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SOIL MOISTURE FLOW MODELLING USING HYDRUS 1D

Water Flow in a Field Soil Profile under Grass

A Case Study of NIH

A Full semester project report Submitted by

VIKRANT (PR14CE2002)

in partial fulfillment for the award of the degree

of

MASTER OF TECHNOLOGY

in

INTEGRATED WATER RESOURCES MANAGEMENT

Under the supervision of

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WATER INSTITUTE

KARUNYA UNIVERSITY

(Karunya Institute of Technology and Sciences)

(Declared as Deemed-to-be-under Sec-3 of the UGC Act, 1956)

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APRIL 2016

BONAFIDE CERTIFICATE

Certified that this project report **"SOIL MOISTURE FLOW MODELLING USING HYDRUS 1D"** is the bonafide work of **"VIKRANT (PR14CE2002)"** who carried out the project work under my supervision.

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PREFACE

Water flow through the variably-saturated zone is an important part of the hydrologic cycle because it influences partitioning of water among various flow components. Depending upon hydrological, geological and soil characteristics, rain and snowmelt is partitioned at the land surface into runoff, infiltration, evapotranspiration, groundwater recharge, and vadose zone storage. Water flow in the vadose zone especially affects the transfer rates between the land surface and the groundwater table, which are two key hydrological boundaries. Evaluation of almost any hydrological process therefore requires that water flow through the vadose zone is appropriately taken into account. However, modeling of vadose zone flow processes is a complex and computationally demanding task that is often handicapped by the lack of data necessary to characterize the hydraulic properties of the subsurface environment.

The HYDRUS Package uses the computer program HYDRUS to simulate water movement in variably-saturated porous media by numerically solving the Richards equation. The HYDRUS package considers the effects of infiltration, soil moisture storage, evaporation, plant water up-take, precipitation, runoff, and water accumulation at the ground surface.

As a part of hydrological studies this report documents version 4.16.0110 of HYDRUS-1D, a software package for simulating water movement in one-dimensional variably saturated media. This report presents the details of the methodology adopted and discusses the results. This report will be highly useful to the engineers and research scholars of water resources organizations of Uttarakhand and other states.

The present study has been carried out by Mr. Vikrant under the guidance of Mr. C.P Kumar, Scientist 'G', Ground Water Hydrology Division, NIH and Dr. Surjeet Singh, Scientist 'D', NIH.

ABSTRACT

During the last several decades, the study of the movement of water in the unsaturated zone has become an issue of great significance due to profound effects of the physical and chemical processes occurring in this zone on the quality of both surface and subsurface waters. It is generally known that the precipitation, pressure and evaporation are the dominant controls on the movement of water into surface and ground waters. In this study, a general methodology has been developed to evaluate the effect of soil water hysteresis, and temporal variability in precipitation and evaporation input data on the movement of water in soils.

This report documents version 4.16.0110 of HYDRUS-1D, a software package for simulating water movement in one-dimensional variably saturated media. The software consists of the HYDRUS computer program, and the HYDRUS1D interactive graphics-based user interface. The HYDRUS program numerically solves the Richards' equation for variably saturated water flow. The flow equation incorporates a sink term to account for water uptake by plant roots. The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The flow region may be composed of no uniform soils. Flow and transport can occur in the vertical, horizontal, or a generally inclined direction. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, as well as free drainage boundary conditions. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes.

The present study aims to study the movement of water in the unsaturated zone. A one-dimensional unsaturated transport model was used to simulate the movement of water in the vadose zone. Simulations were conducted in HYDRUS-1D code using measured precipitation data for the period January 1st-2015 to March 31st-2016.

The results so obtained is discussed in the Results and discussion part of the project.

ACKNOWLEDGEMENT

Ability is of little account without opportunity, but if it gets gentle and brilliant hands, it gets the ability to top.

With due respect, I would like to express my thanks to some great personalities to whom I interact for their valuable suggestions and methodology approach during my project work.

I am deeply indebted to Dr. E JAMES and Dr. P.Jegathambal, Professor & Coordinator of Water institute, Karunya University, Coimbatore that they gave me this Opportunity.

It's my great privilege to express my thanks to Er. R