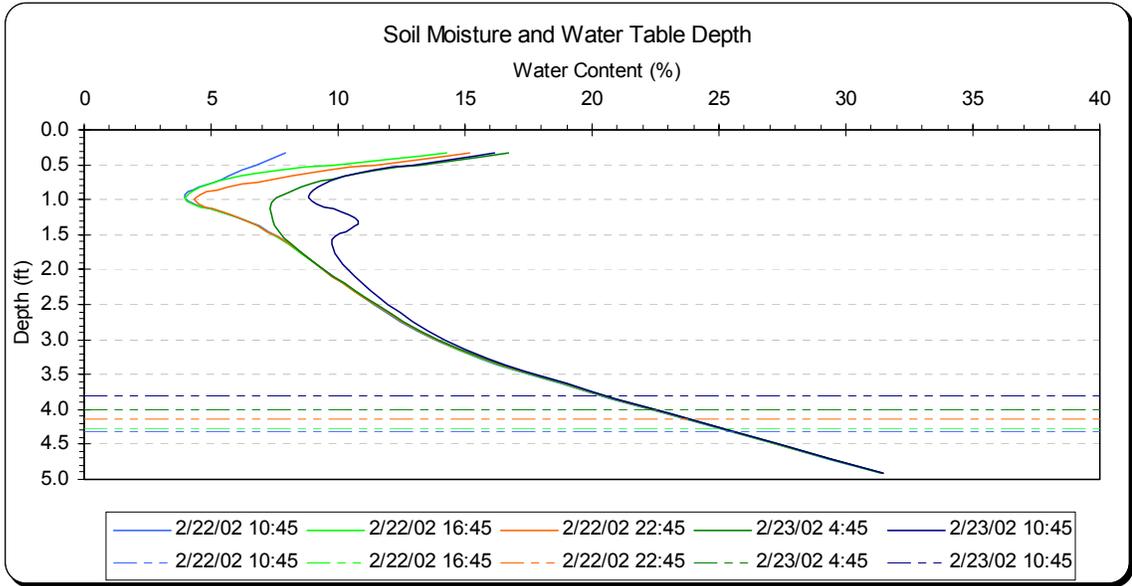


Figure 2 – Air Compression Effect on Water Table Elevation on 2/22/02

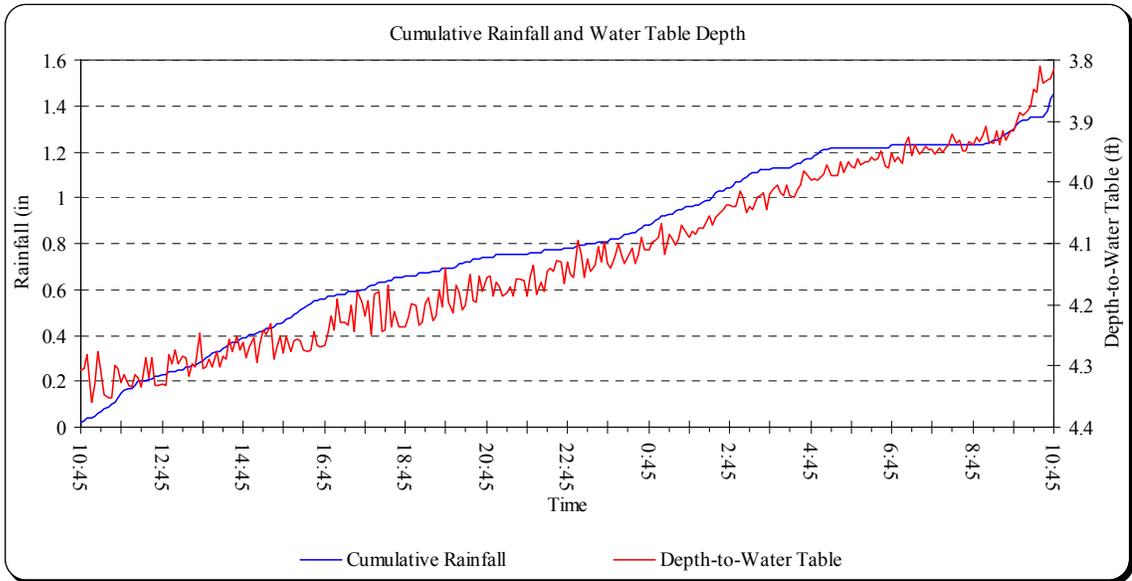


Figure 3 – Rain Event on 2/22/02

Later in this study, air phase effect on infiltration rate will be quantified. This quantification will provide a way to account for possibility of occurrence of a Hortonian-type runoff in environments where a saturation excess runoff is considered the dominant runoff mechanism. Also, saturation excess runoff will be defined herein as a runoff observed after infiltration capacity of the soil reaches zero, rather than the traditional concept of full saturation. To make this argument there is a need to review traditional runoff generation mechanisms in literature and to adapt an infiltration model, i.e., Green and Ampt, to bridge between the two runoff mechanisms.

1.4 Literature Review

This section contains a review of runoff mechanisms, rainfall-runoff studies in Florida, the Green and Ampt equation, and previous studies on air phase effect on infiltration.

1.4.1 Runoff Mechanisms

Effective rainfall or runoff is traditionally defined as net liquid water supplied to channels at time scales comparable to duration of storm after evaporation, interception, surface retention, infiltration, and percolation to underlying aquifers (Bras, 1990). But quantifying runoff depends on the process that generated it and the modeling approach that is used. Soils, topography, climate and vegetation are factors influencing runoff mechanisms. Figure 4 (Dunne, 1983) shows these factors' effects on the runoff processes. In general, an overland flow is considered to be either an infiltration excess runoff or a

saturation excess runoff. This study will account for the necessity to bridge between these two types due to the impact of air phase on infiltration rate.

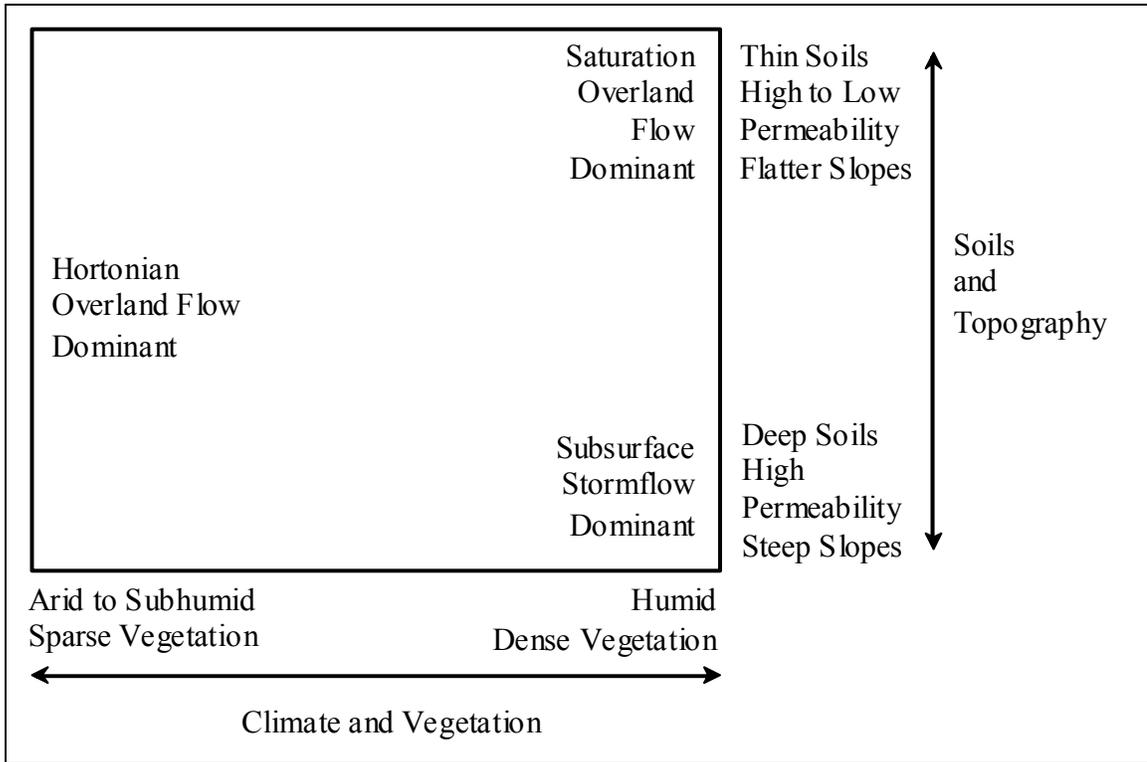


Figure 4 – Factors Influencing Runoff Mechanisms (Dunne, 1983)

Horton (1939) found that infiltration capacity of soil decreases with rainfall time to reach a constant minimum value. He fitted the following exponential model to infiltration capacity with time,

$$f = f_c + (f_0 - f_c)e^{-K_f t}, \tag{Equation 1}$$

where f is the infiltration-capacity at time t ; f_0 is the initial infiltration-capacity at $t = 0$; f_c is the minimum constant infiltration-capacity known also as permeability at natural saturation, K_{ns} ; and K_f is constant for a given curve. This type of runoff occurs when

rainfall intensity exceeds infiltration capacity of soil causing ponding at surface. If soils are highly conductive, rainfall intensities might not exceed the infiltration capacity and no runoff will be observed until soil storage is filled, which is known by saturation excess runoff.

However, presence of air in the soil matrix may reduce infiltration rate substantially and to a point where a Hortonian runoff might occur when a saturation excess runoff is expected. Touma et al. (1984) reported that the primary effect of air pressure in a confined column is to reduce infiltration rate to about one-third of its value in comparison with cases where air is free to escape. On a catchment scale, due to spatial variability in rainfall and catchment characteristics, it is unlikely for runoff to be generated by one mechanism. Even at one location, simulations have shown that runoff generation can switch from infiltration to saturation excess depending on initial conditions and rainfall events (Loague and Abrams, 2001). A deeper insight of air phase effect is presented later in section 1.4.4.

1.4.2 Green and Ampt Equation

In 1911, Green and Ampt suggested a theoretical approach for modeling infiltration in their paper “The Flow of Air and Water through Soils”. The authors main assumptions are that there exists a distinct and precisely definable wetting front during infiltration, and that although this wetting front moves progressively downward as the process proceeds, it is characterized by a constant matric suction, regardless of time and position. Furthermore, this approach assumes that in the transmission zone behind the wetting front the soil is uniformly wet and of constant conductivity. The wetting front is

thus viewed as a plane separating a uniformly wetted infiltrated zone and as-yet totally uninfiltreated zone (Hillel, 1998). Green and Ampt proposed the simplified picture of infiltration below (Chow et al., 1988).

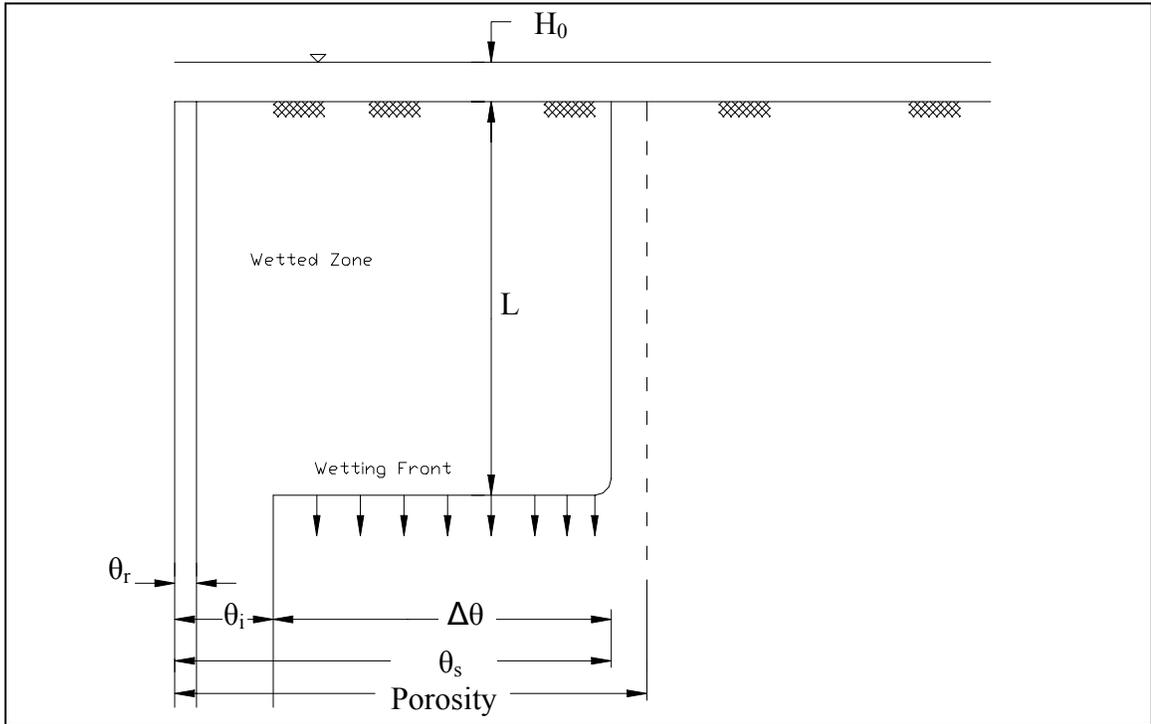


Figure 5 – Green and Ampt Infiltration Model (Chow et al., 1988)
(Scanned and digitized copy using AutoCAD®)

Taking these assumptions into account, the Green and Ampt theory can be formulated as follow,

$$f = \frac{dF}{dt} = K_{ns} \frac{H_0 + H_c + L}{L} = K_{ns} \left[1 + \frac{H_c (\theta_s - \theta_i)}{F} \right]. \quad \text{Equation 2}$$

By integrating between ponding time t_p and time t , we get

$$F = K_{ns} (t - T_p) + F_p - SLn \left(\frac{S + F_p}{S + F} \right), \quad \text{Equation 3}$$

where f is infiltration rate [L/T]; K_{ns} is hydraulic conductivity at natural saturation [L/T]; H_0 is ponding depth at the surface [L] (assuming that ponded water becomes runoff, $H_0=0$); L is depth to wetting front [L]; θ_s is saturated water content [L^3/L^3]; θ_i is initial water content [L^3/L^3]; H_c is wetting front suction head [L]; F is cumulative infiltration [L] ($F = L(\theta_s - \theta_i)$); F_p is cumulative infiltration at ponding time [L]; t is time [T]; T_p is ponding time [T]; and $S = H_c(\theta_s - \theta_i)$.

The air phase being neglected in this approach, it is necessary to adapt this equation to account for air compression and the fact that we have a two-phase flow in soil and that air in soil does not remain at atmospheric pressure.

1.4.3 Air Phase Effect on Infiltration

Under most applications, neglecting resistance to water flow caused by flow of air is not a problem. However, various exceptions arise, including that of infiltration under ponded conditions in shallow water table conditions where this resistance cannot be ignored (Charbeneau, 2000). In addition to theoretical and analytical studies, both field and laboratory experiments have been done to account for air phase effect on infiltration rate, infiltration depth, and water table fluctuation.

Using a single vertical column of fine sand packed into an acrylic plastic cylinder 56 cm long and 5 cm inside diameter, Vachaud et al. (1974) studied the effects of air movement and compression during ponded infiltration. They showed that if air cannot escape freely, there is a considerable reduction in infiltration rate, the shape of water

profiles is significantly different, and air pressure gradients are not negligible. Figure 6 and Figure 7 represent their documentation of air compression effect on water content profile and cumulative infiltration.

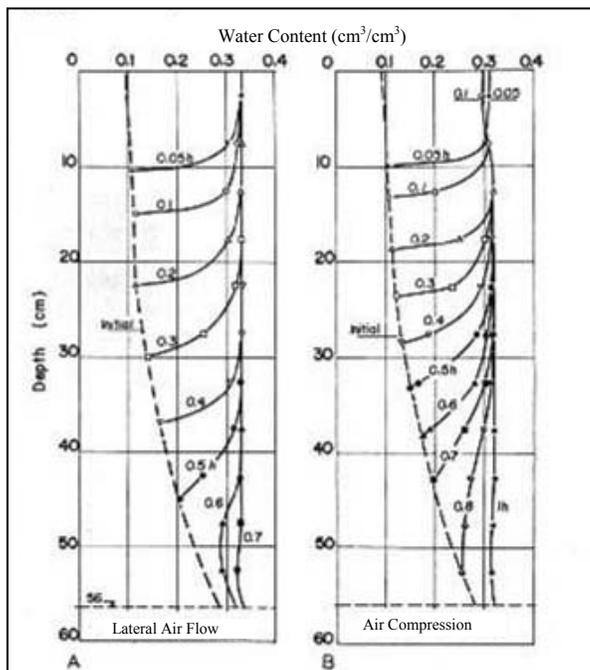


Figure 6 – Air Effect on Water Content Profiles (Vachaud et al., 1974)

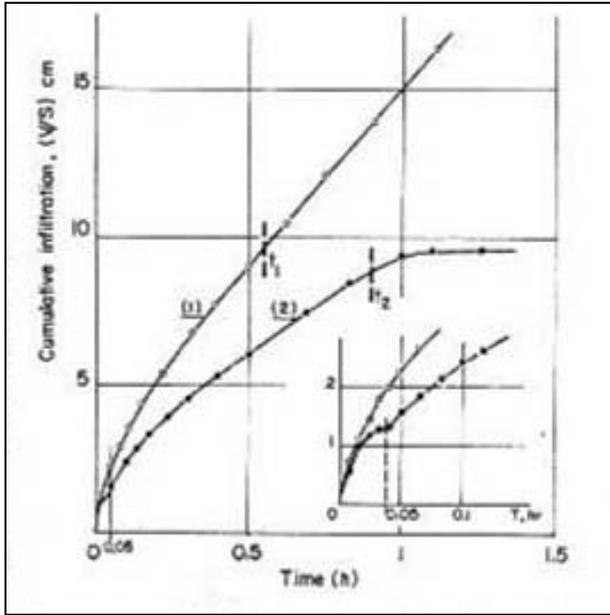


Figure 7 – Air Effect on Cumulative Infiltration (Vachaud et al., 1974)

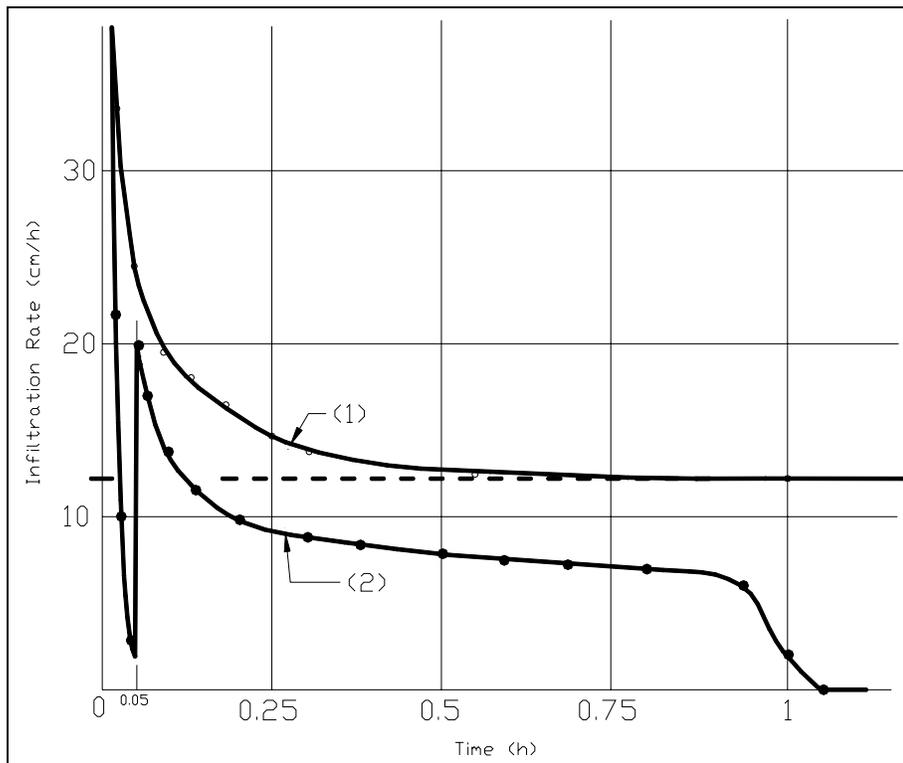


Figure 8 – Air Effect on Infiltration Rate (Vachaud et al. 1974)
(Scanned and digitized copy using AutoCAD®)

Figure 8 is a plot of the infiltration rate they obtained during their experiment. It shows that due to air compression, infiltration capacity of soil reaches zero (curve 2), while it reaches some constant value when air is allowed to escape (curve 1). This confirms the hypothesis of defining the starting point of saturation excess runoff when the infiltration capacity of soil reaches zero and not when storage is full. Also note that at any time, t , infiltration capacity of soil is less if the air is compressed. Thus, for highly conductive soils where saturation excess runoff is anticipated, we might observe a Hortonian runoff due to air compression effect. These findings support the purpose of this research to bridge between two runoff-generation mechanisms by modifying the simple Green and Ampt model to account for air phase.

Air entrapment during groundwater recharge can cause an anomalously large rise of water levels in observation wells in shallow unconfined aquifers during heavy rainstorms (Freeze and Cherry, 1979). Fayer and Hillel (1986b) concluded from a field experiment that encapsulated air is an important component of shallow water table fluctuations. In fact, they found that depending on initial depth of water table and soil moisture characteristics, water table rises were two to five times those when air was not encapsulated: the shallower the water table, the higher the rise. Fayer and Hillel (1986a) reported volumetric air encapsulation as function of depth in their paper "Air Encapsulation: I. Measurement in a Field Soil." They measured volume of encapsulated air for their field experiment at 15 cm depth intervals after water table rose to land surface from a depth of 1.5m. Air entrapped was assumed to be the difference between soil porosity and moisture content measured just after water table had reached surface. They studied also the effect of rain intensity on air encapsulation by sprinkling the site at

different rates. Later, Constantz et al. (1988) conducted field and laboratory experiments to measure effects of air encapsulation on infiltration and reported a value of 19% of entrapped air for the Olympic Sand. Wang et al. (1998) reported that residual encapsulated air in an air-confining condition increased 7% on average in comparison to an air-draining condition.

Wangemann et al. (2000) studied effects of antecedent soil water content and air entrapment on infiltration. The authors found that wetter initial surface water content resulted in lower infiltration rates and attributed this effect to more rapid aggregate breakdown and surface seal development under wetter initial conditions as compared to drier. In contrast, due to air entrapment, they found that wetter initial conditions resulted in higher percolation rates: dryer soil would have more air to block conducting pores.

In shallow water table environments, as the wetting front moves downward through soil, air gets trapped between wetting front and water table, which impedes further infiltration and causes a reduction in infiltration rate. Wang et al. (1998) compared air effect on infiltration rate in a laboratory experiment using some 45cm long columns packed with oven-dried sand (4.5% clay, 11.3% silt, and 84.2% sand). Their results showed that infiltration rates for air-draining condition were 3-10 times larger than those obtained under air-confining condition. Under non-ponding condition, infiltration rate, i_w , decreased on average from 55% of the saturated conductivity, K_s , for air draining condition to 18% of K_s for air-confining condition. Under ponded condition it was reduced by an average factor of 6. Wilson et al., (1982) reported a substantial difference between saturated hydraulic conductivity values obtained in the lab and field conductivity rates obtained in the field using a modified Purdue-type infiltrometer. They measured the

field conductivity for “dry” and “wet” runs. Dry runs refer to experiments that were performed on soils at initial moisture content occurring naturally in the field; wet runs were run 24 hours after dry runs to obtain higher initial soil moisture content. They noted a difference between wet and dry runs, but they couldn’t explain this in their study. Constantz et al. (1988) studied the effect of air on infiltration rate also and reported substantial effect of air phase in both field and laboratory experiments. They compared infiltration rates of four soil types for two gases in the soil matrix: air and CO₂, which was injected in soil to replace air and minimize air effect on infiltration. Their values are documented in Table 1, where “Control” refers to the experiments without CO₂ pre-treatment (infiltration controlled by air).

Table 1 – Infiltration Rates (cm/h) Impacted by Air (Constantz et al., 1988)

	Field Experiments		Laboratory Experiments	
	Los Gatos Gravelly Loam	Diablo Sandy Loam	Olympic Sand	Aiken Loam
Control	25.2	5.4	15.0	1.2
CO ₂	264	25.2	73.8	6.0

Faybishenko (1995) introduced the term “quasi-saturated soils” to define soils beneath water table which contain entrapped air. Darcy’s coefficient accounting to air entrapment is called “quasi-saturated hydraulic conductivity”. This terminology is used to distinguish between the terms unsaturated hydraulic conductivity (used for unsaturated soils in the vadose zone) and saturated hydraulic conductivity (used for saturated soils in the aquifer). The author distinguished three stages in temporal behavior of quasi-saturated

hydraulic conductivity since it varied significantly with time. The first stage represents decreases in the quasi-saturated hydraulic conductivity by as much as 5-8 times. He attributed this effect to entrapped air blocking large pores – this period lasted 0.5 to 2 days. During the second stage, entrapped air moves as free gas and as dissolved state in the water phase. As mobile air discharges progressively from soil, quasi-saturated hydraulic conductivity increases slowly. When the remaining immobile air is discharged as a dissolved phase, quasi-saturated hydraulic conductivity is increased by 2 orders of magnitude reaching the value of saturated conductivity. During the third stage, decrease in hydraulic conductivity is attributed to surface sealing and microbiological activities. In this study, work is in the first stage, since modeling the infiltration process is during rainfall events which last for only a few hours.

Several works have been done in modeling the infiltration process. Wilson et al. (1982) compared the results from three models: The GAML-UNMOD model developed by Mein and Larson (1973) using the infiltration equation proposed by Green and Ampt (1911), the GAML-ETA model to account for the air entrapment effect, which is a modified version of the GAML-UNMOD, and GAML-ART, which accounts for both air entrapment and resistance effect. They reported that GAML-UNMOD failed to predict ponding time due to use of unmodified saturated conductivity values: in all but three of the simulations, ponding time was ∞ , which means that no ponding is reached. GAML-ETA did a better job in predicting ponding time on dry soils, yet it over-predicted infiltration on wetter soils. GAML-ART did the best overall job in predicting infiltration but it also over-predicted infiltration on wet soils. Table 2 contains an average value comparison of these models.

Table 2 – Comparison of Three Infiltration Models (Wilson et al., 1982)

	Predicted Value/ Observed Value, Ponding Time: $t_{p(PRE)}/t_{p(OBS)}$			Predicted Value/ Observed Value, Infiltration Rate: $I_{(PRE)}/I_{(OBS)}$	
	UNMOD	GAML-ETA	GAML-ART	GAML-ETA	GAML-ART
Dry Soils	∞	3.64	1.52	1.26	0.99
Wet Soils	∞	4.63	2.03	2.95	2.12

Morel-Seytoux and Khanji (1974) adjusted the Green and Ampt formula to account for viscous resistance due to air movement. Their modified infiltration rate equation is

$$f = \frac{K_{ns}}{\beta} \frac{H_0 + H_c + L}{L}, \quad \text{Equation 4}$$

where the dimensionless total viscous resistance factor β (like the effective capillary drive H_c) is solely a function of soil and fluid characteristics. For most soils β is greater than 1, which may explain why the Green and Ampt equation over-predicts infiltration. In a later paper (1975) they modified the equation above to account for air compression and counterflow effects. The terms for air compression and counterflow were derived separately even though all effects occur simultaneously. For air compression effect the authors added a term to the numerator of Equation 4 using Boyle's law to quantify air pressure in the vadose zone for deep water tables. Their adjusted formula is,

$$f = \frac{K_{ns} \left(H_0 + H_c + L - \frac{H_{atm} L}{D} \right)}{\beta L}, \quad \text{Equation 5}$$

where H_{atm} refers to atmospheric pressure, and D is depth-to-water table. Unlike Equations 4 and 5, the formula Morel-Seytoux and Khanji (1975) derived to account for

counterflow does not have the Green and Ampt functional form. In fact, a term was added to the denominator of Equation 5 to account for counterflow effect which tends to reduce the total viscous resistance. Equation 6 below is the model they presented to account for viscous resistance, air compression, and counterflow,

$$f = \frac{K_{ns} \left(H_0 + H_c + L - \frac{H_{atm} L}{D} \right)}{\beta L - \frac{\gamma K_{ns} t}{\theta_s - \theta_i}}, \quad \text{Equation 6}$$

where, dimensionless quantity, γ , is a counterflow correction factor.

1.5 Contribution of This Study

Even though effect of air on infiltration has been widely studied, in this paper mass flux of air will be quantified as well as air pressure in the porous medium. Researches done to date have decoupled air flux and compression. In fact, so far air pressure in the soil matrix has been calculated using Boyle's law, which assumes the air mass to remain constant during infiltration. Some formulas accounted for that by adding a term to the equation to account for counterflow. In addition, while using Boyle's law, water table was assumed to be deep; an assumption that restrains these equations from being applied to shallow water table environments. However, in this research, the pressure of air in the porous medium is found by application of the perfect gas law to the remaining mass of air and the volume occupied at the beginning of each time step. The model provided can be used for both deep and shallow water table environments. Coupling between air compression and counterflow for one and with water infiltration on

the other side is a new method of approaching the two-phase flow. A complete description of methodology is provided later in chapter 2.

CHAPTER 2: METHODOLOGY

2.1 Empirical vs. Theoretical Approach

First, this study was supposed to derive an empirical model from field observations of soil moisture and water table level. As seen in Figure 2 above, water table rise can be observed in the monitoring well before change in soil moisture reaches the capillary fringe. Thus, this rise can not be attributed to recharge. Instead, the only physical explanation is to attribute it to an air pressure difference between air in the porous medium (compressed air) and air in the monitoring well open to atmosphere (atmospheric pressure). Attempts to model this rise empirically and use it as the air pressure term in the Green and Ampt model were made. Rise of water table represents air pressure to include in the Green and Ampt equation. Yet, this phenomenon could not be modeled empirically due to the large number of parameters and factors included, the complexity of the coupling between air compression and counterflow, and the infiltration of water. To overcome this issue, a conceptual model was built where the parameters variation is limited and the water and air phase were decoupled. A description of this model can be seen below.

2.2 Methodology Briefing

This chapter describes the modified Green and Ampt model proposed to account for air phase impact on infiltration. The model is similar to the Green and Ampt except for an additional term accounting for air pressure. This suggested model is similar to the one presented by Morel-Seytoux in Equations 5 and 6 above, but instead of accounting for air pressure in the numerator using Boyle's law ($H_{\text{atm}} * L/D$) and counterflow in the denominator, air pressure in the porous medium (due to compression and counterflow) is introduced in the numerator, but will not be found using Boyle's law. Instead, at each time step air pressure is calculated by estimating air flux out of the soil and applying the perfect gas law for the remaining mass and volume of air ahead of the wetting front. This way air compression and counterflow are coupled, which is not the case when using Boyle's law.

2.3 Air Compression using Boyle's Law

As seen already in the literature review, air pressure ahead of the wetting front was found using Boyle's law. Since a different approach is proposed here, the reasons for which Boyle's law will not be used needs to be highlighted. Boyle's law states that under isothermal conditions, and for a perfect gas (like air), the pressure of gas is inversely proportional to the volume it occupies, i.e., $P * V = \text{constant}$.

Applying this formula for air mass ahead of the wetting front, replacing pressure by pressure head and volume by depth-to-water table, yields to:

$H_{atm} * D = H_p * (D - L) = \text{Constant}$. If H_a is the gage air pressure head in the porous medium, $H_a = H_p - H_{atm}$, then $H_a = \frac{H_{atm} * D}{D - L} - H_{atm} = \frac{H_{atm} * L}{D - L}$. For deep water tables, i.e., $D \gg L$, this equation can be written as,

$$H_a = \frac{H_{atm} * L}{D}. \quad \text{Equation 7}$$

As explicitly seen in the derivation of Equation 7 above, this approach is only valid for deep water tables where wetting front depth can be neglected in front of depth-to-water table. Also, implicitly included in the application of Boyle's law, is the fact that mass of air in the porous medium remains the same during infiltration, since counterflow is neglected, and air pressure continues to increase. Some research previously done accounted for counterflow by adding two terms to the Green and Ampt approach to account for air compression and counterflow. In this paper air compression and counterflow effect will be lumped into one term, which simplifies the equation and allows accounting for mutual effect of air compression and counterflow on one another.

2.4 Modified Green and Ampt Approach (MODGA)

The pressurized air in the porous medium will reduce the soil's ability to absorb water, i.e., infiltration capacity. To account for this effect air pressure in the porous medium will be plugged in the numerator of Equation 2 above. The proposed model is represented by the following equations, $f > i$ for $t < T_p$, and for $t > T_p$,

$$f = K_{ns} \frac{H_0 + H_c + L - H_a}{L}, \quad \text{Equation 8}$$

where, H_a is the gage air pressure head in the porous medium. Below is a the description of the air pressure quantification.

For simplification purposes, consider that there's no ponding at the surface, i.e., $H_0 = 0$. Knowing that $F = L^*(\theta_s - \theta_i)$, Equation 7 can be written as:

$$f = \frac{dF}{dt} = K_{ns} \left(1 + \frac{S - S_a}{F} \right), \text{ where } S_a = H_a^*(\theta_s - \theta_i). \text{ Separation of variables leads to}$$

$$\frac{F * dF}{F + S - S_a} = K_{ns} dt, \text{ with } S \text{ being constant for a soil type and } S_a \text{ assumed constant during}$$

a time step. This equation, integrated for each time step as follows,

$$\int_{F_b}^{F_e} \frac{F * dF}{F + S - S_a} = \int_t^{t+\Delta t} K_{ns} dt, \text{ where, } F_b \text{ and } F_e \text{ are the cumulative infiltration at the beginning}$$

and end of a time step, yields to the following equation,

$$F_e - F_b - (S - S_a) * Ln \left(\frac{F_e + S - S_a}{F_b + S - S_a} \right) = K_{ns} * \Delta t. \quad \text{Equation 9}$$

This is the same form as the regular Green and Ampt equation, with the exception that the integration is carried by time step instead of carrying it between ponding time and any time, t , because the term S_a varies each time step. To solve this equation, i.e., find the cumulative infiltration, some iteration must be carried as an explicit form for F_e cannot be reached.

Equations 8 and 9 apply after ponding because before ponding all rain infiltrates. Ponding occurs when $f = i$, where i is the rainfall rate. Incorporating $f = i$, and $F = i * T_p$ into Equation 7 above yields to the following formula for ponding time,

$$T_p = K_{ns} \frac{S - S_a}{i * (i - K_{ns})}. \quad \text{Equation 10}$$

The suction head, H_c , and therefore S , is a function of soil properties.

2.5 Finite Difference Approach

The infiltration process is continuous with time. Thus, infiltration capacity of soil, air pressure and mass in porous medium, and counterflow of air vary continuously with time. Due to the large amount of variables affecting the process, an approach through finite difference, i.e., each of these quantities will be considered constant within a time step, will be used to model infiltration. The model will be tested for convergence with time steps for results accuracy.

2.6 Air Pressure Quantification

Instead of using Boyle's law to calculate pressure in porous medium as described in Equation 7 above, air pressure ahead of the wetting front will be calculated using the perfect gas law,

$$P = \rho * R * T, \quad \text{Equation 11}$$

where P is the pressure in Pascal [Pa]; ρ is the air density [Kg/m^3]; R is the perfect gas constant; $R = 286.9$ [$\text{J}/\text{Kg.K}$]; and T is the temperature of the air in Kelvin [K].

Each time step air density changes because both the space volume available in soil and air mass change due to infiltration of water and counterflow of air. Volume of space available is the pore space between water table and wetting front, i.e.,

$V = (D - L) * A * (n - \theta_i)$, where n is porosity of the soil, and A is area. Mass of air

remaining in soil at the end of a time step is mass at the beginning of this time step minus counterflow. Thus, if assuming a constant mass flux of air during a time step, mass of air remaining in the soil is, $m_e = m_i - m_f * dt$, where m_e and m_i represents mass of air at the beginning and end of a time step [Kg]; m_f mass flux of air [Kg/s]; and dt time step [s]. The following section represents the formula used to calculate air mass flux from soil during infiltration.

2.7 Air Mass Flux

A description of the formula used to account for counterflow is presented hereby. Flow of air will be approached as a mass flux. This approach is described by Charbeneau (2000) and will be reviewed here. The general Darcy's equation for both compressible and incompressible fluids is

$$\vec{q} = -\frac{k}{\mu} \left(\nabla P + \rho \vec{g} \right), \quad \text{Equation 12}$$

where k is the intrinsic permeability of the soil [m^2]; μ is the dynamic viscosity of fluid [Ns/m^2]; ρ is the fluid's density [Kg/m^3]; and g is the gravitational acceleration [m/s^2]. If the fluid in consideration is air, gravitational effect can be neglected and Equation 11 above yields to

$$\vec{q} = -\frac{k}{\mu} \nabla P. \quad \text{Equation 13}$$

For cross section A, and for one-dimensional flow, fluid mass flux is

$$m_f = \rho q A = -\rho A \frac{k}{\mu} \frac{dP}{dL}. \quad \text{Equation 14}$$

For isothermal conditions the pressure is given by $P = \rho \frac{P_0}{\rho_0}$, where p_0 and ρ_0 are reference values for the fluid pressure and density at standard atmospheric condition.

Thus, Equation 14 can be written as $m_f = -PA \frac{k}{\mu} \frac{\rho_0}{P_o} \frac{dP}{dL}$. Variable separation yields to

$$\Leftrightarrow m_f dL = -A \frac{k}{\mu} \frac{\rho_0}{P_o} (PdP). \quad \text{Equation 15}$$

For a wet soil, multiply the intrinsic permeability of soil by relative permeability of air, k_{ra} , to account for pores filled with water. Since this model follows the same assumption of an advancing sharp wetting front presented by Green and Ampt, air mass flux will cross a column of soil at natural saturation of a height equal to the wetting front depth. Integrating Equation 14 between wetting front and land surface results in

$$m_f = A \frac{k.k_{ra}}{\mu} \frac{\rho_0}{P_o} \frac{P_p^2 - P_0^2}{2L}, \quad \text{Equation 16}$$

where P_p is pressure in porous medium ahead of wetting front.

Relative permeability of air is function of soil water content and can be calculated using the following formula by Charbeneau (2000):

$$k_{ra} = (1 - \Theta)^2 (1 - \Theta^{(1+2/\lambda)}), \quad \text{Equation 17}$$

where λ is the pore size distribution index; and $\Theta = \frac{\theta - \theta_r}{n - \theta_r}$ is the normalized water

content in the Brooks and Corey Model (B-C). The value used of water content at natural saturation is critical for this model because of its impact on counterflow: Equation 17 is a non linear equation. Some simulations were done to choose representative values of θ_s :

the formula $\theta_s = \theta_r + (n - \theta_r) \left(\frac{1}{2} \right)^{1/\varepsilon}$, derived using the B-C model and Bouwer's suggestion $K_s = \frac{K}{2}$ (1966), didn't yield to physically acceptable results. Thus, in this research a value for saturated water content close to porosity is assumed. The wetting front suction head can be calculated using B-C parameters and the equation below (Nachabe and Illangasekare, 1994),

$$H_c = \frac{2 + 3\lambda}{1 + 3\lambda} h_b, \quad \text{Equation 18}$$

where $\varepsilon = 3 + 2/\lambda$ and h_b is Brooks and Corey's bubbling pressure.

These equations have been programmed using Visual Basic® to model the infiltration process. In addition to modeling infiltration to account for air compression and counterflow, two other models were programmed: one accounting for air compression but neglecting counterflow, and a second where air phase in the soil matrix is neglected (original Green and Ampt approach). The following section represents the algorithm of this program.

2.8 Algorithm for the Modified Green and Ampt Model (MODGA)

A description of the algorithm and use of the above formulas is presented below. In addition, the assumptions included in the formulas derivation will be explicitly shown before the presentation of the program's flow chart.

2.8.1 MODGA's Assumptions

The derivation of formulas was based on the assumption of considering the variable parameters of the infiltration process as quasi steady. This means that different parameters which continuously vary with time will be considered as constant within a time step. Thus, MODGA is sensitive to the time step used and this sensitivity will be tested in the following section. The basic assumptions and limitations for this model are the following:

- i. Sharp wetting front is maintained during infiltration;
- ii. Constant initial soil moisture content;
- iii. Constant rainfall rate;
- iv. Uniform air pressure in porous medium;
- v. Air pressure ahead of the wetting front is constant during a time step, i.e., mass flux is constant during a time step, as well (when counterflow is not neglected); and
- vi. Constant infiltration capacity during a time step.

2.8.2 MODGA's Description

A literal description of MODGA and the Algorithm's flow chart, drawn using Microsoft Visio ®, are represented hereby. Two main sections are distinguished in the program: before and after ponding time.

2.8.2.1 Ponding Time Calculation

Before surface ponding, all rainfall infiltrates into the soil and infiltration capacity of the soil is higher than rainfall intensity. Thus, first step in the program is to find time at which surface ponding is reached, known as ponding time, T_p , using Equation 10.

i. At time, t , $H_a = \text{constant until } t + \Delta t$

ii. $S_a = H_a * (\theta_s - \theta_i)$

iii. $T_p = K_s \frac{S - S_a}{i * (i - K_s)}$

iv. If $T_p > t + \Delta t$, ponding does not occur in this time step and all rain infiltrates.

v. Calculate $m_f = A \frac{k.k_{ra} \rho_0}{\mu P_0} \frac{P_p^2 - P_0^2}{2L} \rightarrow M = M - M_f * \Delta t$

vi. $F_e = F_b + i * \Delta t \rightarrow L = \frac{F_e}{\theta_s - \theta_i} \rightarrow V = (n - \theta_i) * (D - L) \rightarrow P_p = \frac{M}{V} RT$

If $P_p < P_{atm}$, it is a mathematical consequence that is physically incorrect of this finite difference approach, ($M_f = \text{constant}$). To correct it, set $P_p = P_{atm}$ and recalculate the mass of air in porous medium.

vii. $H_a = \frac{P_p}{\gamma_{water}} - H_{atm}, F_b = F_e$

viii. Repeat these steps until $T_p < t + \Delta t$, which corresponds to ponding time.

N.B.: If counterflow is neglected, Boyle's law is used to calculate H_a and $M_f = 0$. If air phase is neglected completely (Green and Ampt Approach), H_a and M_f are null. Clearly Equation 10 shows that air phase reduces ponding time, as will be seen in the following chapter.

2.8.2.2 Infiltration Capacity Calculation

After ponding, infiltration proceeds at soil's capacity. To find the infiltration capacity, iterate using Equation 9. The steps are as follow:

- i. At time, t , $H_a = \text{constant}$ until $t + \Delta t$
- ii. $S_a = H_a * (\theta_s - \theta_i)$
- iii. Calculate $m_f = A \frac{k.k_{ra}}{\mu} \frac{\rho_0}{P_0} \frac{P_p^2 - P_0^2}{2L} \rightarrow M = M - M_f * \Delta t$
- iv. $F_e - F_b - (S - S_a) * Ln\left(\frac{F_e + S - S_a}{F_b + S - S_a}\right) = K_s * \Delta t$

To find total infiltration at the end of a time step, iterations are needed to solve this equation. Incremental values are functions of infiltration capacity at the previous time step (or saturated hydraulic conductivity), and time step.

- v. $f_c = \frac{F_e - F_b}{\Delta t}$ (if $f_c < K_s/100 \rightarrow f_c = 0$)
- vi. $L = \frac{F_e}{\theta_s - \theta_i} \rightarrow V = (n - \theta_i) * (D - L) \rightarrow P_p = \frac{M}{V} RT$ (same condition as before)
- vii. $H_a = \frac{P_p}{\gamma_{water}} - H_{atm}, F_b = F_e$
- viii. Repeat these steps until end of the storm is reached.

The steps presented above are a major description of the proposed model. A detailed description is provided in the flow chart below (soil saturation, storm ending without ponding the soil...). The complete Visual Basic® model is documented in Appendix A.

2.8.3 Flow Chart

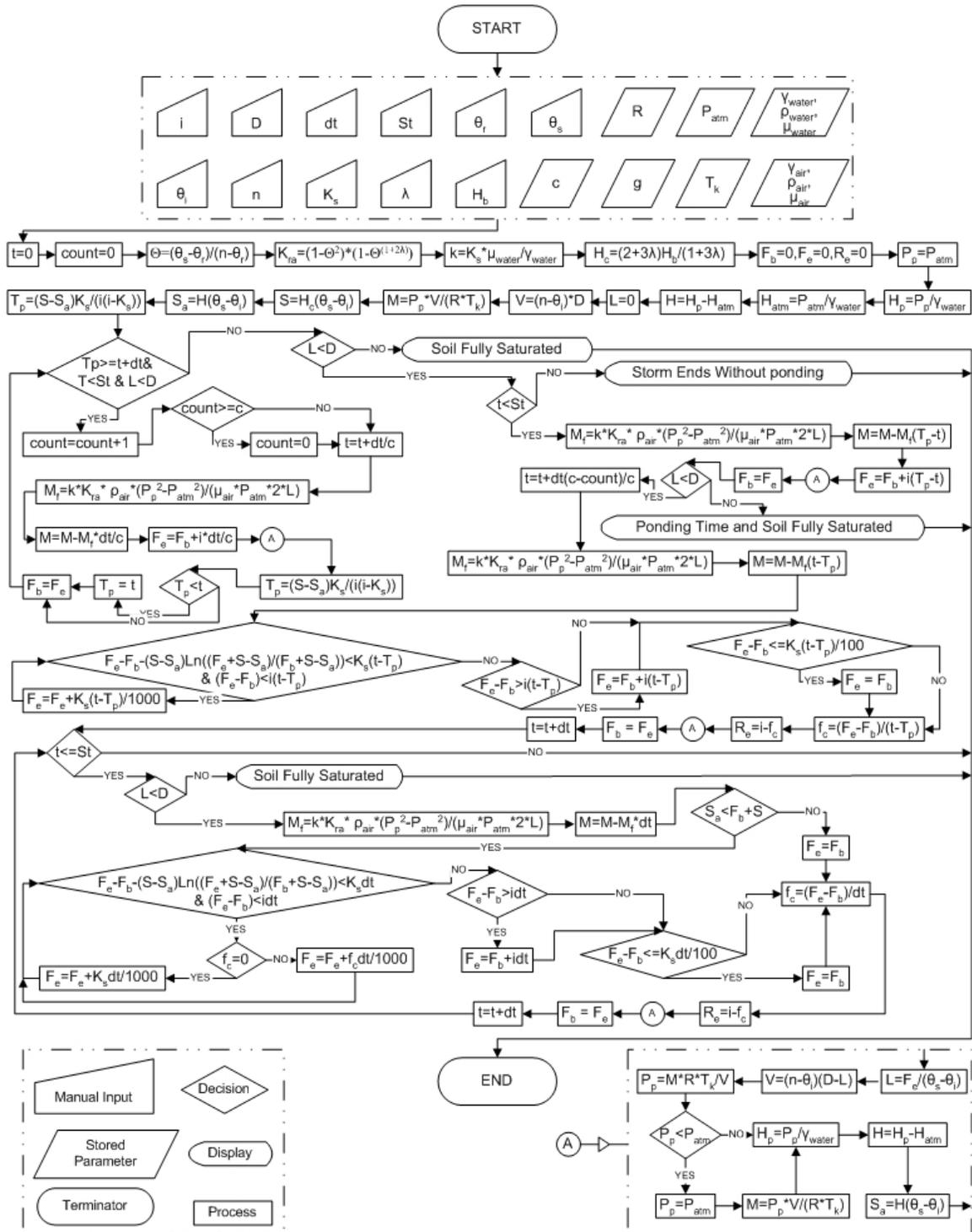


Figure 9 – Modified Green and Ampt Model (MODGA) Algorithm

2.9 MODGA's Sensitivity to Time Step

For a reference soil type and properties, water table depth, and rainfall rate, MODGA was run for different time steps until convergence was reached. Parameters related to the reference simulation are documented in Appendix B. Time steps that were used are: 5 min., 3 min., 1 min., 30 sec., 15 sec., and 9 sec. The figures below show sensitivity to time step of air pressure, depth to wetting front, total infiltration, and infiltration rate.

Table 3 – Parameters Used for the Reference Simulation

Soil Type: Sandy Loam									Water Table and Rainfall	
n	θ_s	θ_r	θ_i	K_s (cm/hr)	H_b (m)	H_c (m)	k_{ra}	λ	D(m)	i(cm/hr)
0.41	0.39	0.065	0.207	1.0	0.13	0.165	0.017	0.89	0.5	3.0

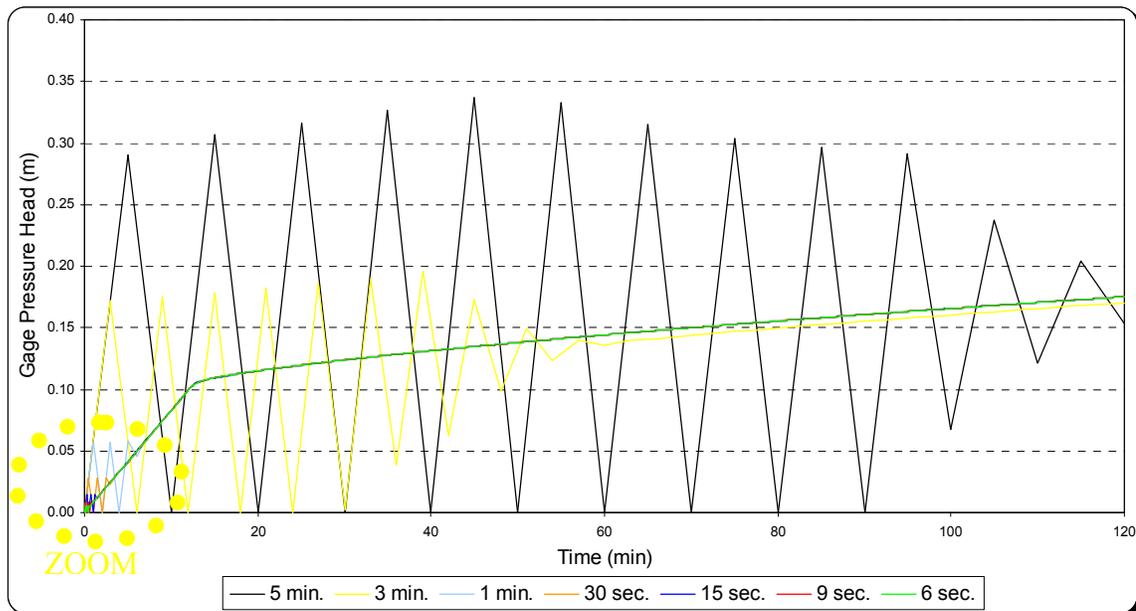


Figure 10 – Air Pressure Sensitivity to Time Step

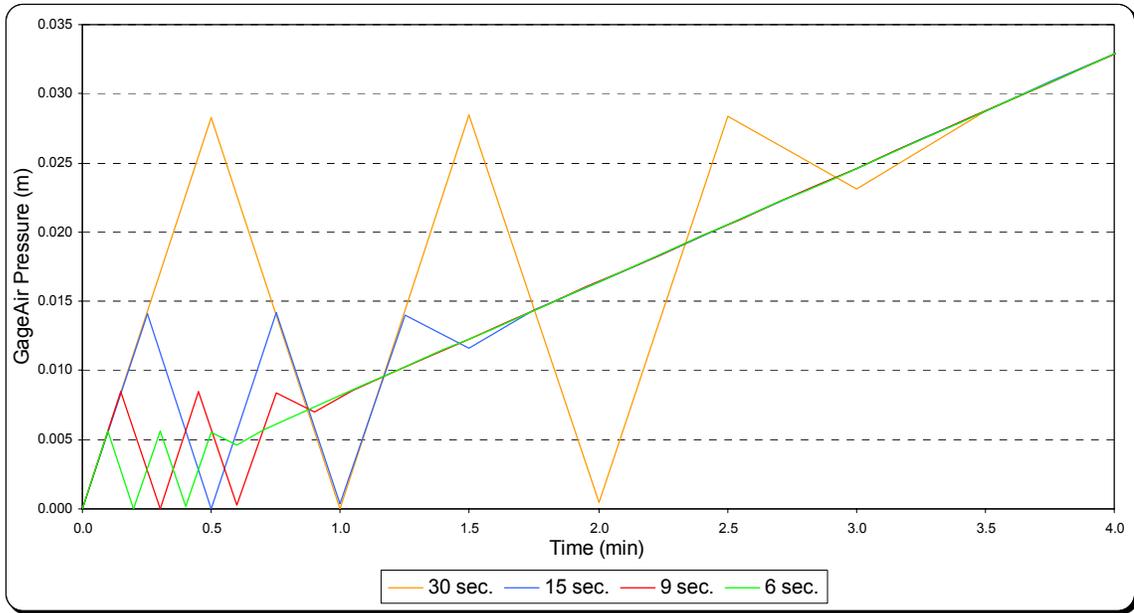


Figure 11 – Air Pressure Sensitivity to Time Step (Zoom)

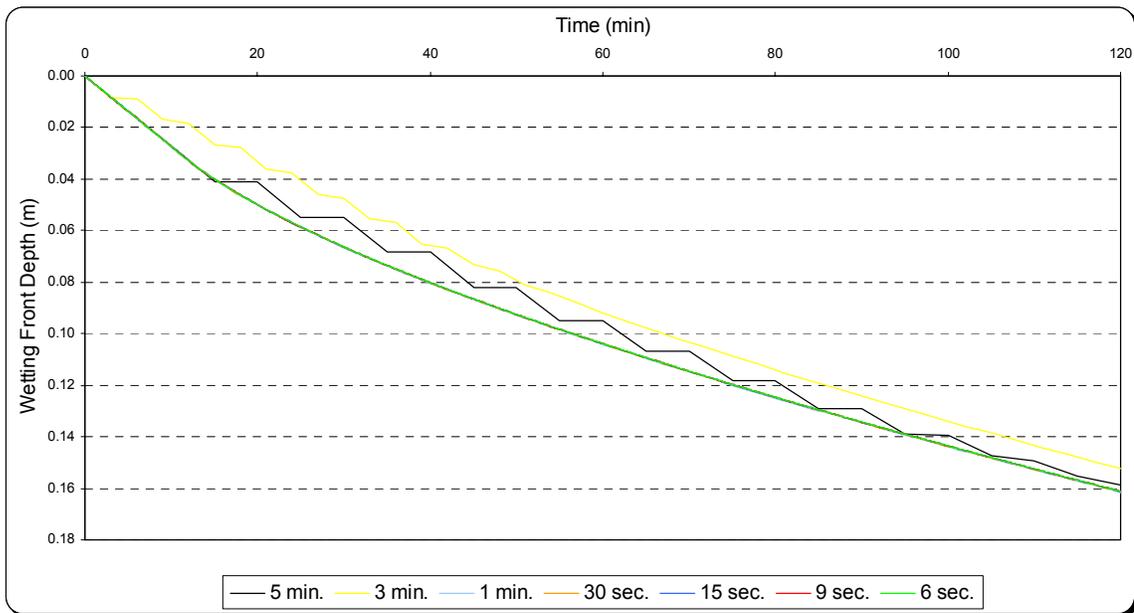


Figure 12 – Wetting Front Depth Sensitivity to Time Step

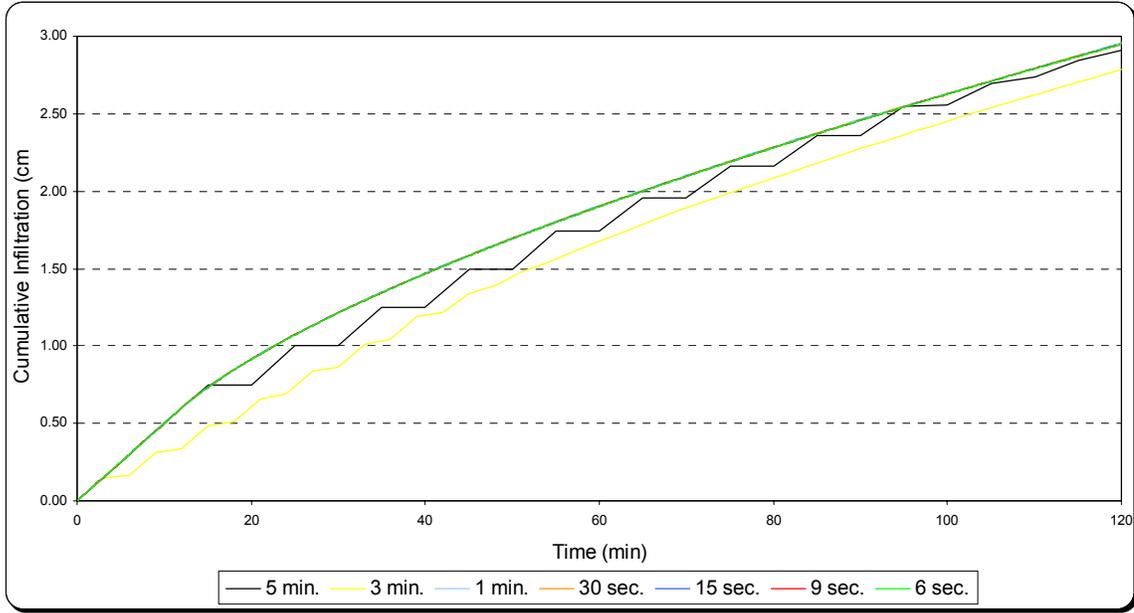


Figure 13 – Infiltration Sensitivity to Time Step

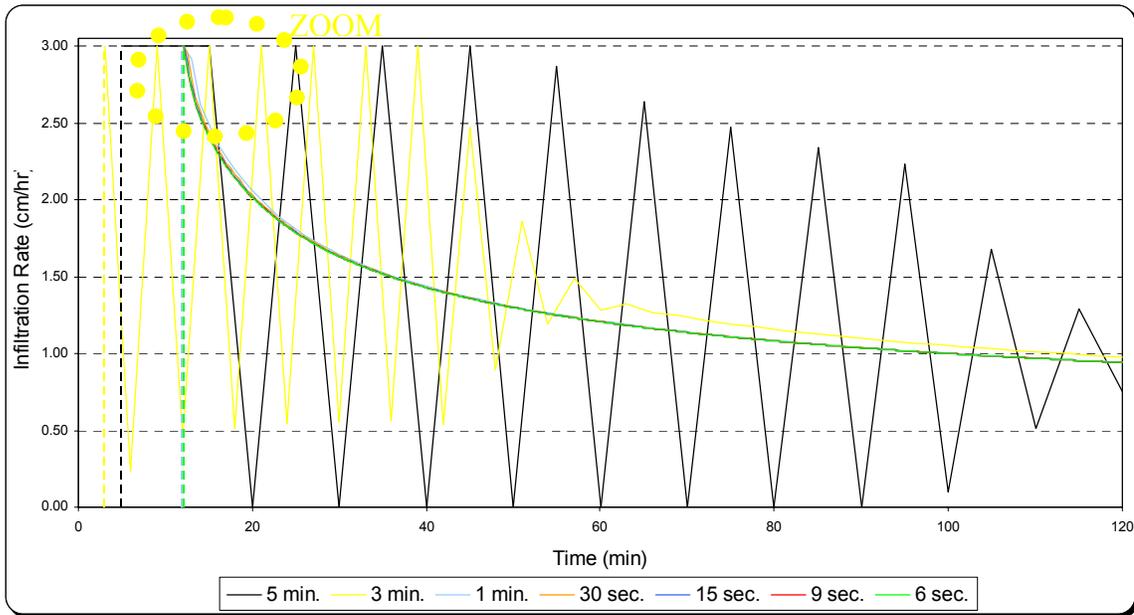


Figure 14 – Infiltration Rate Sensitivity to Time Step

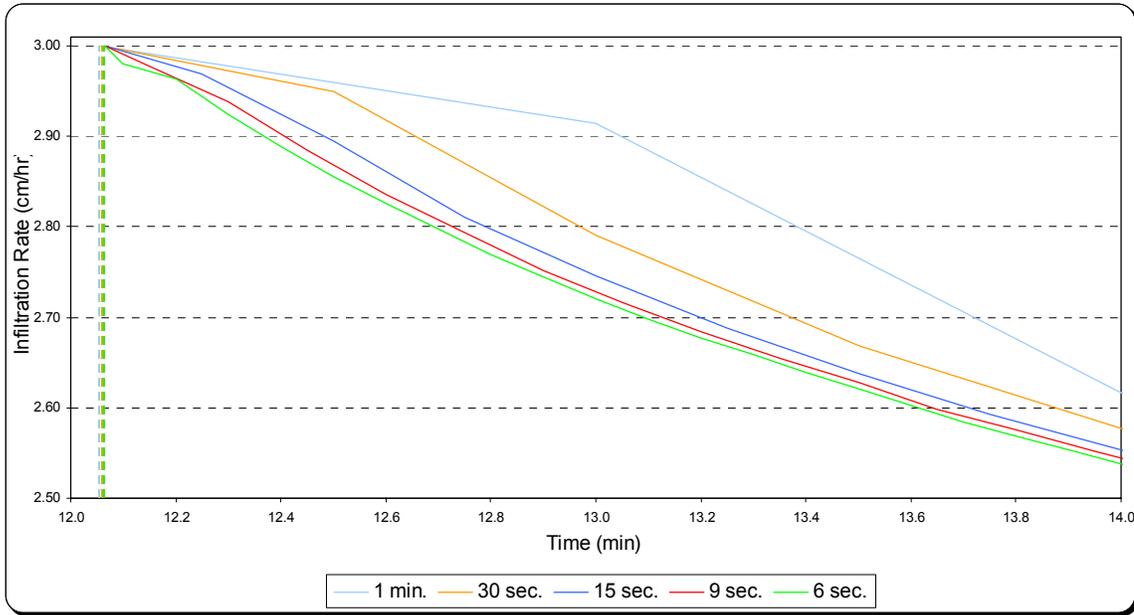


Figure 15 – Infiltration Rate Sensitivity to Time Step (Zoom)

Figures 12 and 13 above show that for $dt \leq 1 \text{ min}$, wetting front depth, i.e., cumulative infiltration, is not affected by time step. Figures 14 and 15 above, in addition to Table 4 below, reflect sensitivity of ponding time and infiltration rate to time step: for $dt \leq 1 \text{ min}$., convergence is reached and curves are smooth. In contrast, Figures 10 and 11 above show that air pressure and infiltration rate are more sensitive to time step than other parameters. Therefore, the smaller the time step, the shorter the oscillation period and amplitude. These oscillations are in part due to the finite difference approach and in part can be considered as physically justifiable. In fact, air mass flux, which is inversely proportional to wetting front depth, is large at the beginning of the event when wetting front is not deep enough to reduce air flux.

Table 4 - Ponding Time Sensitivity to Time Step (MODGA)

Time Step	5 min.	3 min.	1 min.	30 sec.	15 sec.	9 sec.	6 sec.
Ponding Time (min)	5	3	12.06	12.06	12.06	12.07	12.07

To minimize numerical errors finer time steps are needed. Oscillations occur before ponding, thus variable time steps can be used. Before ponding the model will run for a time step equal to 1/60 of the time step after it. For the rest of the simulations in this study, the model is run for a time step of 15 sec., the calculations before ponding are done at a time step of 0.25 sec consequently.

Note: this dual time step is used to model infiltration while accounting for air phase; for original Green and Ampt approach, only one time step will be used for the entire simulation.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Introduction

This chapter, containing the results of different simulations run using MODGA, is divided into six sections in addition to the introduction. First section contains a comparison between the results of three infiltration approaches: original Green and Ampt, a modified approach accounting for air compression but only, and MODGA. The five other sections underline MODGA's sensitivity to (1) depth to water table, (2) initial water content, (3) rainfall intensity, (4) saturated hydraulic conductivity, and (5) soil type.

3.2 Comparison of Three Infiltration Modeling Approaches

Three approaches are compared: original Green and Ampt model that neglects air effect on infiltration, a model accounting for air compression only, and the MODGA approach described in Chapter 2. Comparison including a description of air pressure trends, propagation of the wetting fronts (cumulative infiltration), effect on ponding times, and infiltration rates obtained from the three models. This comparison is conducted for shallow and deep water table environments (SWT/DWT).

3.2.1 Shallow Water Table Environment (SWT)

The comparison of three infiltration models will be conducted in a shallow water table environment ($D = 0.5\text{m}$). Other parameters are those used for reference simulation.

3.2.1.1 Modeling Air Pressure Ahead of the Wetting Front

For the original Green and Ampt approach, air in the porous medium is assumed to remain at atmospheric pressure. The figures below represent a comparison of the pressure build up in the porous medium in case counterflow is either neglected or accounted for. (For the reference simulation described above).

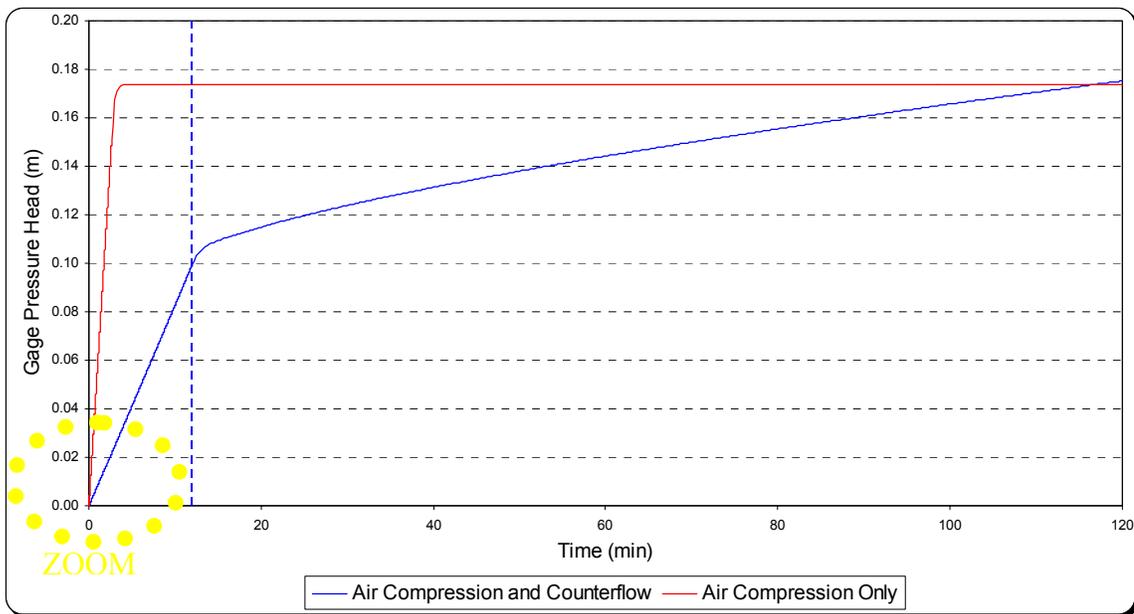


Figure 16 – Air Pressure Ahead of the Wetting Front (SWT)

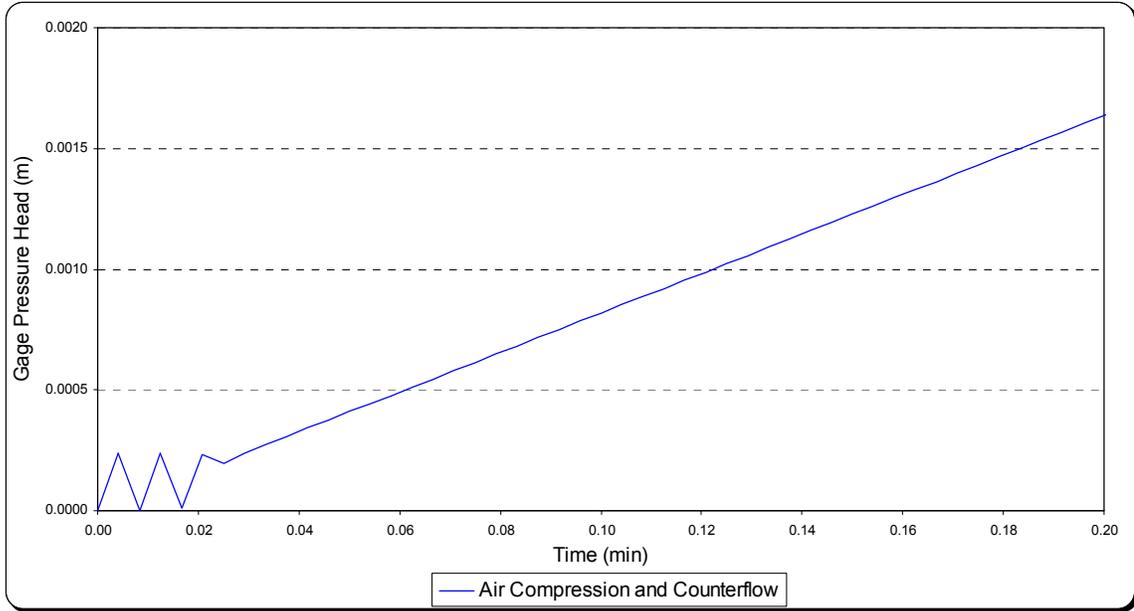


Figure 17 – Air Pressure Ahead of the Wetting Front (SWT) (Zoom)

The red curve in Figure 16 shows a rapid increase of pressure head in case counterflow of air is neglected, which results in an early and complete blockage of infiltration when soil is not yet saturated. In contrast, when counterflow is accounted for, pressure increases with a lower gradient allowing for soil to reach natural saturation before infiltration shuts-off completely (this will be discussed in details later in this chapter). The blue curve in Figure 16 can clearly be broken into two lines based on the slope: a high slope before ponding time (dashed blue line) and a milder slope after ponding. The high slope is a result of high infiltration rate before ponding: the more infiltration, the higher the air space decrease, thus the higher the pressure increase. Even though pressure builds up at a lower gradient when counterflow is accounted for, it can reach a value higher than that reached when air counterflow is neglected: the blue curve is higher than the red by end of storm event. Therefore, even though pressure is higher,

infiltration won't stop because the wetting front is deeper and thus requires a higher pressure to block its further downward movement. As discussed in Chapter 2, Figure 17 shows oscillations of pressure at the beginning of infiltration: for the first three seconds counterflow and air compression effects are of similar magnitude in that air pressure keeps going back to atmospheric pressure. Once the wetting front is deep enough to reduce the counterflow, a linear trend starts to be seen.

3.2.1.2 Modeling Wetting Front Depth and Cumulative Infiltration

The figures below represent wetting front depth and cumulative infiltration for the same physical parameters and storm event using three different modeling approaches.

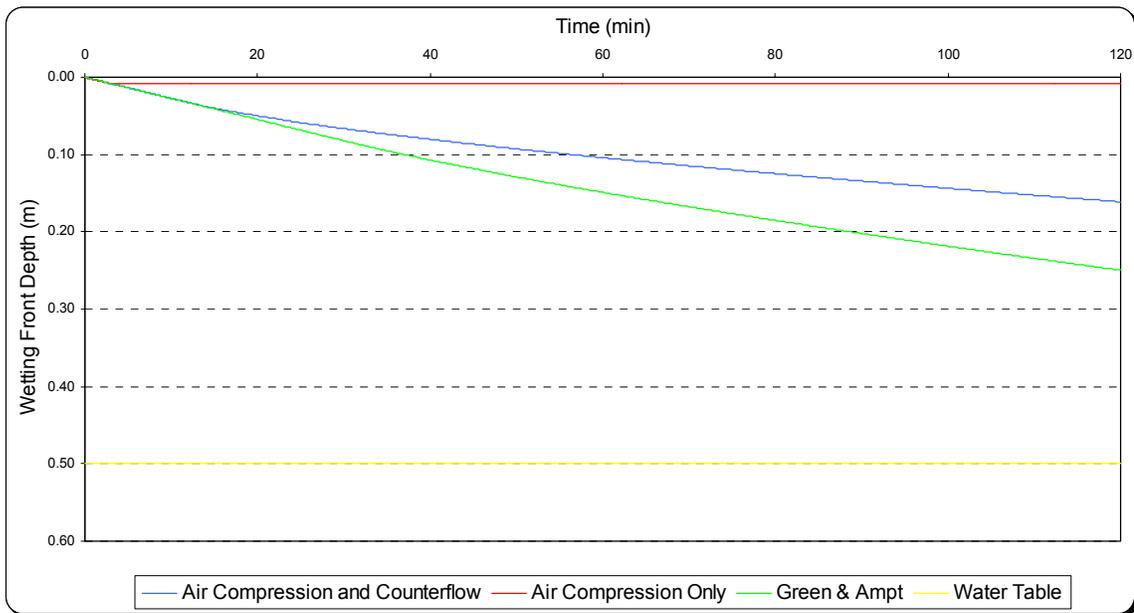


Figure 18 – Wetting Front Depth (SWT)

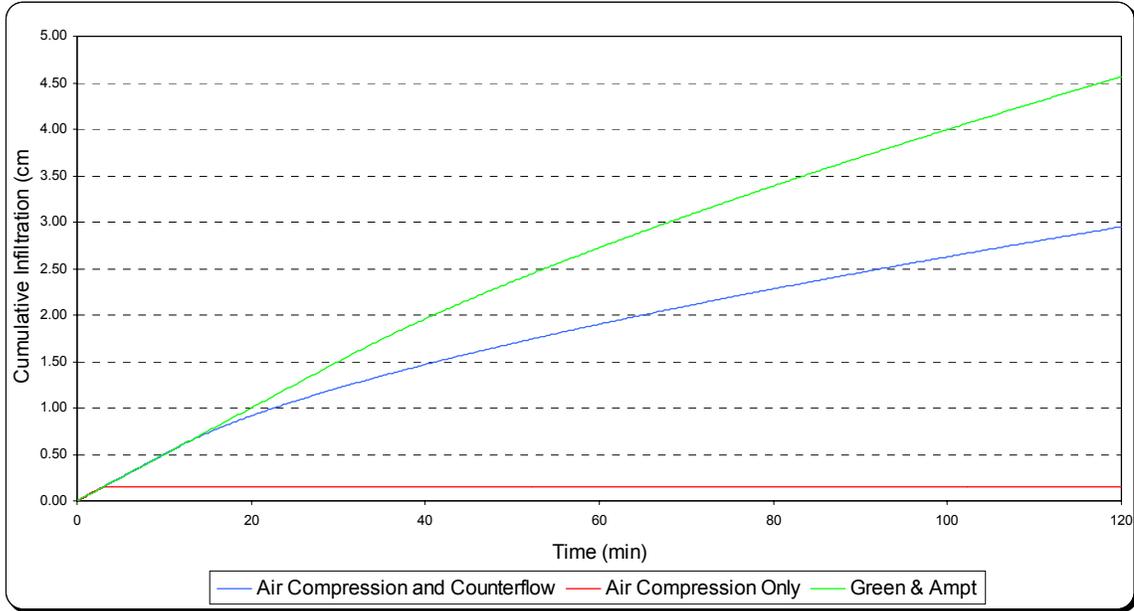


Figure 19 – Cumulative Infiltration (SWT)

As discussed previously, high pressure built up ahead of the wetting front if counterflow of air is neglected will shut off infiltration and results in an underestimation of amount of water infiltrated. On the other hand, using the original Green and Ampt approach results in an underestimation of runoff by overestimating infiltration. Accounting for both air compression and counterflow yields to different results of the infiltration process. Note that for a storm long enough soil will never reach natural saturation if air compression only is accounted for, while wetting front reaches the water table if air effect was neglected, or if both air compression and counterflow were accounted for. Saturation time comparison of the three models for the reference simulation is represented in Table 5 of the following section.

3.2.1.3 Modeling the Infiltration Rate

In this section the impact of air pressure on ponding time and infiltration rate will be discussed. As seen in Equation 10, the higher the air pressure the faster the ponding. For the reference simulation, ponding time is documented in Table 5 and Figure 20 below.

Table 5 – Air Effect on Ponding and Saturation Times (SWT)

	Air Compression & Counterflow	Air Compression Only	Green and Ampt
Ponding Time (min)	12.03	2.64	30.27
Saturation Time (min)	647	Infiltration stops after 4.75 min. without saturating the soil.	309

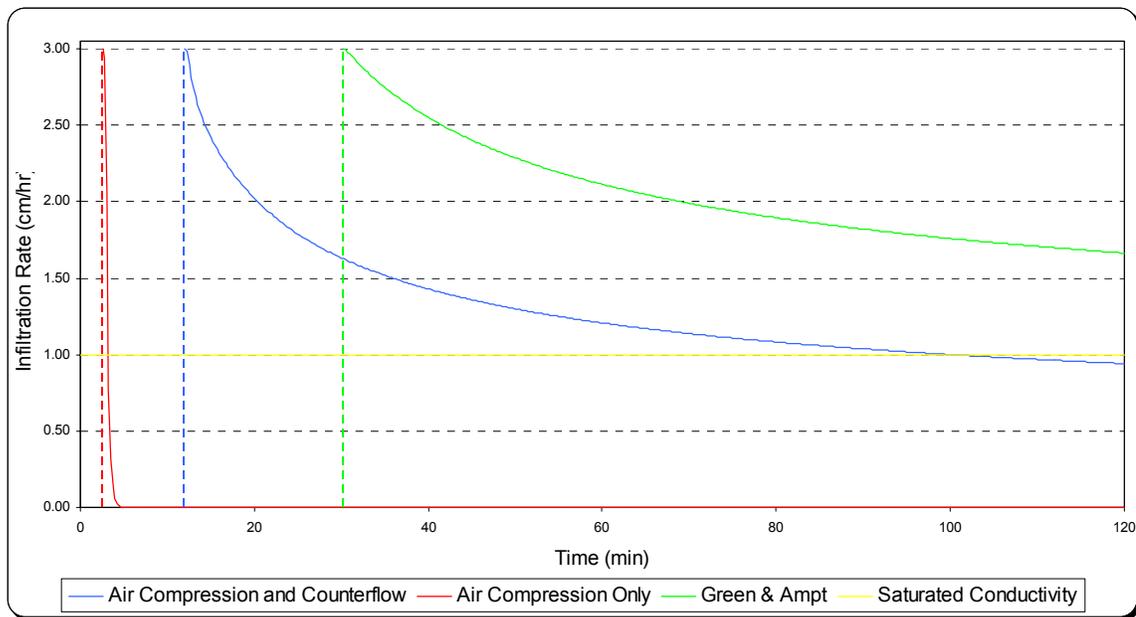


Figure 20 – Infiltration Rate Modeling (SWT)

After ponding, infiltration proceeds at capacity and infiltration capacity of soil at any point in time obtained from the MODGA approach is lower than that obtained from the Green and Ampt approach. Even though trends of infiltration rates of the two models are similar in the beginning, infiltration capacity drops below saturated hydraulic conductivity in the MODGA approach, while it approaches it asymptotically in the Green and Ampt. Figure 21 below represents infiltration rate directly before saturation: infiltration capacity of soil dropped below saturated hydraulic conductivity due to air and oscillations at the end were due to high pressure built up then the air release as seen in Figure 22.

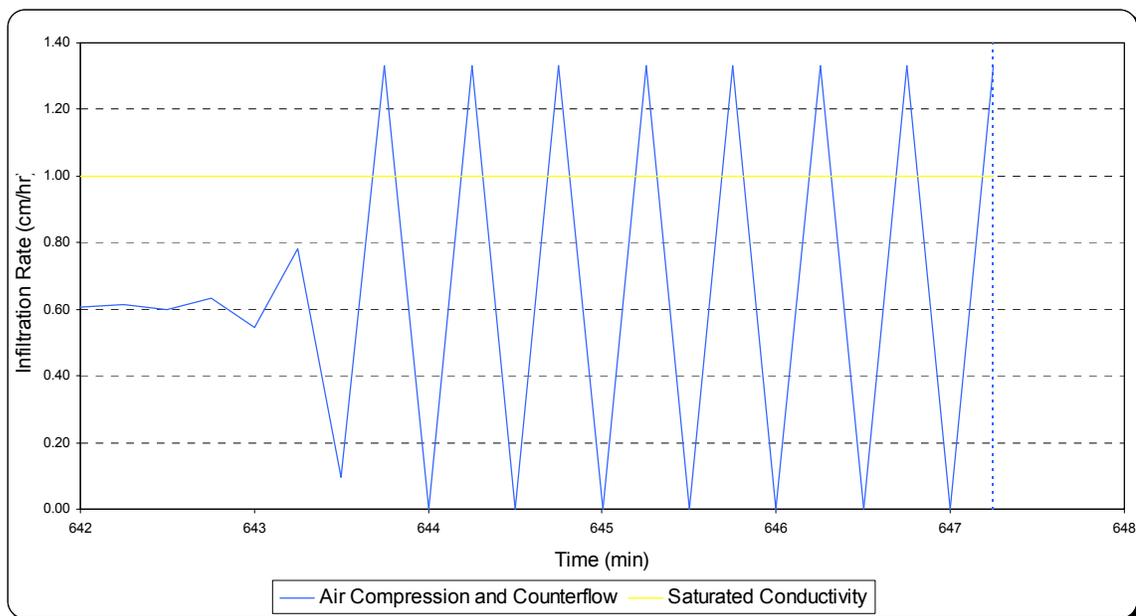


Figure 21 – Infiltration Capacity at Saturation

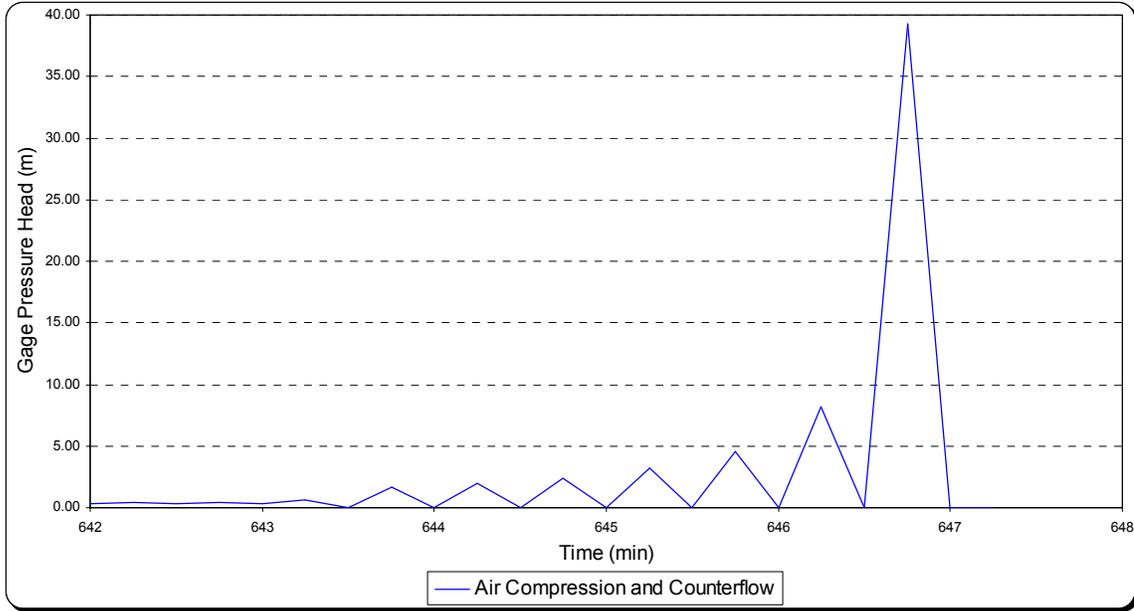


Figure 22 – Air Pressure at Saturation

3.2.2 Deep Water Table Environment (DWT)

Simulations above were repeated for environments with deep water table, (D=10m, and D=100m). Conclusions are the same regarding the general comparison of the three models. Oscillations of pressure associated with MODGA do not exist in these environments since pressure increases are slower due to large pore space available. Results for a deep water table environment are shown in Figures 23 to 26 below. It is clear that the deeper the water table, the more similar are the results which is physically correct since for deeper water table pore space is available: For a 100m deep water table, the three models give approximately the same results, substantial differences are not seen in the figures below, yet for a 10m deep water table, it is important to account for air phase in the infiltration model.

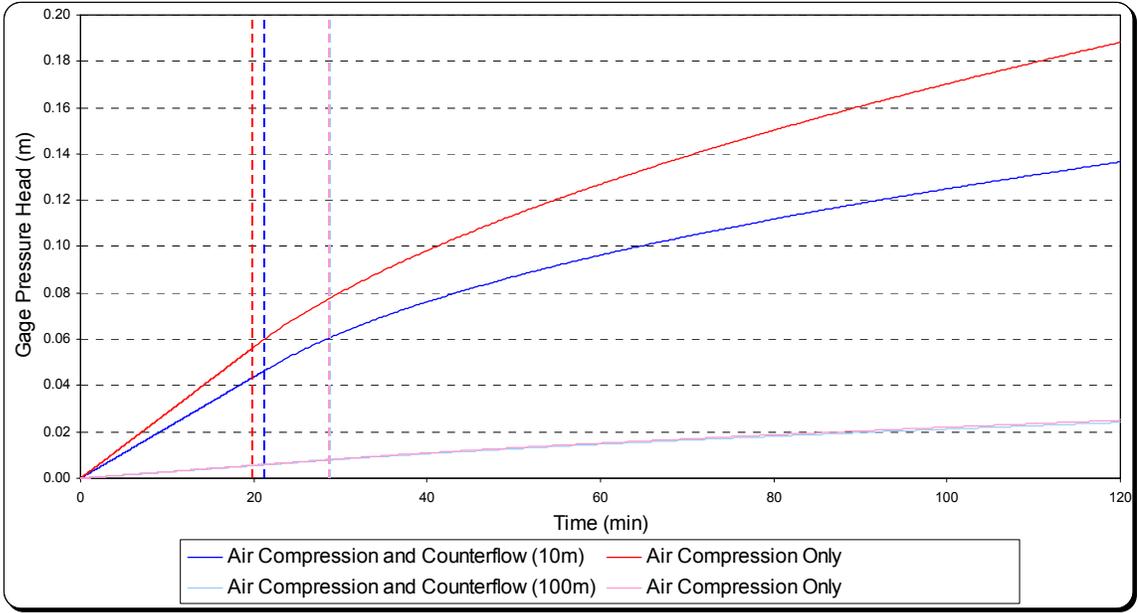


Figure 23 – Air Pressure Ahead of the Wetting Front (DWT)

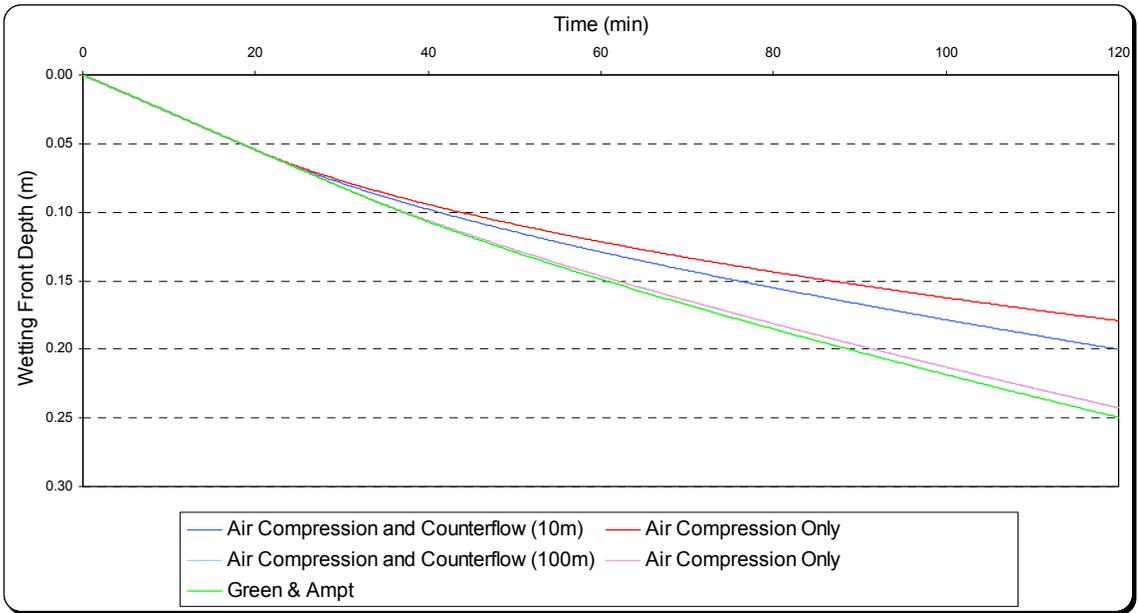


Figure 24 – Wetting Front Depth (DWT)

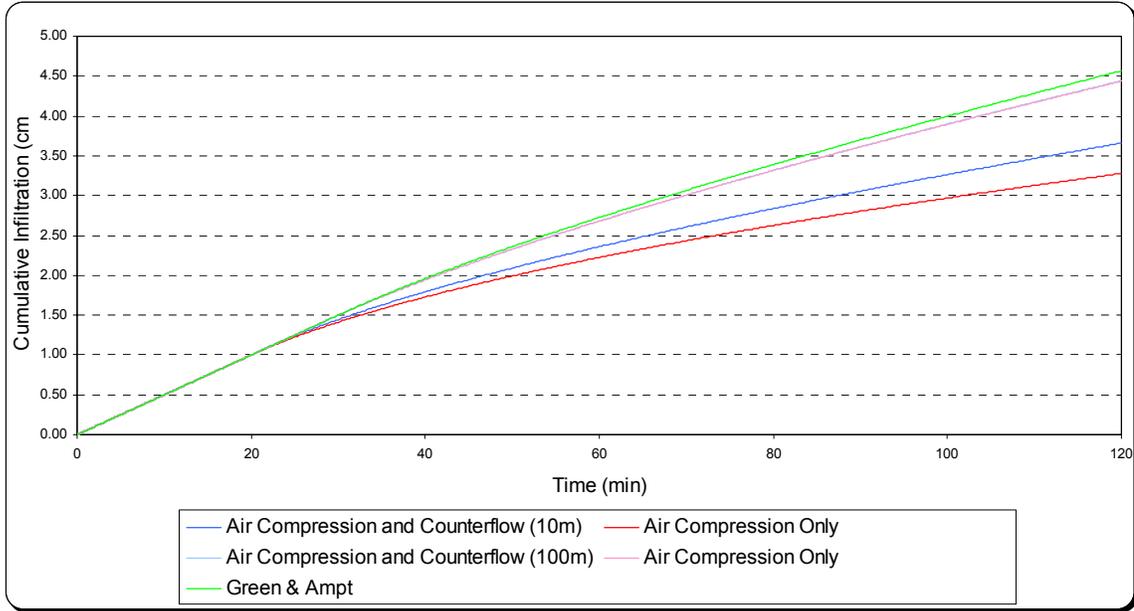


Figure 25 – Cumulative Infiltration (SWT)

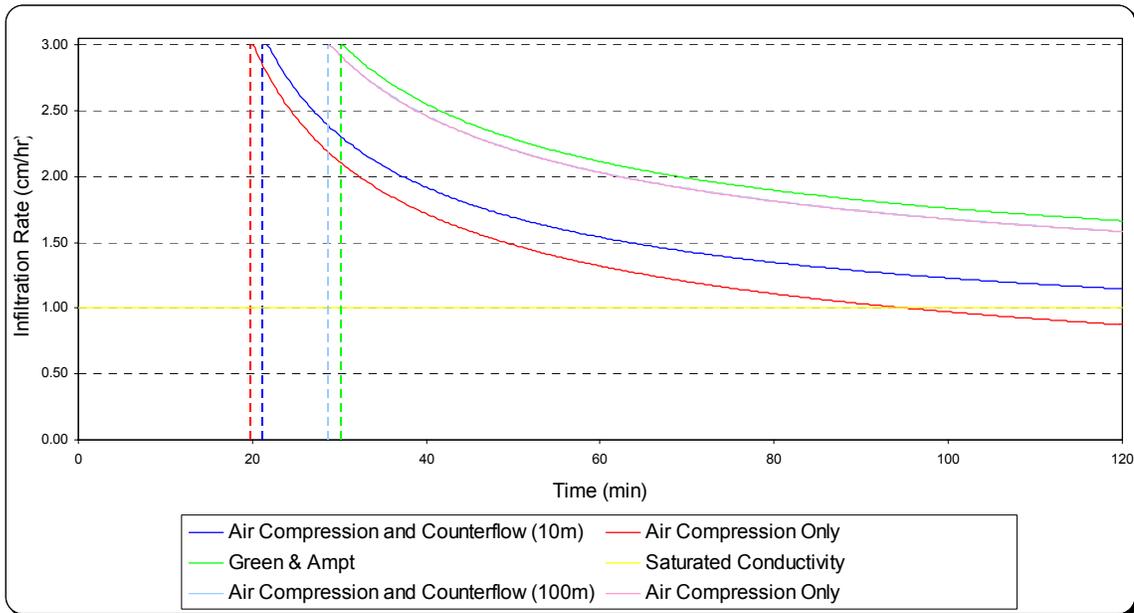


Figure 26 – Infiltration Rate Modeling (DWT)

In conclusion, accounting for both air compression and counterflow improves infiltration modeling: even for a water table as deep as 10m, the differences between the three models were substantial (for a relatively high initial uniform soil moisture content, $\theta_i = \theta_{-33\text{KPa}}$). High sensitivity of the model to time step, as well as oscillations of air pressure at the beginning of the rainfall event make it essential to minimize time steps for decoupling both effects. The remaining part of this chapter includes impacts of depth to water table, initial soil moisture content, rainfall intensity, and soil type on MODGA.

3.3 Impact of Depth-to-Water Table

In addition to the reference simulation, MODGA was run for a depth-to-water table of 1, 3, 10 and 100m to assess the impact of water table depth on infiltration. Since all parameters of the reference simulation are kept the same, differences in results reflect the impact water table depth. Figures 27 to 30 and Table 6 show that the deeper the water table the less the air effect on infiltration. Yet, as seen in section 3.2.2 above, air affects the infiltration for a water table as deep as 10 meters (under same soil moisture conditions).

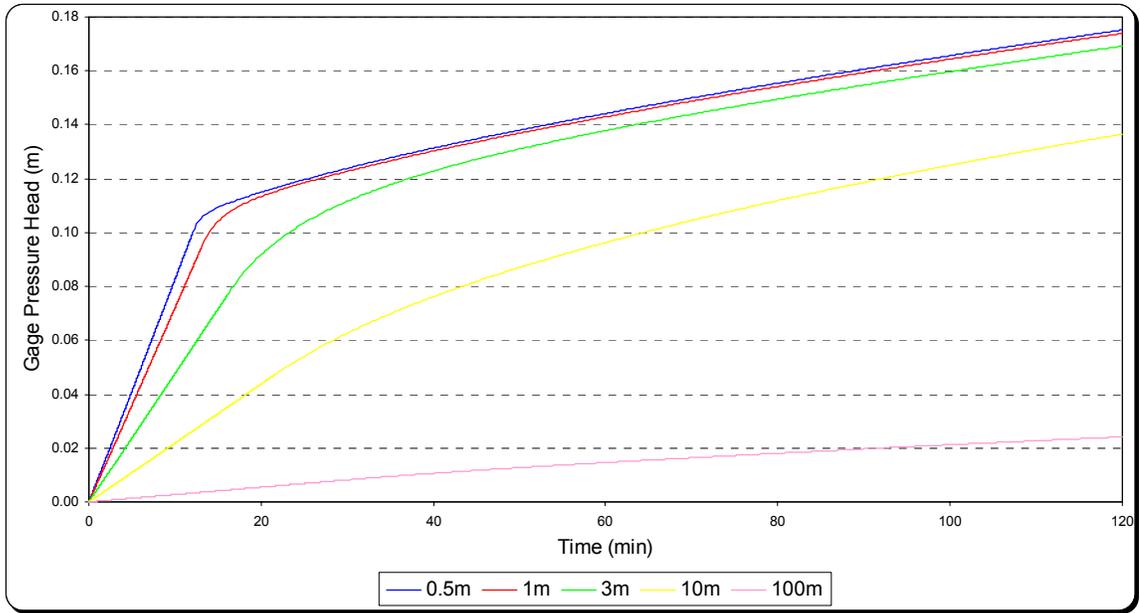


Figure 27 – Impact of Depth-to-Water Table on Air Pressure

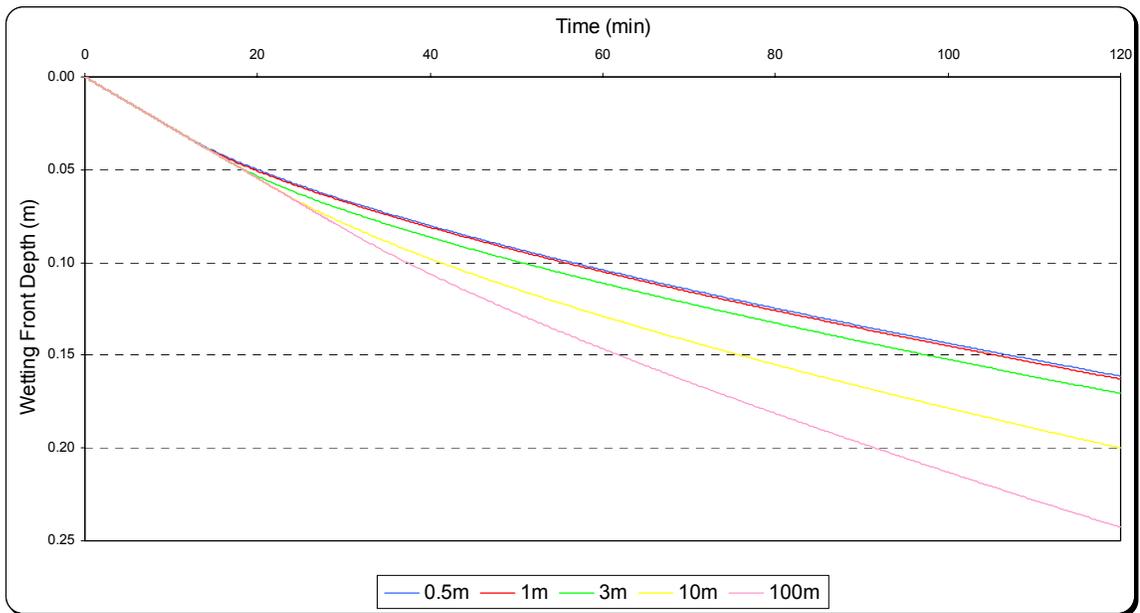


Figure 28 – Impact of Depth-to-Water Table on Wetting Front

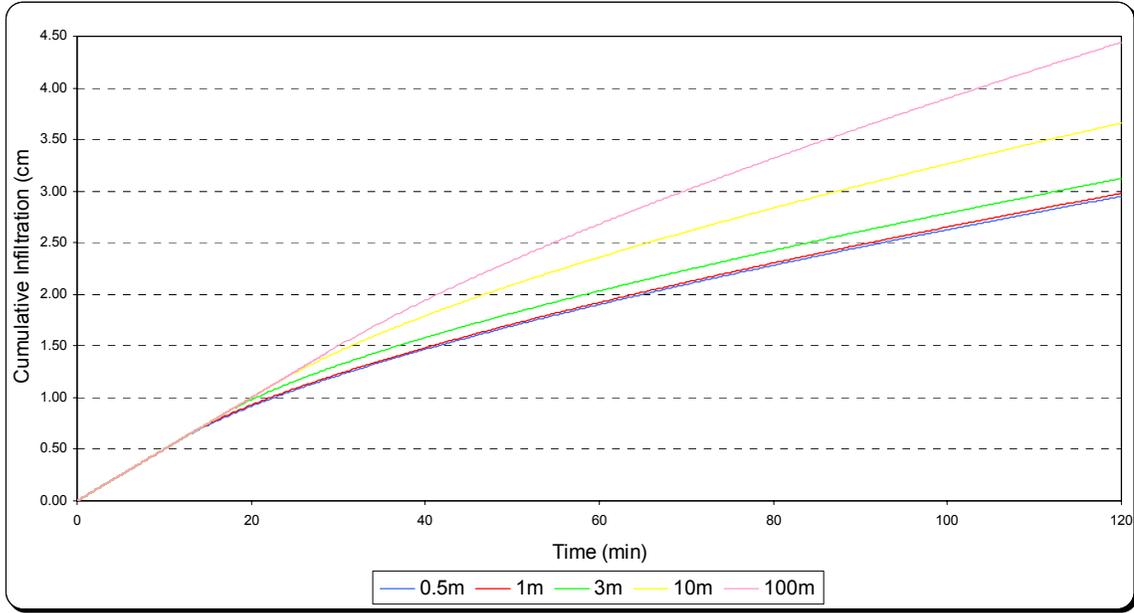


Figure 29 – Impact of Depth-to-Water Table on Cumulative Infiltration

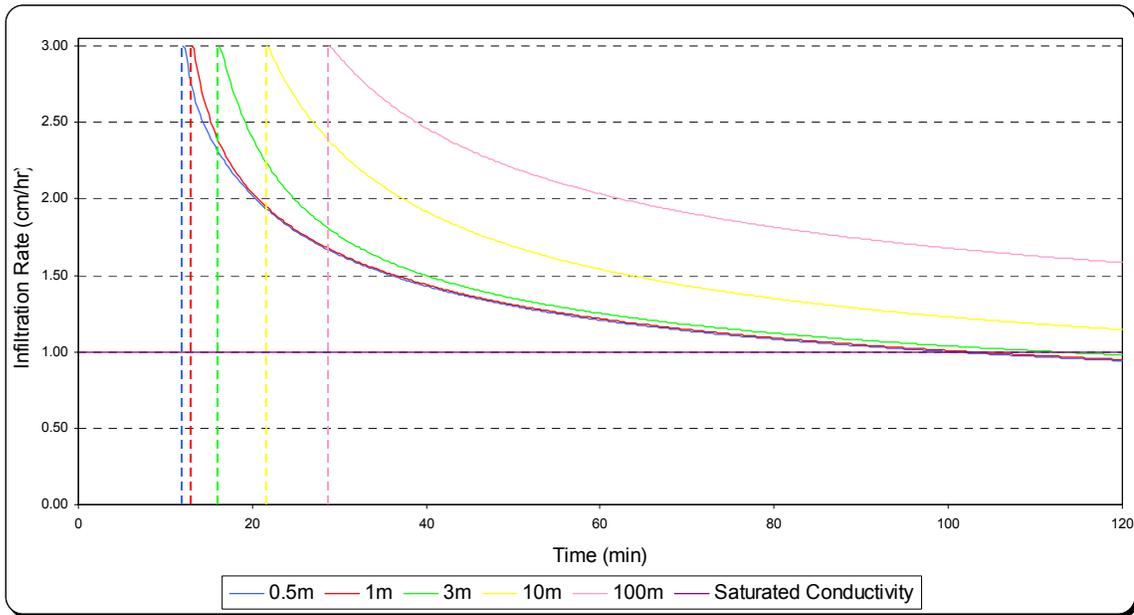


Figure 30 – Impact of Depth-to-Water Table on Cumulative Infiltration Rate

Table 6 – Impact of Depth-to-Water Table on Ponding Time

D (m)	0.5	1	3	10	100
T _p (min)	12.03	13.03	16.14	21.62	28.83

Results above show sensitivity of infiltration to depth-to-water table in the MODGA model. Clearly, in shallower water table ponding occurs earlier and more runoff is generated: infiltration capacity is reduced and the air pressure gradient is higher. For deeper water table, more water infiltrates into the soil. For very deep water tables (D=100m), air pressure is of no great influence and the regular Green and Ampt approach can be used as described in the previous section (air pressure less than 3cm after 2 hours of a 3cm/hr storm).

3.4 Impact of Initial Soil Moisture Content

A major factor known to affect infiltration is antecedent soil moisture content. A wet soil absorbs less water than a dry one. The effect of initial soil moisture content on infiltration using MODGA is represented below: results include a comparison between different soil moisture contents ($\theta_i = \theta_r = 0.065$ (dry), $\theta_i = 0.15$, $\theta_i = 0.30$ in addition to the reference simulation). Also, a simulation is run showing the case where soil is almost saturated before a storm.

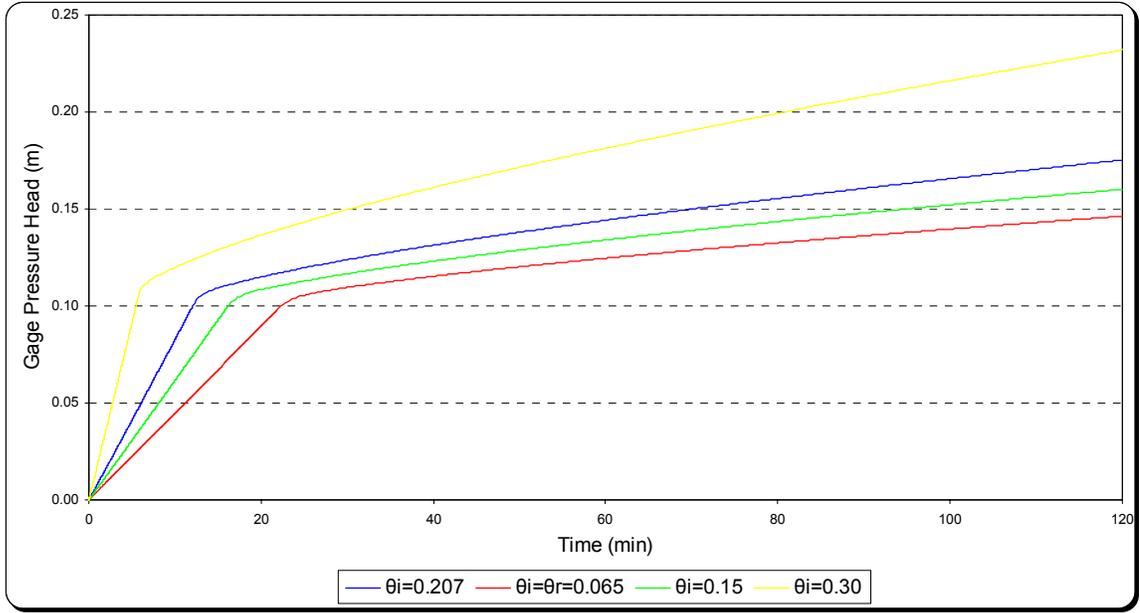


Figure 31 – Impact of Initial Soil Moisture Content on Air Pressure

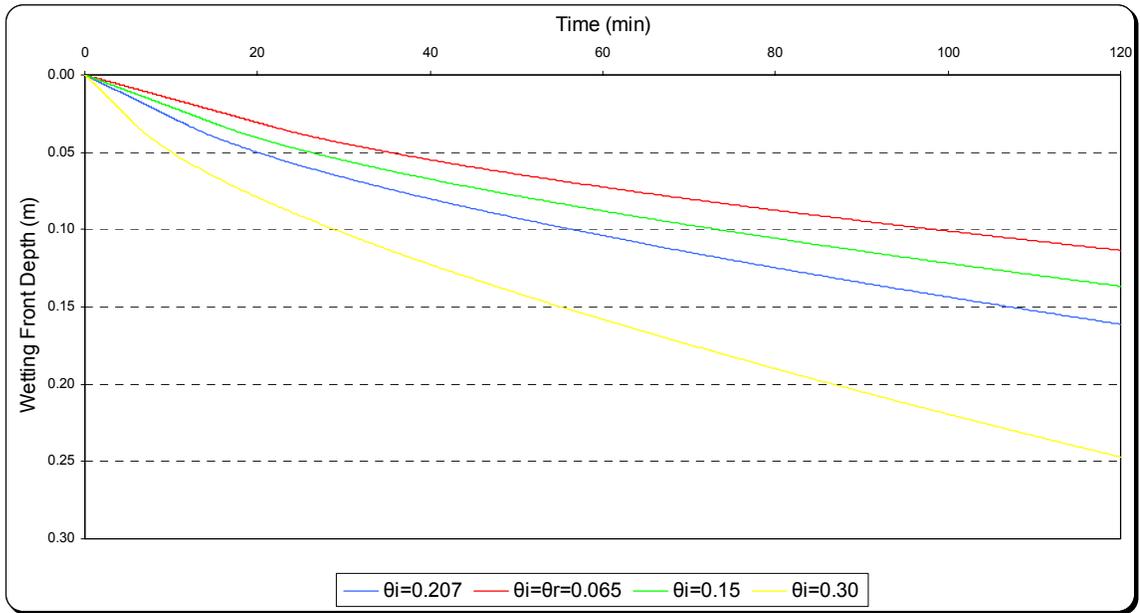


Figure 32 – Impact of Initial Water Content on Wetting Front

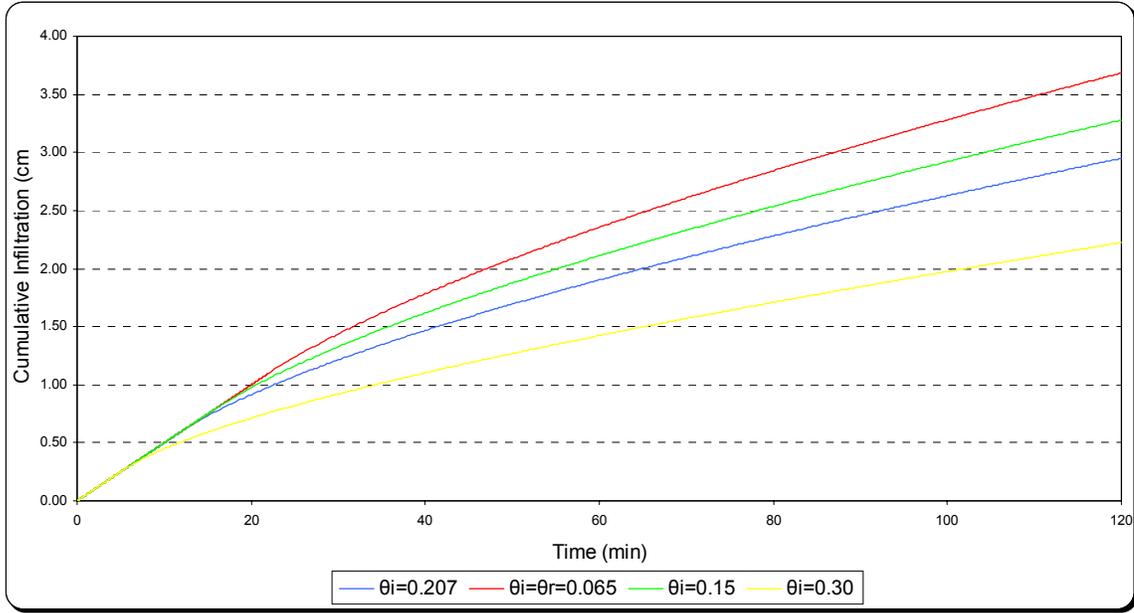


Figure 33 – Impact of Initial Water Content on Cumulative Infiltration

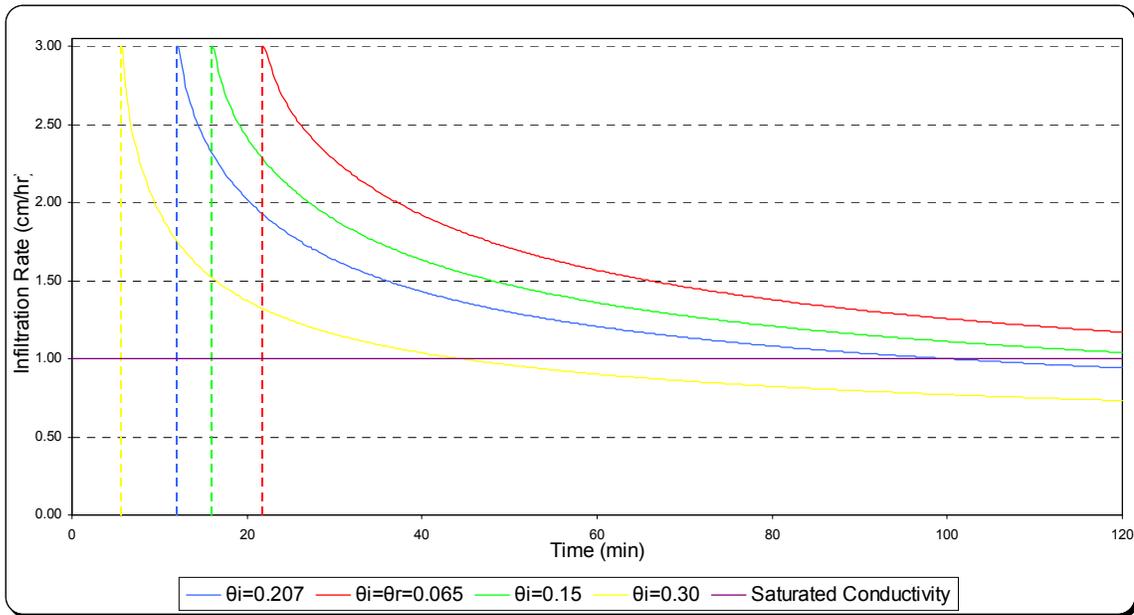


Figure 34 – Impact of Initial Water Content on Infiltration Rate

Table 7 – Impact of Initial Water Content on Ponding Time

θ_i	0.065	0.15	0.207	0.30
T_p (min)	21.85	15.97	12.03	5.63

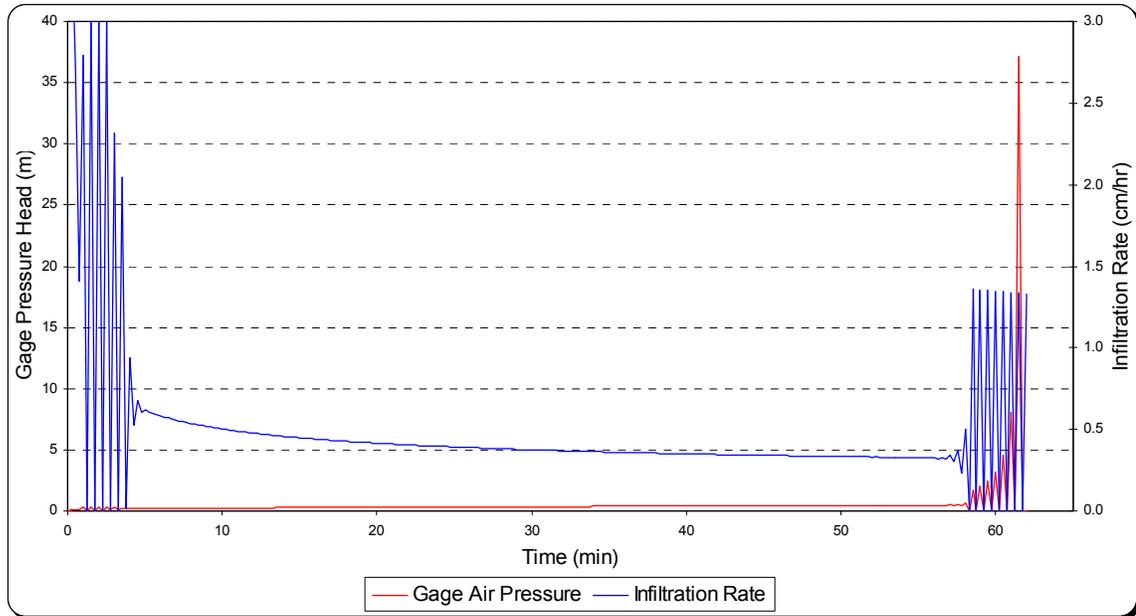


Figure 35 – Infiltration when Soil is Near Saturation

Figure 31 above shows that the dryer the soil, the lower the air pressure. In fact, for a dry soil, pore space is larger and as pressure is inversely proportional to volume the result is physically correct. For wet soils, gradient of air pressure is higher since the same amount of infiltration results in a deeper wetting front depth, i.e., higher reduction in air volume (Figure 32). Figure 33 shows that a dryer soil absorbs more water than a wet one for a same storm event (~2.2cm vs. ~3.7cm). Ponding time and infiltration capacity sensitivity to initial soil moisture content are represented in Figure 34 and Table 7 above: infiltration rate is higher for a dry soil and it takes more time to reach ponding. The case

where soil is nearly saturated ($\theta_i=0.38\sim\theta_s$) is represented in Figure 35 above: oscillations in air pressure are due the small air volume available, which causes abrupt increases in pressure and thus higher counterflow.

3.5 Impact of Rainfall Intensity

As the source of infiltration is rainfall, checking the rainfall intensity effect on infiltration and air pressure is intuitive: Figures 36 to 39 below show this effect, and Table 8 shows variation of ponding time with rainfall intensity.

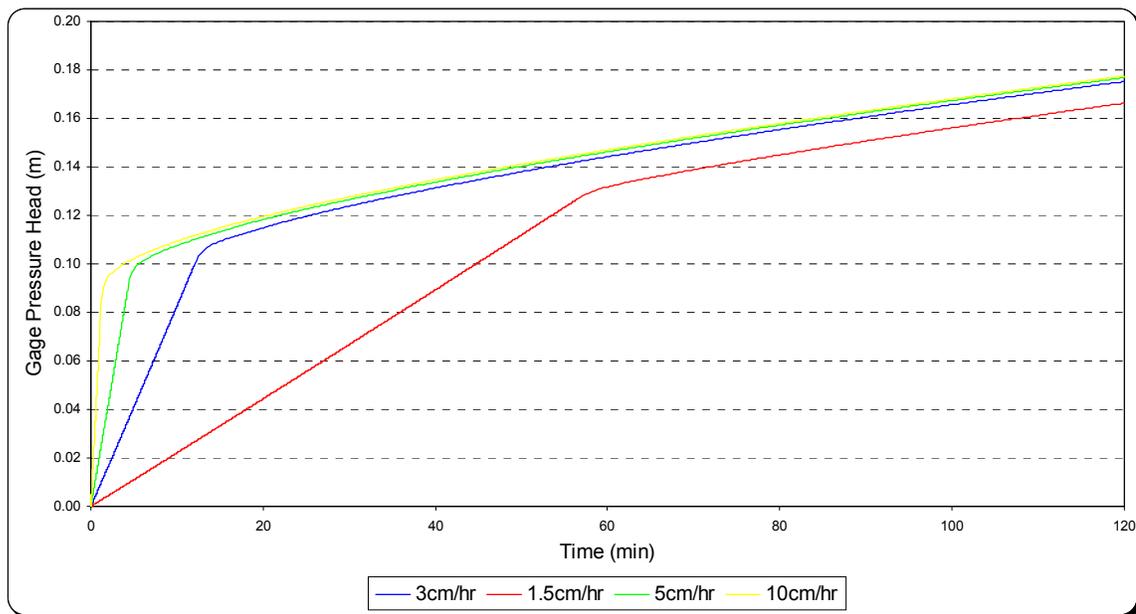


Figure 36 – Impact of Rainfall Intensity on Air Pressure

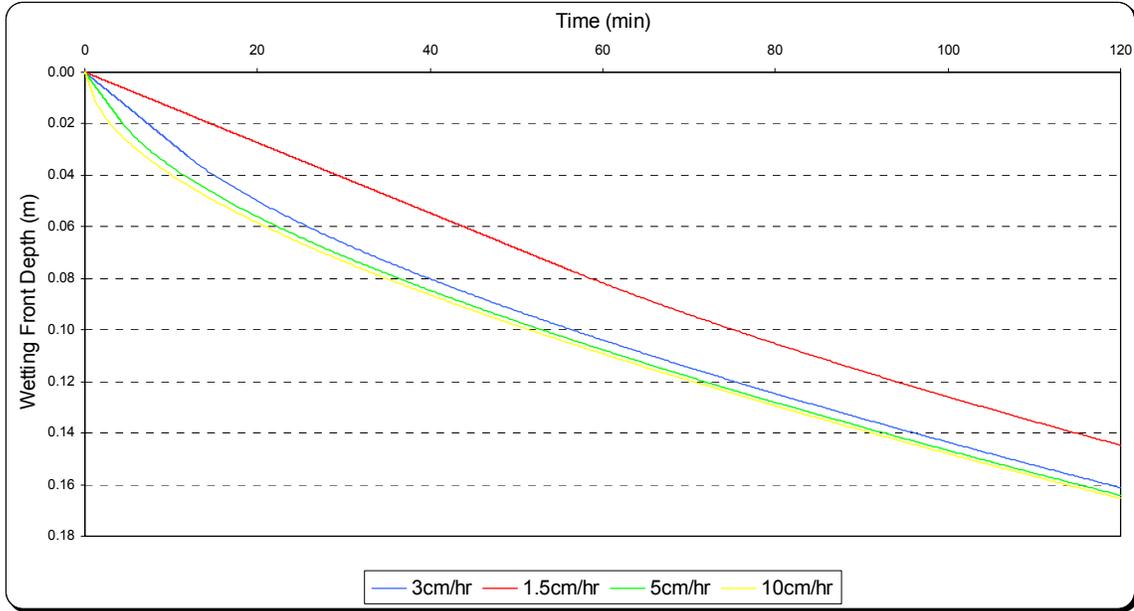


Figure 37 – Impact of Rainfall Intensity on Wetting Front

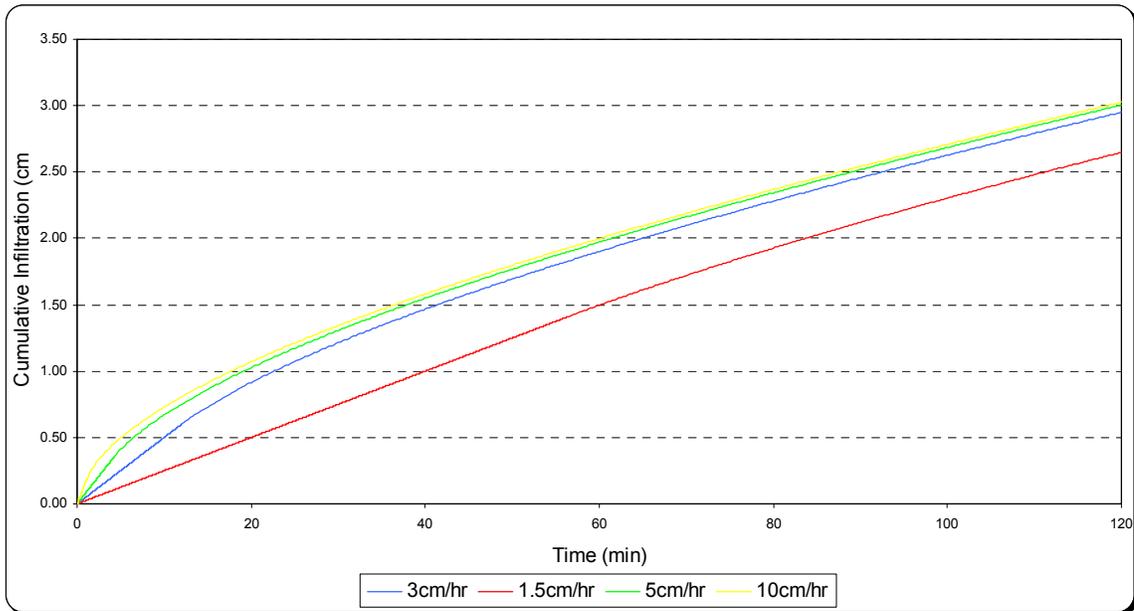


Figure 38 – Impact of Rainfall Intensity on Cumulative Infiltration

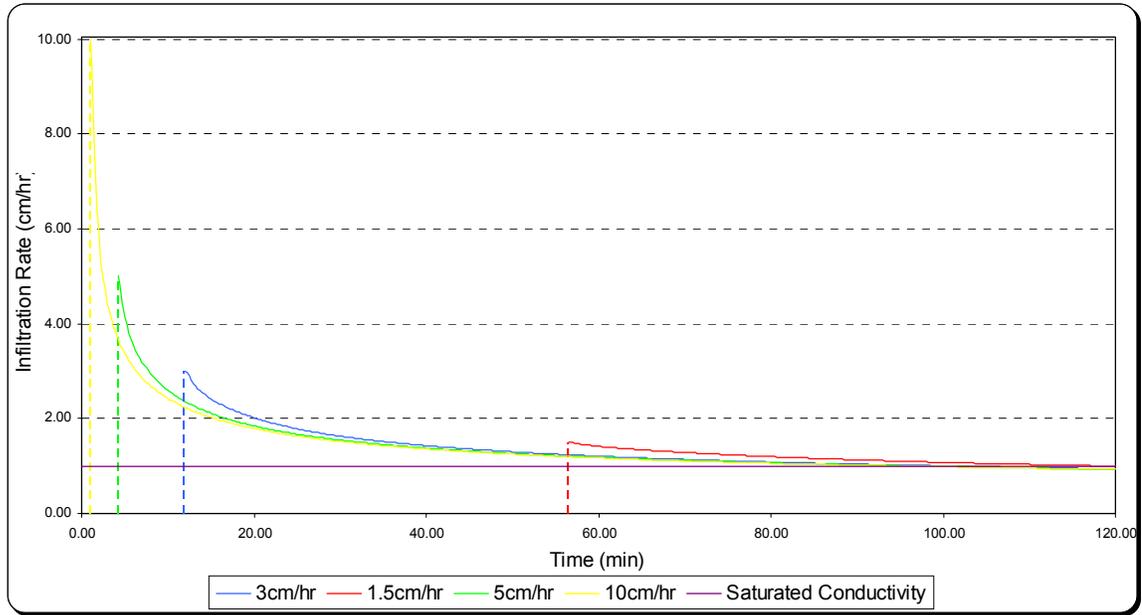


Figure 39 – Impact Rainfall Intensity on Infiltration Rate

Table 8 – Impact of Rainfall Intensity on Ponding Time

I (cm/hr)	1.5	3	5	10
T_p (min)	56.51	12.03	4.23	1.1

Figure 36 shows that air pressure is highly dependant on rainfall rate before ponding. This is attributed to the fact that before ponding all the rain infiltrates and thus air compression is a function of rainfall intensity, while after ponding infiltration proceeds at soil’s capacity and a higher rainfall intensity yields to a higher runoff but infiltration is not affected. This explains why after ponding air pressure curves are close regardless of rainfall intensity. The greatest effect of rainfall intensity is on ponding time as it can be seen in the results above. After ponding infiltration capacity curves are also

similar. Of course, for low rainfall intensity (1.5cm/hr) the propagation of wetting front is slow, which allows for a larger counterflow and thus air pressure reduction.

3.6 Impact of Saturated Hydraulic Conductivity

Soil conductivity is of critical importance as it directly affects infiltration and counterflow. Thus, the necessity to study the model's sensitivity to this parameter, especially since the values used for conductivities can vary by more than an order of magnitude. Figures 40 to 43 and Table 9 below are the results obtained after running the model for $K_s = 0.5, 0.8, 1.2, 1.5,$ and 2.0cm/hr .

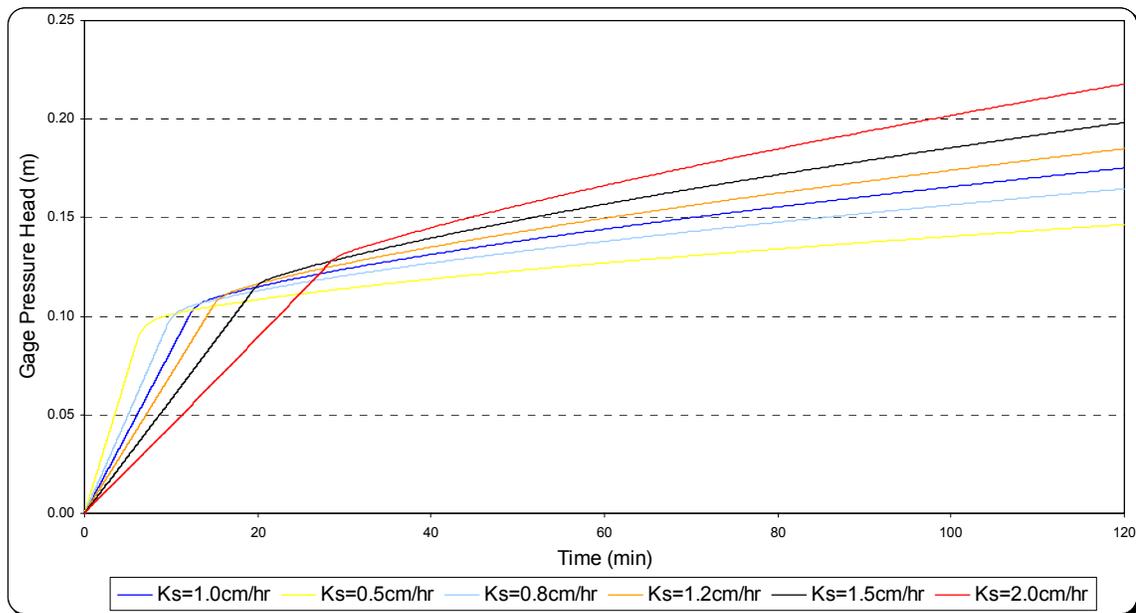


Figure 40 – Impact of Saturated Hydraulic Conductivity on Air Pressure

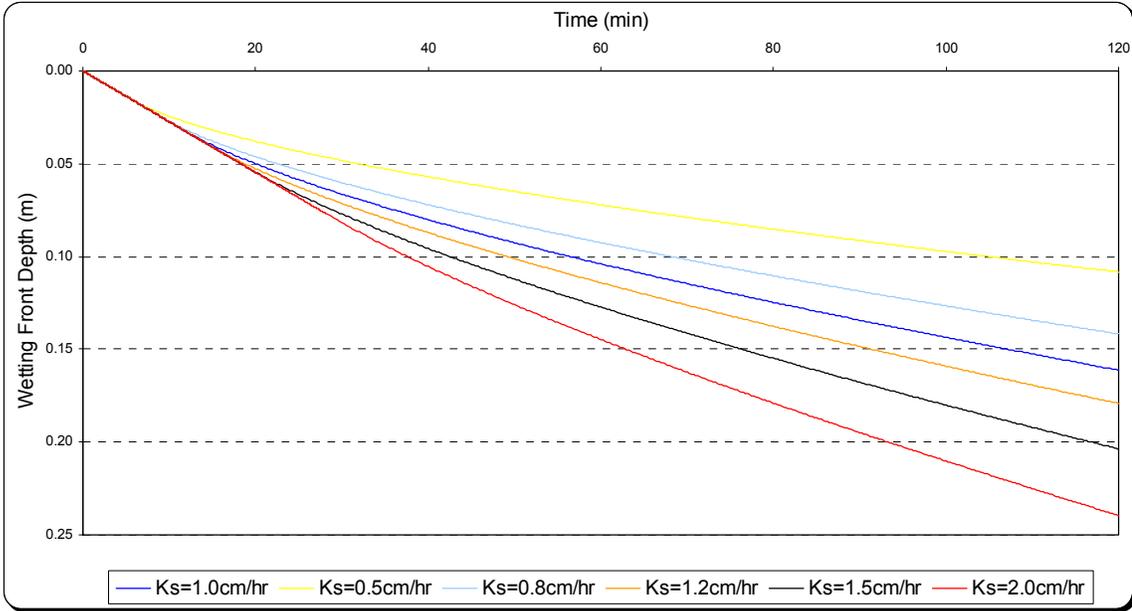


Figure 41 – Impact of Saturated Hydraulic Conductivity on Wetting Front

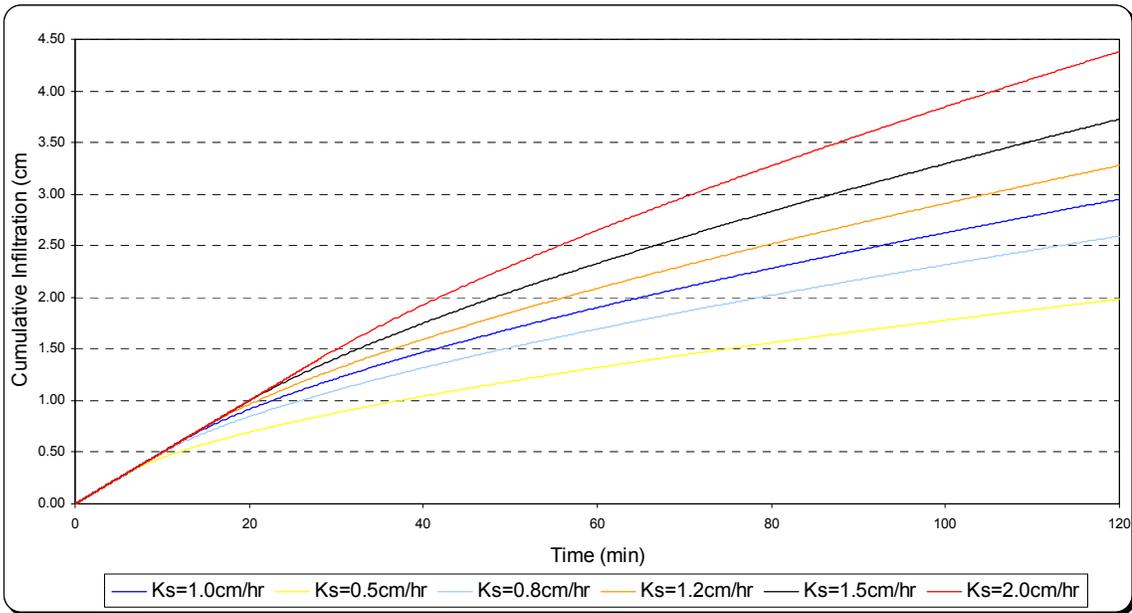


Figure 42 – Impact of Saturated Hydraulic Conductivity on Cumulative Infiltration

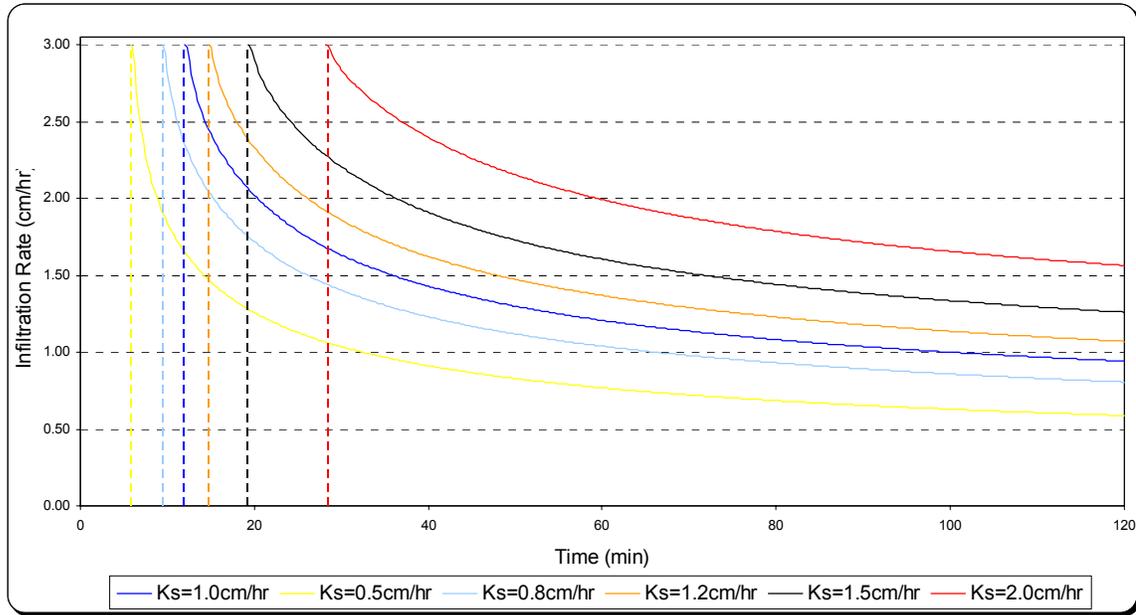


Figure 43 – Impact of Saturated Hydraulic Conductivity on Infiltration Rate

Table 9 – Impact of Saturated Hydraulic Conductivity on Ponding Time

K_s (cm/hr)	0.5	0.8	1.0	1.2	1.5	2.0
T_p (min)	5.89	9.45	12.03	14.79	19.35	28.26

Figure 40 shows the effect of saturated hydraulic conductivity, i.e., intrinsic permeability, on air compression. Air pressure behavior can be divided into two categories: before and after ponding time. Before ponding, at any point of time, the higher the hydraulic conductivity the lower the air pressure. In fact, for any time we have similar amount of infiltration thus same air volume change. But a higher intrinsic permeability (proportional to hydraulic conductivity) yields to a higher counterflow, which explains the lower air pressure for a higher conductivity before ponding. After ponding, conductivity has an opposite effect: the higher the saturated conductivity, the

higher the air pressure. In fact, a higher conductivity means more infiltration is allowed into the soil. Of course, counterflow is still higher also, but since counterflow proceeds at a low relative permeability, the effect of infiltration is of greater importance. This effect can also be seen in Figures 41 to 43, which show that a higher infiltration (cumulative infiltration and infiltration capacity) is associated with a higher conductivity.

3.7 Impact of Soil Type

A rainfall rate of 3cm/hr and a 0.5m depth-to-water table are maintained during the simulations while all soil properties are changed (Table 10). All soils are considered dry for this set of simulations. Three soil types will be compared: Sandy Loam, Loam, and Clay Loam. Table 10 below includes the soils' physical properties. Results are shown in Figures 44 to 47 and Table 11 below.

Table 10 – Parameters Used for the Impact of Soil Type Simulation

Soil type	n	θ_s	θ_r	θ_i	K_s (cm/hr)	H_b (m)	H_c (m)	k_{ra}	λ
Sandy Loam	0.41	0.39	0.065	0.065	2.18	0.13	0.165	0.017	0.89
Loam	0.43	0.40	0.078	0.078	1.32	0.28	0.384	0.028	0.56
Clay Loam	0.41	0.39	0.095	0.095	0.20	0.53	0.805	0.012	0.31

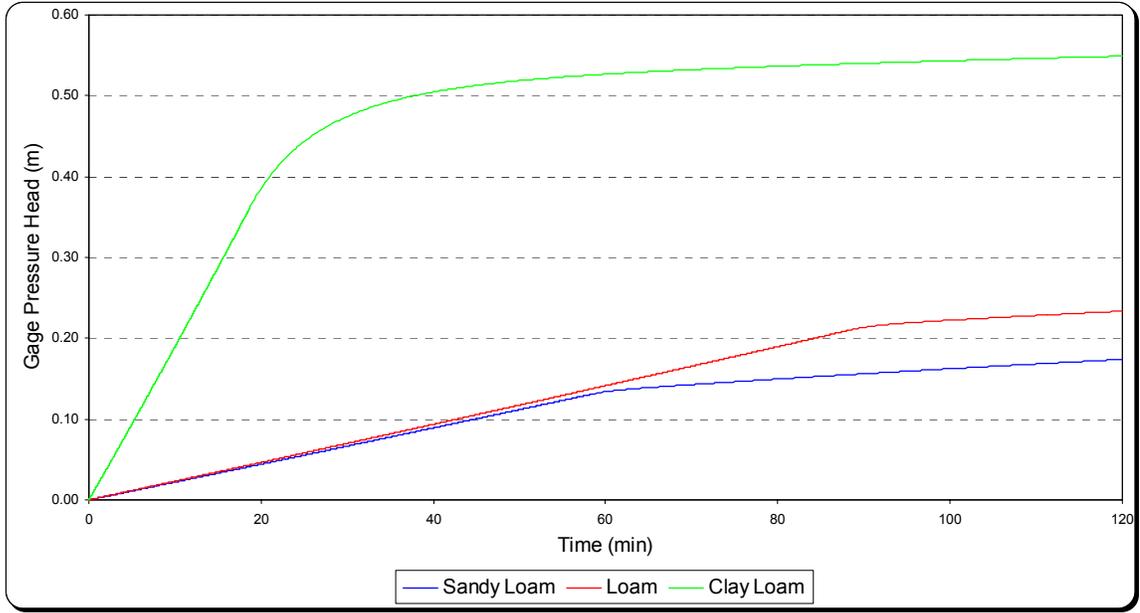


Figure 44 – Impact of Soil Type on Air Pressure

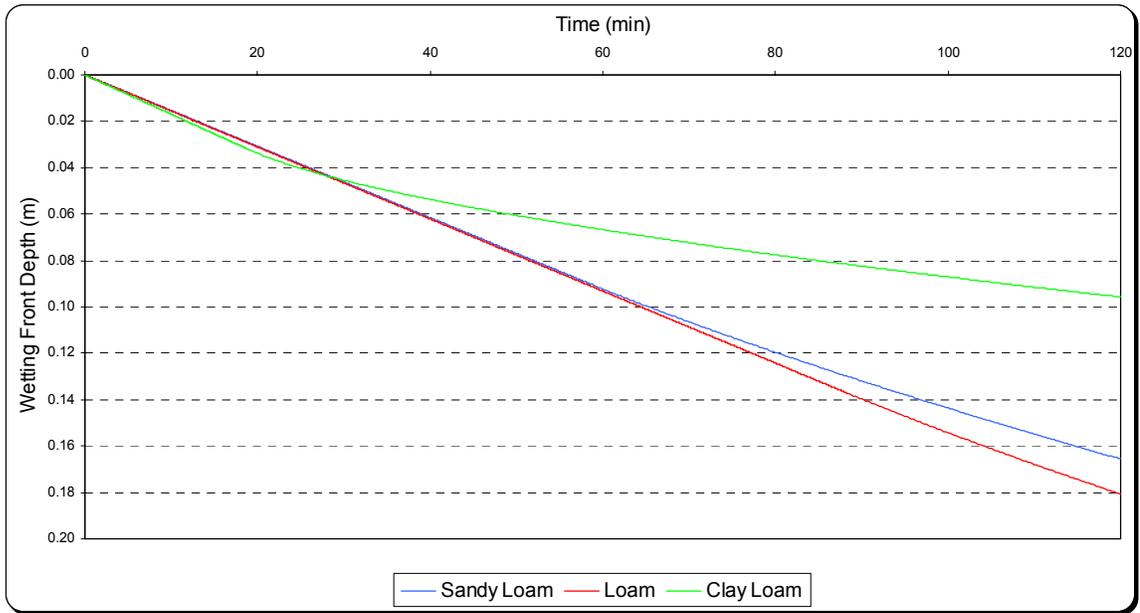


Figure 45 – Impact of Soil Type on Wetting Front

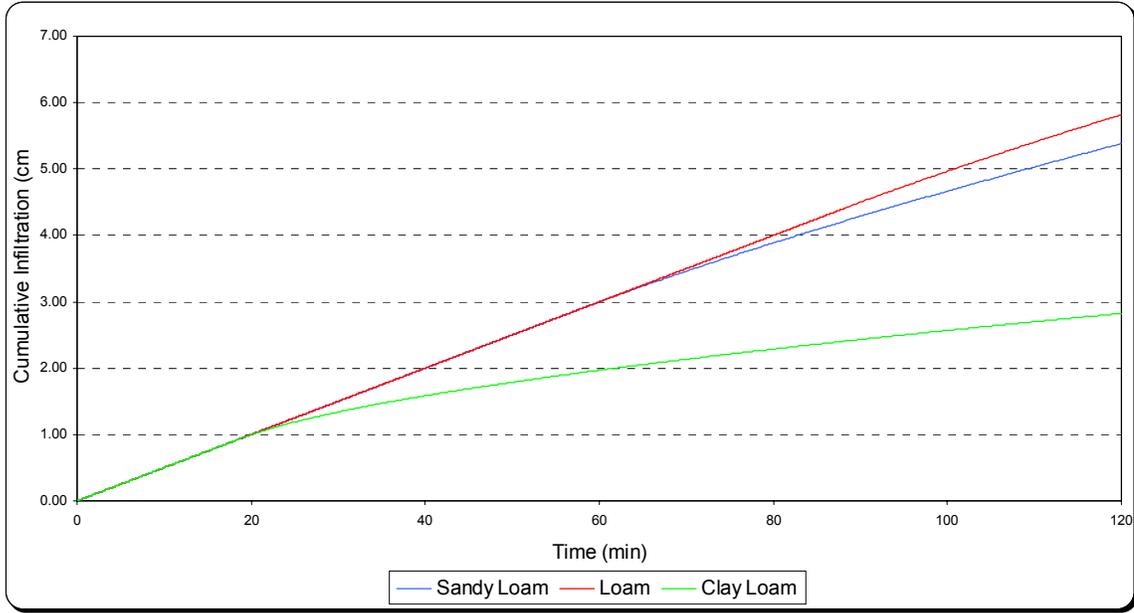


Figure 46 – Impact of Soil Type on Cumulative Infiltration

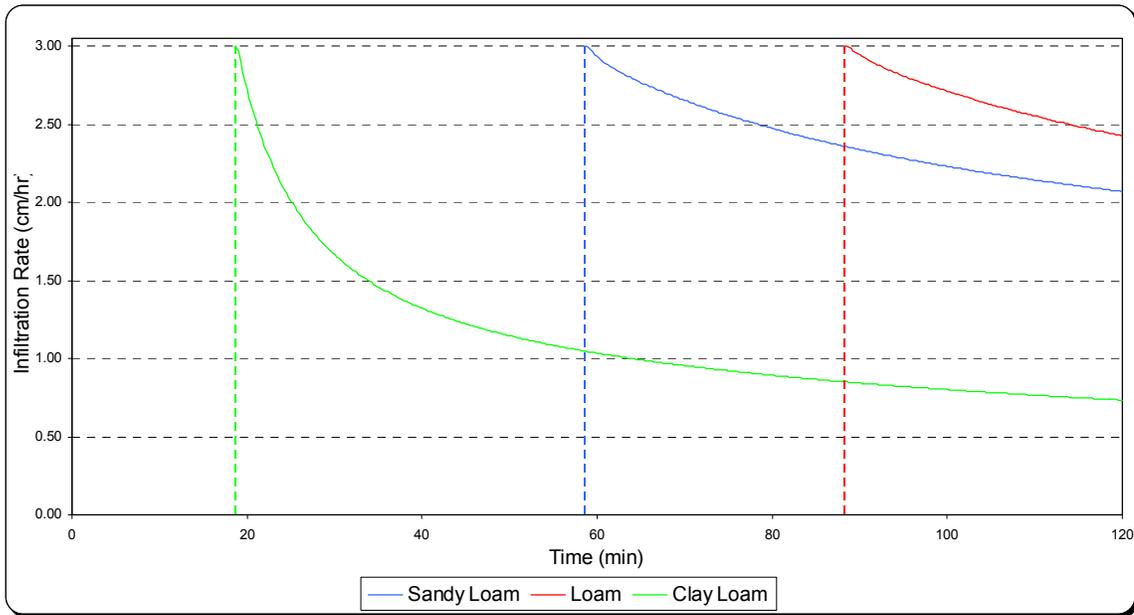


Figure 47 – Impact of Soil Type on Infiltration Rate

Table 11 – Impact of Soil Type on Ponding Time

Soil Type	Sandy Loam	Loam	Clay Loam
T _p (min)	58.65	88.29	18.68

Results obtained in this section are in fact a combination of several physical parameters at a time. First, results here underline the combined effect of conductivity and relative permeability: in fact, Figure 44 shows that air pressure for Sandy Loam (S.L) and Loam (L.) are comparable even though we have large differences in hydraulic conductivity; while air pressure for Clay Loam (C.L.) is higher. This can be interpreted by looking at the combined value of conductivity and relative permeability of air: $(K_s \cdot k_{ra})_{(S.L.)} \approx (K_s \cdot k_{ra})_{(L.)} \approx 0.037 > (K_s \cdot k_{ra})_{(C.L.)} = 0.0024$ – the higher the ratio, the higher the counterflow, and the lower the air pressure. Of course, the amount of available pore space is an influencing factor too, but in this case we almost have similar initial air volumes.

Even though saturated hydraulic conductivity of Sandy Loam is almost twice that of Loam, total infiltration into Loam is the highest. This can be explained by ponding occurring later for Loam resulting in a lower infiltration into Sandy Loam between for the duration between the two ponding times. As for the ponding time difference, it's a combination of K_s , H_c and H_a that resulted in having an earlier ponding for Sandy Loam: air pressure is almost the same for both soils, and the higher hydraulic conductivity results in a later ponding but a lower suction head results in an earlier ponding.

CHAPTER 4: CONCLUSION

4.1 Comparison of Three Infiltration Approaches

An objective of this study is to underline the effect of air on infiltration using a simple model. For this, the original Green and Ampt model that does not account for air phase was compared to two other models: one accounting for air compression only, and one accounting for air compression and counterflow (MODGA). To account for air effect, only one term was added to the Green and Ampt model: air pressure in the porous medium. For the air compression only model, air pressure was calculated using Boyle's law, considering that air mass remains the same during the infiltration process (counterflow = 0), whereas for MODGA counterflow was accounted for using Equation 16 to calculate the mass flux of air and the perfect gas law to find air pressure.

First, the models were compared for shallow water table environments (0.5m). If counterflow is neglected, air pressure builds up quickly in soil to a point where infiltration is shut-off without saturating the soil. As for the Green and Ampt model, ponding occurs later and infiltration rate decreases with time reaching saturated hydraulic conductivity asymptotically. Whereas for the MODGA approach, ponding occurs earlier than Green and Ampt ponding time yet not as dramatically as for air compression only, and infiltration rate drops below saturated hydraulic conductivity. Like in the original Green and Ampt model, the soil reaches natural saturation, but it takes a longer time for

that since the infiltration rate is overestimated in the regular Green and Ampt model. For deep water table environments, two cases were explored: $D = 10\text{m}$, and 100m . Results showed that the air effect on infiltration is substantial for water tables as deep as 10m . While for $D = 100\text{m}$, we can simply use the Green and Ampt approach and the minor air effect on infiltration can be neglected. Therefore, for areas where the water table is very deep, using a model that accounts for the air phase is contra-indicated, while it is essential in environments with shallow impervious layers.

4.2 MODGA Sensitivity to Different Parameters

Remainder of the results derived in this research represents sensitivity of MODGA to different parameters. First, for deeper water tables, infiltration, i.e., infiltration capacity, increases because of reduction in air pressure. Initial soil moisture content is of significance on infiltration as well: a dryer soil absorbs more water and the dryer the soil the larger the air volume and the less the air compression. For general applications, a more practical step is to lump these two parameters into a single dimensionless parameter, space volume over water table depth, especially if the model is modified to account for variable initial soil moisture with depth. This can be the subject for future research. On the other hand, the rainfall rate's effect is almost restricted to ponding time only. While soil conductivity has a major effect, since it influences both infiltration and counterflow: a higher hydraulic conductivity results in a higher counterflow, which explains the slower pressure build up before ponding. After ponding the soil conductivity limits infiltration and the higher the conductivity, the more infiltration and air compression. Also, a dimensionless parameter to lump rainfall rate and

soil's conductivity can be the subject of further research. Dimensionless analysis, i.e., lumping different parameters together, might result in the possibility of defining a sharp threshold on whether to account to air or not. Finally, three simulations with three different soils were run to see a combined effect of all soil's parameters: air bubbling pressure also has a major role on infiltration, as well as the relative permeability of the air pore size index.

REFERENCES

- Bouwer, H., (1966). "Rapid Field Measurements of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis." *Water Resources Research*, 2, 729-738.
- Bras, R., (1990). "Flow in Unsaturated Porous Media and Infiltration." *Hydrology: An Introduction to Hydrologic Cycle*, Addison-Wesley Publishing Company, 349-393.
- Charbeneau, R., (2000). *Groundwater Hydraulics and Pollutant Transport*, Prentice-Hall inc., 18-90.
- Chow, V., Maidment, D., Mays, L. (1988). "Subsurface Water." *Applied Hydrology*, McGraw-Hill inc., 99-126.
- Constantz, J., Herkelrath, W., and Murphy, F. (1988). "Air Encapsulation During Infiltration." *Soil Science Society of America Journal*, 52(1), 10-16.
- Culligan, P., Barry, D., Parlange, J., Steenhuis, T., and Haverkamp, R. (2000). "Infiltration with Controlled Air Escape." *Water Resources Research*, 36(3), 781-785.
- Dunne, T. (1983). "Relation of Field Studies and Modeling in the Prediction of Storm Runoff." *Journal of Hydrology*, 65(1-3), 25-48.
- Faybishenko, B. (1995). "Hydraulic Behavior of Quasi-Saturated Soils in Presence of Entrapped Air: Laboratory Experiments." *Water Resources Research*, 31(10), 2421-1435.
- Fayer, M., and Hillel, D. (1986a). "Air Encapsulation: I. Measurement in a Field Soil." *Soil Science Society of America Journal*, 50, 568-572.
- Fayer, M., and Hillel, D. (1986b). "Air Encapsulation: II. Profile Water Storage and Shallow Water Table Fluctuations." *Soil Science Society of America Journal*, 50, 572-577.
- Freeze, R., and Cherry, J. (2000). "Groundwater and the Hydrologic Cycle." *Groundwater*, Prentice-Hall inc., 192-236.

- Freeze, R., (1980). "A Stochastic Conceptual Analysis of Rainfall-Runoff Process on a Hillslope." *Water Resources Research*, 16(2), 395.
- Hillel, D., (1998). "Entry of water into soil." *Environmental Soil Physics*, Academic Press, 385-426.
- Hillel, D., and Gardner, W. (1970). "Transient Infiltration into Crust-Topped Profiles." *Soil Science*, 109(2), 69-76.
- Horton, R. (1939). "Analysis of Runoff Plot Experiments with Varying Infiltration Capacity." *Transactions, American Geophysical Union*, Part IV, 693-711.
- Loague, K., and Abrams, R. (2001). "Stochastic-Conceptual Analysis of Near-Surface Hydrological Response." *Hydrological Processes*, 15(14), 2715-2728.
- Morel-Seytoux, H., and Khanji, J. (1974). "Derivation of an Equation of Infiltration." *Water Resources Research*, 10(4), 795-800.
- Morel-Seytoux, H., and Khanji, J. (1975). "Equation of Infiltration with Compression and Counterflow Effect." *Hydrological Science Bulletin*, 20(4), 505-517.
- Nachabe, M., and Illangasekare, T. (1994). "Use of Tension Infiltrometer Data with Unsaturated Hydraulic Conductivity Models." *Ground Water*, 32(6), 1017-1021.
- Touma, J., Vachaud, G., and Parlange, J.-Y. (1984). "Air and Water Flow in a Sealed, Pondered Vertical Soil Column: Experiment and Model." *Soil Science*, 137(3), 181-187.
- Vachaud, G., Gaudet, J.P., and Kuraz, V. (1974). "Air and Water Flow During Pondered Infiltration in a Vertical Bounded Column of Soil." *Journal of Hydrology*, 22, 89-108.
- Vomacka, J., Thompson, D., Ross, M., Nachabe, M., and Tara, P. (2002). "Measurement of Surficial Aquifer Recharge, ET, Rainfall, Runoff and Stream-Aquifer Interaction Characteristics of the Central and Southern Region of the Southwest Florida Water Management District." *A Field Project Providing Hydrologic Data Collection and Analysis*. Center for Modeling Hydrologic and Aquatic Systems. Department of Civil and Environmental Engineering. University of South Florida.
- Wang, Z., Feyen, J., Nielsen, D., and van Genuchten, M. (1997). "Two-phase Flow Infiltration equations accounting for air entrapment effects." *Water Resources Research*, 33(12), 2759-2767.
- Wang, Z., Feyen, J., van Genuchten, M., and Nielson, D. (1998). "Air Entrapment Effects on Infiltration Rate and Flow Instability." *Water Resources Research*, 34(2), 213-222.

- Wangemann, S., Kohl, R., and Molumeli, P. (2000). "Infiltration and Percolation Influenced by Antecedent Soil Water Content and Air Entrapment." *Transactions of the American Society of Agricultural Engineers*, 43(6), 1517-1523.
- Wilson, B., Slack, D., and Young, R. (1982). "A Comparison of Three Infiltration Models." *Transactions of the American Society of Agricultural Engineers*, 25(2), 349-356.

APPENDICES

Appendix A. MODGA Programmed with Visual Basic®

The screenshot shows the 'Infiltration Models' window with the following parameters and options:

- Rainfall intensity i (cm/hr): 3
- Depth to Water Table D (m): 0.5
- Time Step dt (sec): 15
- Storm Duration (hr): 2
- Soil Type: Sandy Loam
- Initial Water Content (%): 20.7
- Porosity n (%): 41
- Residual Water Content (%): 6.5
- Saturated Water Content (%): 39
- Saturated Hydraulic Conductivity (cm/hr): 1
- Bubbling Pressure H_b (m): 0.13
- Brooks Corey Pore Size Distribution Index: 0.89
- Options:
 - Air Compression and CounterFlow
 - Air Compression NO CounterFlow
 - Neglect Air Effect on Infiltration
- Buttons: Run, Exit

Figure 48 – MODGA’s Graphical Interface

Option Explicit

'Variables Defined in the Graphical Interface:

'Txti: Rainfall intensity (cm/hr)
 'TxtTetai: Initial Water Content (%)
 'Txtn: Porosity (%)
 'txtTetar: Residual Water Content (%)
 'txtTetas: Saturated Water Content (%)
 'Txtdt: Time Step (min)
 'TxtD: Depth to Water Table (m)
 'TxtKs: Saturated Hydraulic Conductivity (cm/hr)
 'TxtHb: Bubbling Pressure (m)
 'TxtSt: Storm Duration (hr)
 'TxtSoilType: Soil Type
 'TxtLambda: Brooks and Corey Pore Size Distribution Index
 'OpCompCount: Option Button for Compression and Counterflow Calculations
 'OpComp: Option Button for Compression while Neglecting Counterflow Calculations
 'OpNoAir: Option Button for the Option Neglecting the Air Phase in the Calculations

'Perfect Gas Constant for air:

Const R = 286.9 'm²/(s².K) (or J/Kg.K). (P=Rho*R*T)

'Standard Atmospheric Pressure:

Const Patm = 101000# 'N/m² (Pa)

'Gravitationnal acceleration:

Const g = 9.807 'm/s²

'Temperature in Kelvine (20C)

Const Tk = 293# 'K

'Physical properties of air at standard atmospheric pressure and temperature = 20C

Const GammaAir = 11.81 'N/m³

Const RhoAir = 1.204 'Kg/m³

Const MuAir = 1.82 * 10^{^-5} 'Ns/m²

Const NuAir = 1.51 * 10^{^-5} 'm²/s

'Physical properties of water at temperature = 20C

Const GammaWater = 9789# 'N/m³

Const RhoWater = 998.2 'Kg/m³

Const MuWater = 1.002 * 10^{^-3} 'Ns/m²

Const NuWater = 1.004 * 10^{^-6} 'm²/s

'Sub-timeStep

Const c = 60#

Private Sub CmdExit_Click()

End

End Sub

Private Sub CmdRun_Click()

'Definition of the different Variables

Dim t As Single 'time in minutes

Dim Tp As Single 'Ponding time in minutes

Dim CapTeta As Double 'Dimensionless Water Content = (Teta-Tetar)/(Porosity-Tetar)

Dim Kra As Double 'Relative Permeability of air

Dim k As Double 'Intrinsic permeability(cm²)= Saturated Hydraulic Conductivity x MuWater/GammaWater

Dim Fb, Fe As Double 'Total infiltration at Beginning and End of a time step (cm)

Dim Re As Double 'Excess Rainfall (cm/hr)

Dim Pp, Hp As Double 'Pressure (pa) and Pressure Head (m of water) of the air phase in porous medium

Dim Pptmp As Double 'Temporary variable use in the pressure iterations

Appendix A. (Continued)

```
Dim Hatm As Double 'Standard Atmospheric Pressure Head (m)
Dim H As Double 'Pressure Head difference between air inside and outside porous medium (m of water)
Dim Hc As Double 'Suction Head (m) = (2+3*Lambda)*Hb/(1+3*Lambda)
Dim L As Double 'Wetting Front Depth (m)
Dim V As Double 'Volume of air in porous medium for a unit area (m3)
Dim m As Double 'Mass of air in porous medium (Kg)
Dim Mf As Double 'Mass Flux of air from porous medium (Kg/s)
Dim fc As Double 'Infiltration Capacity of the soil (cm/hr)
Dim S, Sa As Double 'S=Hc/(TxtTetas-tetai); Sa=H/(TxtTetas-tetai)
Dim count As Integer 'Counter
Dim Msg As String 'Message Box
```

'Creating an Excel File

```
Dim oXL As Object 'Excel application
Dim oBook As Object 'Excel workbook
Dim oSheet As Object 'Excel Worksheet
Dim Table() 'Table of values to be stored
Dim iRow As Long 'Index variable for the current Row
Dim nRow As Long 'Number of Rows in the table
Dim nCol As Integer 'Number of Columns in the table
```

'Start Excel and create a new workbook

```
Set oXL = CreateObject("Excel.application")
Set oBook = oXL.Workbooks.Add
Set oSheet = oBook.Worksheets.Item(1)
```

'Define the table

```
iRow = 1
nRow = 65536
nCol = 13
ReDim Table(1 To nRow, 1 To nCol)
```

If OpCompCount Then 'Infiltration While Accounting for Air Compression and CounterFlow

```
Table(iRow, 1) = "Infiltration While Accounting for Air Compression and CounterFlow"
```

```
iRow = iRow + 1
Table(iRow, 1) = "Time (min)"
Table(iRow, 2) = "Rainfall (cm/hr)"
Table(iRow, 3) = "Air Volume (m)"
Table(iRow, 4) = "Air Mass (Kg)"
Table(iRow, 5) = "Air Mass Flux (Kg/hr)"
Table(iRow, 6) = "Absolute Air Pressure Head (m)"
Table(iRow, 7) = "Gage Air Pressure Head (m)"
Table(iRow, 8) = "Wetting Front Depth (m)"
Table(iRow, 9) = "Total Infiltration (cm)"
Table(iRow, 10) = "Incremental Infiltration (cm)"
Table(iRow, 11) = "Infiltration Capacity (cm/hr)"
Table(iRow, 12) = "Excess Rainfall (cm/hr)"
Table(iRow, 13) = "Comments"
iRow = iRow + 1
'Initial Values
t = 0
count = 0
Table(iRow, 1) = t / 60
Table(iRow, 2) = ""
Table(iRow, 5) = ""
Table(iRow, 10) = ""
```

```
Table(iRow, 11) = ""
Table(iRow, 12) = ""
CapTeta = (TxtTetas - TxtTetar) / (Txtn - TxtTetar)
Kra = (1 - CapTeta ^ 2) * (1 - CapTeta ^ (1 + 2 * TxtLambda))
k = TxtKs * MuWater / (GammaWater * 100 * 3600 * 10 ^ (-4))
Hc = (2 + 3 * TxtLambda) * TxtHb / (1 + 3 * TxtLambda)
Fb = 0
Table(iRow, 9) = Fb
Fe = 0
Re = 0
Pp = Patm
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
Hatm = Patm / GammaWater
H = Hp - Hatm
Table(iRow, 7) = H
L = 0.000001
Table(iRow, 8) = L
V = ((Txtn - TxtTetai) / 100) * TxtD
Table(iRow, 3) = V
m = Pp * V / (R * Tk)
Table(iRow, 4) = m
S = Hc * (TxtTetas - TxtTetai) / 100
Sa = H * (TxtTetas - TxtTetai) / 100
iRow = iRow + 1
```

'Estimation of ponding time

```
Tp = ((S - Sa) * 100 * TxtKs / (Txi * (Txi - TxtKs))) * 3600
While (Tp >= t + Ttxt / c And t < TxtSt * 3600 And L < TxtD)
```

```
count = count + 1
If count >= c Then
    count = 0
End If
t = t + Ttxt / c
Table(iRow, 2) = Txi
Table(iRow, 1) = t / 60
Mf = k * 10 ^ (-4) * Kra * RhoAir * (Pp ^ 2 - Patm ^ 2) / (MuAir * Patm * 2 * L)
Table(iRow, 5) = Mf
m = m - Mf * Ttxt / c
Fe = Fb + Txi * Ttxt / (3600 * c)
Table(iRow, 10) = Fe - Fb
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Pp = m * R * Tk / V
If (Pp < Patm) Then
    Pp = Patm
    m = Pp * V / (R * Tk)
End If
Table(iRow, 4) = m
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
H = Hp - Hatm
Table(iRow, 7) = H
Sa = H * (TxtTetas - TxtTetai) / 100
Tp = ((S - Sa) * 100 * TxtKs / (Txi * (Txi - TxtKs))) * 3600
If (Tp < t) Then
    Tp = t
End If
```

Appendix A. (Continued)

```

Fb = Fe
Table(iRow, 9) = Fb
Table(iRow, 11) = ""
Table(iRow, 12) = 0
iRow = iRow + 1
Wend
If (L < TxtD) Then
  If (t < TxtSt * 3600) Then
    'Infiltration up to ponding time
    If (Tp = t) Then
      'Step to prevent having the ponding time appear twice in
the table
      Table(iRow - 1, 11) = Txti
      Table(iRow - 1, 13) = "Ponding Time"
    Else
      Table(iRow, 1) = Tp / 60
      Table(iRow, 2) = Txti
      Mf = k * 10 ^ (-4) * Kra * RhoAir * (Pp ^ 2 - Patm ^
2) / (MuAir * Patm * 2 * L)
      Table(iRow, 5) = Mf
      m = m - Mf * (Tp - t)
      Fe = Fb + Txti * (Tp - t) / 3600
      Table(iRow, 10) = Fe - Fb
      L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
      Table(iRow, 8) = L
      V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
      Table(iRow, 3) = V
      Pp = m * R * Tk / V
      If (Pp < Patm) Then
        Pp = Patm
        m = Pp * V / (R * Tk)
      End If
      Table(iRow, 4) = m
      Hp = Pp / GammaWater
      Table(iRow, 6) = Hp
      H = Hp - Hatm
      Table(iRow, 7) = H
      Sa = H * (TxtTetas - TxtTetai) / 100
      Fb = Fe
      Table(iRow, 9) = Fb
      Table(iRow, 11) = Txti
      Table(iRow, 12) = 0
      Table(iRow, 13) = "Ponding Time"
      iRow = iRow + 1
    End If
    'Calculations for the rest of the time step corresponding to
ponding time
    'Fe-Fb-(S-Sa)Ln[(Fe+S-Sa)/(Fb+S-Sa)]=Ks*dt
    If (L < TxtD) Then
      t = t + Txtdt * (c - count) / c
      Table(iRow, 1) = t / 60
      Table(iRow, 2) = Txti
      Mf = k * 10 ^ (-4) * Kra * RhoAir * (Pp ^ 2 - Patm ^
2) / (MuAir * Patm * 2 * L)
      Table(iRow, 5) = Mf
      m = m - Mf * (t - Tp)
      While (Fe - Fb - (S - Sa) * 100 * Log((Fe + (S - Sa) *
100) / (Fb + (S - Sa) * 100)) < TxtKs * (t - Tp) / 3600 And (Fe -
Fb) < Txti * (t - Tp) / 3600)
        Fe = Fe + TxtKs * (t - Tp) / (3600# * 1000#)
      Wend
      If ((Fe - Fb) > Txti * (t - Tp) / 3600) Then
        Fe = Fb + Txti * (t - Tp) / 3600
      End If
    End If
  End If
  If ((Fe - Fb) <= TxtKs * (t - Tp) / (3600# * 100#))
Then
    Fe = Fb
  End If
  Table(iRow, 10) = Fe - Fb
  fc = ((Fe - Fb) / (t - Tp)) * 3600
  Table(iRow, 11) = fc
  Re = Txti - fc
  Table(iRow, 12) = Re
  L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
  Table(iRow, 8) = L
  V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
  Table(iRow, 3) = V
  Pp = m * R * Tk / V
  If (Pp < Patm) Then
    Pp = Patm
    m = Pp * V / (R * Tk)
  End If
  Table(iRow, 4) = m
  Hp = Pp / GammaWater
  Table(iRow, 6) = Hp
  H = Hp - Hatm
  Table(iRow, 7) = H
  Sa = H * (TxtTetas - TxtTetai) / 100
  Fb = Fe
  Table(iRow, 9) = Fb
  t = t + Txtdt
  iRow = iRow + 1
Else
  Table(iRow - 1, 13) = "Ponding Time and Soil Fully
Saturated"
  iRow = iRow + 1
  Table(iRow + 1, 1) = "Soil Type: "
  Table(iRow + 1, 6) = TxtSoilType
  Table(iRow + 2, 1) = "Porosity: "
  Table(iRow + 2, 6) = Txtn
  Table(iRow + 3, 1) = "Saturated Water Content: "
  Table(iRow + 3, 6) = TxtTetas
  Table(iRow + 4, 1) = "Residual Water Content: "
  Table(iRow + 4, 6) = TxtTetar
  Table(iRow + 5, 1) = "Initial Water Content: "
  Table(iRow + 5, 6) = TxtTetai
  Table(iRow + 6, 1) = "Saturated Hydraulic
Conductivity (cm/hr): "
  Table(iRow + 6, 6) = TxtKs
  Table(iRow + 7, 1) = "Bubbling Pressure (m): "
  Table(iRow + 7, 6) = TxtHb
  Table(iRow + 8, 1) = "Suction Head (m): "
  Table(iRow + 8, 6) = Hc
  Table(iRow + 9, 1) = "Pore Size Distribution Index: "
  Table(iRow + 9, 6) = TxtLambda
  Table(iRow + 10, 1) = "Depth to Water Table (m): "
  Table(iRow + 10, 6) = TxtD
  Table(iRow + 11, 1) = "Relative Permeability of Air: "
  Table(iRow + 11, 6) = Kra
  'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
  'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Else

```

Appendix A. (Continued)

```

Table(iRow - 1, 13) = "Storm ends without ponding the
soil"
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Else
Table(iRow - 1, 13) = "Soil Fully Saturated"
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True

Exit Sub
End If
'Calculations of infiltration at soil capacity
While (t <= TxtSt * 3600)
If (L < TxtD) Then
Table(iRow, 1) = t / 60
Table(iRow, 2) = Txti
Mf = k * 10 ^ (-4) * Kra * RhoAir * (Pp ^ 2 - Patm ^ 2) /
(MuAir * Patm * 2 * L)
Table(iRow, 5) = Mf
m = m - Mf * Txtdt
If (Sa * 100 < Fb + S * 100) Then
While (Fe - Fb - (S - Sa) * 100 * Log((Fe + (S - Sa) *
100) / (Fb + (S - Sa) * 100))) < TxtKs * Txtdt / 3600 And (Fe -
Fb) < Txti * Txtdt / 3600)
If (fc = 0) Then
Fe = Fe + TxtKs * Txtdt / (3600# * 1000#)
Else
Fe = Fe + fc * Txtdt / (3600# * 1000#)
End If
Wend
If ((Fe - Fb) > Txti * Txtdt / 3600) Then
Fe = Fb + Txti * Txtdt / 3600
End If
If ((Fe - Fb) <= TxtKs * Txtdt / (3600# * 100#)) Then
Fe = Fb
End If
Else
Fe = Fb
End If
Table(iRow, 10) = Fe - Fb
fc = ((Fe - Fb) / Txtdt) * 3600
Table(iRow, 11) = fc
Re = Txti - fc
Table(iRow, 12) = Re
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Pp = m * R * Tk / V
If (Pp < Patm) Then
Pp = Patm
m = Pp * V / (R * Tk)
End If
Table(iRow, 4) = m
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
H = Hp - Hatm
Table(iRow, 7) = H
Sa = H * (TxtTetas - TxtTetai) / 100
Fb = Fe
Table(iRow, 9) = Fb
t = t + Txtdt
iRow = iRow + 1
Else
Table(iRow - 1, 13) = "Soil is fully saturated"
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar

```

Appendix A. (Continued)

```

Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Wend
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True

ElseIf OpComp Then 'Infiltration While Accounting for Air
Compression but Neglecting the CounterFlow

Table(iRow, 1) = "Infiltration While Accounting for Air
Compression Only"
iRow = iRow + 1
Table(iRow, 1) = "Time (min)"
Table(iRow, 2) = "Rainfall (cm/hr)"
Table(iRow, 3) = "Air Volume (m)"
Table(iRow, 4) = "Air Mass (Kg)"
Table(iRow, 5) = "Air Mass Flux (Kg/hr)"

Table(iRow, 6) = "Absolute Air Pressure Head (m)"
Table(iRow, 7) = "Gage Air Pressure Head (m)"
Table(iRow, 8) = "Weeting Front Depth (m)"
Table(iRow, 9) = "Total Infiltration (cm)"
Table(iRow, 10) = "Incremental Infiltration (cm)"
Table(iRow, 11) = "Infiltration Capacity (cm/hr)"
Table(iRow, 12) = "Excess Rainfall (cm/hr)"
Table(iRow, 13) = "Comments"
iRow = iRow + 1
'Initial Values
t = 0
count = 0
Table(iRow, 1) = t / 60
Table(iRow, 2) = ""
Table(iRow, 10) = ""
Table(iRow, 11) = ""
Table(iRow, 12) = ""
CapTeta = (TxtTetas - TxtTetar) / (Ttxn - TxtTetar)
Kra = (1 - CapTeta ^ 2) * (1 - CapTeta ^ (1 + 2 *
TxtLambda))
k = TxtKs * MuWater / (GammaWater * 100 * 3600 * 10 ^ (-
4))
Hc = (2 + 3 * TxtLambda) * TxtHb / (1 + 3 * TxtLambda)
Fb = 0
Table(iRow, 9) = Fb
Fe = 0
Re = 0
Pp = Patm
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
Hatm = Patm / GammaWater
H = Hp - Hatm
Table(iRow, 7) = H
L = 0.00001
Table(iRow, 8) = 0
V = ((Ttxn - TxtTetai) / 100) * TxtD
Table(iRow, 3) = V
m = Pp * V / (R * Tk)
Table(iRow, 4) = m
S = Hc * (TxtTetas - TxtTetai) / 100
Sa = H * (TxtTetas - TxtTetai) / 100
iRow = iRow + 1

'Estimation of ponding time
Tp = ((S - Sa) * 100 * TxtKs / (Txti * (Txti - TxtKs))) * 3600
While (Tp >= t + Ttxtdt / c And t < TxtSt * 3600 And L <
TxtD)
count = count + 1
If count >= c Then
count = 0
End If
t = t + Ttxtdt / c
Table(iRow, 2) = Txti
Table(iRow, 1) = t / 60
Fe = Fb + Txti * Ttxtdt / (3600 * c)
Table(iRow, 10) = Fe - Fb
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Ttxn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Pp = m * R * Tk / V
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
H = Hp - Hatm
Table(iRow, 7) = H

```

Appendix A. (Continued)

```

Sa = H * (TxtTetas - TxtTetai) / 100
Tp = ((S - Sa) * 100 * TxtKs / (Txti * (Txti - TxtKs))) *
3600
If (Tp < t) Then
    Tp = t
End If
Fb = Fe
Table(iRow, 9) = Fb
Table(iRow, 11) = ""
Table(iRow, 12) = 0
iRow = iRow + 1
Wend
If (L < TxtD) Then
    If (t < TxtSt * 3600) Then
        'Infiltration up to ponding time
        If (Tp = t) Then
            'Step to prevent having the ponding time appear twice in
            the table
            Table(iRow - 1, 11) = Txti
            Table(iRow - 1, 13) = "Ponding Time"
        Else
            Table(iRow, 1) = Tp / 60
            Table(iRow, 2) = Txti
            Fe = Fb + Txti * (Tp - t) / 3600
            Table(iRow, 10) = Fe - Fb
            L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
            Table(iRow, 8) = L
            V = ((Ttxn - TxtTetai) / 100) * (TxtD - L)
            Table(iRow, 3) = V
            Pp = m * R * Tk / V
            Hp = Pp / GammaWater
            Table(iRow, 6) = Hp
            H = Hp - Hatm
            Table(iRow, 7) = H
            Sa = H * (TxtTetas - TxtTetai) / 100
            Fb = Fe
            Table(iRow, 9) = Fb
            Table(iRow, 11) = Txti
            Table(iRow, 12) = 0
            Table(iRow, 13) = "Ponding Time"
            iRow = iRow + 1
        End If
        'Calculations for the rest of the time step corresponding to
        ponding time
        'Fe-Fb-(S-Sa)Ln[(Fe+S-Sa)/(Fb+S-Sa)]=Ks*dt
        If (L < TxtD) Then
            t = t + Txtdt * (c - count) / c
            Table(iRow, 1) = t / 60
            Table(iRow, 2) = Txti
            While (Fe - Fb - (S - Sa) * 100 * Log((Fe + (S - Sa) *
            100) / (Fb + (S - Sa) * 100)) < TxtKs * (t - Tp) / 3600 And (Fe -
            Fb) < Txti * (t - Tp) / 3600)
                Fe = Fe + TxtKs * (t - Tp) / (3600# * 1000#)
            Wend
            If Fe - Fb <= TxtKs * (t - Tp) / (3600# * 100#) Then
                Fe = Fb
            End If
            Table(iRow, 10) = Fe - Fb
            fc = ((Fe - Fb) / (t - Tp)) * 3600
            Table(iRow, 11) = fc
            Re = Txti - fc
            Table(iRow, 12) = Re
            L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
            Table(iRow, 8) = L
            V = ((Ttxn - TxtTetai) / 100) * (TxtD - L)
            Table(iRow, 3) = V
            Pp = m * R * Tk / V
            Hp = Pp / GammaWater
            Table(iRow, 6) = Hp
            H = Hp - Hatm
            Table(iRow, 7) = H
            Sa = H * (TxtTetas - TxtTetai) / 100
            Fb = Fe
            Table(iRow, 9) = Fb
            t = t + Txtdt
            iRow = iRow + 1
        Else
            Table(iRow - 1, 13) = "Ponding Time and Soil Fully
            Saturated"
            iRow = iRow + 1
            Table(iRow + 1, 1) = "Soil Type: "
            Table(iRow + 1, 6) = TxtSoilType
            Table(iRow + 2, 1) = "Porosity: "
            Table(iRow + 2, 6) = Ttxn
            Table(iRow + 3, 1) = "Saturated Water Content: "
            Table(iRow + 3, 6) = TxtTetas
            Table(iRow + 4, 1) = "Residual Water Content: "
            Table(iRow + 4, 6) = TxtTetar
            Table(iRow + 5, 1) = "Initial Water Content: "
            Table(iRow + 5, 6) = TxtTetai
            Table(iRow + 6, 1) = "Saturated Hydraulic
            Conductivity (cm/hr): "
            Table(iRow + 6, 6) = TxtKs
            Table(iRow + 7, 1) = "Bubbling Pressure (m): "
            Table(iRow + 7, 6) = TxtHb
            Table(iRow + 8, 1) = "Suction Head (m): "
            Table(iRow + 8, 6) = Hc
            Table(iRow + 9, 1) = "Pore Size Distribution Index: "
            Table(iRow + 9, 6) = TxtLambda
            Table(iRow + 10, 1) = "Depth to Water Table (m): "
            Table(iRow + 10, 6) = TxtD
            Table(iRow + 11, 1) = "Relative Permeability of Air: "
            Table(iRow + 11, 6) = Kra
            'Export Results to Excel
            oSheet.Range("A1").Resize(nRow, nCol).Value =
            Table()
            'Make Excel Visible
            oXL.Visible = True
            oXL.UserControl = True
            Exit Sub
        End If
    Else
        Table(iRow - 1, 13) = "Storm ends without ponding the
        soil"
        iRow = iRow + 1
        Table(iRow + 1, 1) = "Soil Type: "
        Table(iRow + 1, 6) = TxtSoilType
        Table(iRow + 2, 1) = "Porosity: "
        Table(iRow + 2, 6) = Ttxn
        Table(iRow + 3, 1) = "Saturated Water Content: "
        Table(iRow + 3, 6) = TxtTetas
        Table(iRow + 4, 1) = "Residual Water Content: "
        Table(iRow + 4, 6) = TxtTetar
        Table(iRow + 5, 1) = "Initial Water Content: "
        Table(iRow + 5, 6) = TxtTetai
        Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
        (cm/hr): "
        Table(iRow + 6, 6) = TxtKs
        Table(iRow + 7, 1) = "Bubbling Pressure (m): "
        Table(iRow + 7, 6) = TxtHb
    End If
End If

```

Appendix A. (Continued)

```

Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Else
Table(iRow - 1, 13) = "Soil Fully Saturated"
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
'Calculations of infiltration at soil capacity
While (t <= TxtSt * 3600)
If (L < TxtD) Then
Table(iRow, 1) = t / 60
Table(iRow, 2) = Txti
If (Sa * 100 < Fb + S * 100) Then
While (Fe - Fb - (S - Sa) * 100 * Log((Fe + (S - Sa) *
100) / (Fb + (S - Sa) * 100)) < TxtKs * TxtD / 3600 And (Fe -
Fb) < Txti * TxtD / 3600)
If (fc = 0) Then
Fe = Fe + TxtKs * TxtD / (3600# * 1000#)
Else
Fe = Fe + fc * TxtD / (3600# * 1000#)
End If
Wend
If Fe - Fb <= TxtKs * TxtD / (3600# * 100#) Then
Fe = Fb
End If
Else
Fe = Fb
End If
Table(iRow, 10) = Fe - Fb
fc = ((Fe - Fb) / TxtD) * 3600
Table(iRow, 11) = fc
Re = Txti - fc
Table(iRow, 12) = Re
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Pp = m * R * Tk / V
Hp = Pp / GammaWater
Table(iRow, 6) = Hp
H = Hp - Hatm
Table(iRow, 7) = H
Sa = H * (TxtTetas - TxtTetai) / 100
Fb = Fe
Table(iRow, 9) = Fb
t = t + TxtD
iRow = iRow + 1
Else
Table(iRow - 1, 13) = "Soil is fully saturated"
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Wend
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "

```

Appendix A. (Continued)

```

Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True

ElseIf OpNoAir Then 'Infiltration While Neglecting the Air
Phase in the Porous Media

    Table(iRow, 1) = "Infiltration While Neglecting the Air
Phase"
    iRow = iRow + 1
    Table(iRow, 1) = "Time (min)"
    Table(iRow, 2) = "Rainfall (cm/hr)"
    Table(iRow, 3) = "Air Volume (m)"
    Table(iRow, 4) = "Air Mass (Kg)"
    Table(iRow, 5) = "Air Mass Flux (Kg/hr)"
    Table(iRow, 6) = "Absolute Air Pressure Head (m)"
    Table(iRow, 7) = "Gage Air Pressure Head (m)"
    Table(iRow, 8) = "Weeting Front Depth (m)"
    Table(iRow, 9) = "Total Infiltration (cm)"
    Table(iRow, 10) = "Incremental Infiltration (cm)"
    Table(iRow, 11) = "Infiltration Capacity (cm/hr)"
    Table(iRow, 12) = "Excess Rainfall (cm/hr)"
    Table(iRow, 13) = "Comments"
    iRow = iRow + 1
    'Initial Values
    t = 0
    Table(iRow, 1) = t / 60
    Table(iRow, 2) = ""
    Table(iRow, 10) = ""
    Table(iRow, 11) = ""
    Table(iRow, 12) = ""
    CapTeta = (TxtTetas - TxtTetar) / (Txtn - TxtTetar)
    Kra = (1 - CapTeta ^ 2) * (1 - CapTeta ^ (1 + 2 *
TxtLambda))
    k = TxtKs * MuWater / (GammaWater * 100 * 3600 * 10 ^ (-
4))
    Hc = (2 + 3 * TxtLambda) * TxtHb / (1 + 3 * TxtLambda)
    Fb = 0
    Table(iRow, 9) = Fb
    Fe = 0
    Re = 0
    Pp = Patm
    Hp = Pp / GammaWater
    Table(iRow, 6) = Hp
    Hatm = Patm / GammaWater

    H = Hp - Hatm
    Table(iRow, 7) = H
    L = 0.00001
    Table(iRow, 8) = 0
    V = ((Txtn - TxtTetai) / 100) * TxtD
    Table(iRow, 3) = V
    Table(iRow, 4) = m
    S = Hc * (TxtTetas - TxtTetai) / 100
    iRow = iRow + 1

'Estimation of ponding time
Tp = (S * 100 * TxtKs / (Txtn * (Txtn - TxtKs))) * 3600
While (Tp >= t + TxtD And t < TxtSt * 3600 And L < TxtD)
    t = t + TxtD
    Table(iRow, 2) = Txtn
    Table(iRow, 1) = t / 60
    Fe = Fb + Txtn * TxtD / 3600
    Table(iRow, 10) = Fe - Fb
    L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
    Table(iRow, 8) = L
    V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
    Table(iRow, 3) = V
    Tp = (S * 100 * TxtKs / (Txtn * (Txtn - TxtKs))) * 3600
    Fb = Fe
    Table(iRow, 9) = Fb
    Table(iRow, 11) = ""
    Table(iRow, 12) = 0
    iRow = iRow + 1
Wend
If (L < TxtD) Then
    If (t < TxtSt * 3600) Then
        'Infiltration up to ponding time
        If (Tp = t) Then
            'Step to prevent having the ponding time appear twice in
the table
            Table(iRow - 1, 11) = Txtn
            Table(iRow - 1, 13) = "Ponding Time"
        Else
            Table(iRow, 1) = Tp / 60
            Table(iRow, 2) = Txtn
            Fe = Fb + Txtn * (Tp - t) / 3600
            Table(iRow, 10) = Fe - Fb
            L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
            Table(iRow, 8) = L
            V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
            Table(iRow, 3) = V
            Fb = Fe
            Table(iRow, 9) = Fb
            Table(iRow, 11) = Txtn
            Table(iRow, 12) = 0
            Table(iRow, 13) = "Ponding Time"
            iRow = iRow + 1
        End If
        'Calculations for the rest of the time step corresponding to
ponding time
        'Fe-Fb-(S-Sa)Ln[(Fe+S-Sa)/(Fb+S-Sa)]=Ks*dt
        If (L < TxtD) Then
            t = t + TxtD
            Table(iRow, 1) = t / 60
            Table(iRow, 2) = Txtn
            While (Fe - Fb - S * 100 * Log((Fe + S * 100) / (Fb +
S * 100))) < TxtKs * (t - Tp) / 3600 And (Fe - Fb) < Txtn * (t -
Tp) / 3600)
                Fe = Fe + TxtKs * (t - Tp) / (3600# * 1000#)
            Wend
        End If
    End If
End If

```

Appendix A. (Continued)

```

If Fe - Fb <= TxtKs * (t - Tp) / (3600# * 100#) Then
    Fe = Fb
End If
Table(iRow, 10) = Fe - Fb
fc = ((Fe - Fb) / (t - Tp)) * 3600
Table(iRow, 11) = fc
Re = Txti - fc
Table(iRow, 12) = Re
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Ttxn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Fb = Fe
Table(iRow, 9) = Fb
t = t + Ttxt
iRow = iRow + 1
Else
    Table(iRow - 1, 13) = "Ponding Time and Soil Fully
Saturated"
    iRow = iRow + 1
    Table(iRow + 1, 1) = "Soil Type: "
    Table(iRow + 1, 6) = TxtSoilType
    Table(iRow + 2, 1) = "Porosity: "
    Table(iRow + 2, 6) = Ttxn
    Table(iRow + 3, 1) = "Saturated Water Content: "
    Table(iRow + 3, 6) = TxtTetas
    Table(iRow + 4, 1) = "Residual Water Content: "
    Table(iRow + 4, 6) = TxtTetar
    Table(iRow + 5, 1) = "Initial Water Content: "
    Table(iRow + 5, 6) = TxtTetai
    Table(iRow + 6, 1) = "Saturated Hydraulic
Conductivity (cm/hr): "
    Table(iRow + 6, 6) = TxtKs
    Table(iRow + 7, 1) = "Bubbling Pressure (m): "
    Table(iRow + 7, 6) = TxtHb
    Table(iRow + 8, 1) = "Suction Head (m): "
    Table(iRow + 8, 6) = Hc
    Table(iRow + 9, 1) = "Pore Size Distribution Index: "
    Table(iRow + 9, 6) = TxtLambda
    Table(iRow + 10, 1) = "Depth to Water Table (m): "
    Table(iRow + 10, 6) = TxtD
    Table(iRow + 11, 1) = "Relative Permeability of Air: "
    Table(iRow + 11, 6) = Kra
    'Export Results to Excel
    oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
    'Make Excel Visible
    oXL.Visible = True
    oXL.UserControl = True
    Exit Sub
End If
Else
    Table(iRow - 1, 13) = "Storm ends without ponding the
soil"
    iRow = iRow + 1
    Table(iRow + 1, 1) = "Soil Type: "
    Table(iRow + 1, 6) = TxtSoilType
    Table(iRow + 2, 1) = "Porosity: "
    Table(iRow + 2, 6) = Ttxn
    Table(iRow + 3, 1) = "Saturated Water Content: "
    Table(iRow + 3, 6) = TxtTetas
    Table(iRow + 4, 1) = "Residual Water Content: "
    Table(iRow + 4, 6) = TxtTetar
    Table(iRow + 5, 1) = "Initial Water Content: "
    Table(iRow + 5, 6) = TxtTetai
    Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
    Table(iRow + 6, 6) = TxtKs
    Table(iRow + 7, 1) = "Bubbling Pressure (m): "
    Table(iRow + 7, 6) = TxtHb
    Table(iRow + 8, 1) = "Suction Head (m): "
    Table(iRow + 8, 6) = Hc
    Table(iRow + 9, 1) = "Pore Size Distribution Index: "
    Table(iRow + 9, 6) = TxtLambda
    Table(iRow + 10, 1) = "Depth to Water Table (m): "
    Table(iRow + 10, 6) = TxtD
    Table(iRow + 11, 1) = "Relative Permeability of Air: "
    Table(iRow + 11, 6) = Kra
    'Export Results to Excel
    oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
    'Make Excel Visible
    oXL.Visible = True
    oXL.UserControl = True
    Exit Sub
End If
'Calculations of infiltration at soil capacity
While (t <= TxtSt * 3600)
    If (L < TxtD) Then
        If (Sa < Fb + S) Then
            Table(iRow, 1) = t / 60
            Table(iRow, 2) = Txti
            While (Fe - Fb - S * 100 * Log((Fe + S * 100) / (Fb +
S * 100)) < TxtKs * Ttxt / 3600 And (Fe - Fb) < Txti * Ttxt /
3600)
                If (fc = 0) Then
                    Fe = Fe + TxtKs * Ttxt / (3600# * 1000#)
                End If
            End While
        End If
    End If
End While

```

Appendix A. (Continued)

```

Else
    Fe = Fe + fc * Txttdt / (3600# * 1000#)
End If
Wend
If Fe - Fb <= TxtKs * Txttdt / (3600# * 100#) Then
    Fe = Fb
End If
Table(iRow, 10) = Fe - Fb
fc = (Fe - Fb) / Txttdt * 3600
Table(iRow, 11) = fc
Re = Txtti - fc
Table(iRow, 12) = Re
L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
Table(iRow, 8) = L
V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
Table(iRow, 3) = V
Fb = Fe
Table(iRow, 9) = Fb
Else
    Table(iRow, 1) = t / 60
    Table(iRow, 2) = Txtti
    Fe = Fb
    Table(iRow, 10) = Fe - Fb
    fc = (Fe - Fb) / Txttdt * 3600
    Table(iRow, 11) = fc
    Re = Txtti - fc
    Table(iRow, 12) = Re
    L = (Fe / 100) / ((TxtTetas - TxtTetai) / 100)
    Table(iRow, 8) = L
    V = ((Txtn - TxtTetai) / 100) * (TxtD - L)
    Table(iRow, 3) = V
    Fb = Fe
End If
t = t + Txttdt
iRow = iRow + 1
Else
    Table(iRow - 1, 13) = "Soil is fully saturated"
    iRow = iRow + 1
    Table(iRow + 1, 1) = "Soil Type: "
    Table(iRow + 1, 6) = TxtSoilType
    Table(iRow + 2, 1) = "Porosity: "
    Table(iRow + 2, 6) = Txtn
    Table(iRow + 3, 1) = "Saturated Water Content: "
    Table(iRow + 3, 6) = TxtTetas
    Table(iRow + 4, 1) = "Residual Water Content: "
    Table(iRow + 4, 6) = TxtTetar
    Table(iRow + 5, 1) = "Initial Water Content: "
    Table(iRow + 5, 6) = TxtTetai
    Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
    Table(iRow + 6, 6) = TxtKs
    Table(iRow + 7, 1) = "Bubbling Pressure (m): "
    Table(iRow + 7, 6) = TxtHb
    Table(iRow + 8, 1) = "Suction Head (m): "
    Table(iRow + 8, 6) = Hc
    Table(iRow + 9, 1) = "Pore Size Distribution Index: "
    Table(iRow + 9, 6) = TxtLambda
    Table(iRow + 10, 1) = "Depth to Water Table (m): "
    Table(iRow + 10, 6) = TxtD
    Table(iRow + 11, 1) = "Relative Permeability of Air: "
    Table(iRow + 11, 6) = Kra
    'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value =
Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
Exit Sub
End If
Wend
iRow = iRow + 1
Table(iRow + 1, 1) = "Soil Type: "
Table(iRow + 1, 6) = TxtSoilType
Table(iRow + 2, 1) = "Porosity: "
Table(iRow + 2, 6) = Txtn
Table(iRow + 3, 1) = "Saturated Water Content: "
Table(iRow + 3, 6) = TxtTetas
Table(iRow + 4, 1) = "Residual Water Content: "
Table(iRow + 4, 6) = TxtTetar
Table(iRow + 5, 1) = "Initial Water Content: "
Table(iRow + 5, 6) = TxtTetai
Table(iRow + 6, 1) = "Saturated Hydraulic Conductivity
(cm/hr): "
Table(iRow + 6, 6) = TxtKs
Table(iRow + 7, 1) = "Bubbling Pressure (m): "
Table(iRow + 7, 6) = TxtHb
Table(iRow + 8, 1) = "Suction Head (m): "
Table(iRow + 8, 6) = Hc
Table(iRow + 9, 1) = "Pore Size Distribution Index: "
Table(iRow + 9, 6) = TxtLambda
Table(iRow + 10, 1) = "Depth to Water Table (m): "
Table(iRow + 10, 6) = TxtD
Table(iRow + 11, 1) = "Relative Permeability of Air: "
Table(iRow + 11, 6) = Kra
'Export Results to Excel
oSheet.Range("A1").Resize(nRow, nCol).Value = Table()
'Make Excel Visible
oXL.Visible = True
oXL.UserControl = True
End Sub
Msg = MsgBox("Choose a Model to Calculate Infiltration",
vbExclamation)
End If
End Sub

```

Appendix B. Air and Water Physical Properties at 20°C

Table 12 – Air and Water Physical Properties at 20°C

	Specific Weight γ (N/m ³)	Density ρ (Kg/m ³)	Dynamic Viscosity μ (Ns/m ²)	Kinematic Viscosity ν (m ² /s)
Air	11.81	1.204	$1.82 \cdot 10^{-5}$	$1.51 \cdot 10^{-5}$
Water	9789	998.2	$1.002 \cdot 10^{-3}$	$1.004 \cdot 10^{-6}$

- i. Perfect Gas Constant for Air: $R = 286.9 \text{ J/Kg.K}$
- ii. Standard Atmospheric Pressure: $P_{atm} = 101,000 \text{ N/m}^2 \text{ (Pa)}$
- iii. Gravitational Acceleration: $g = 9.807 \text{ m/s}^2$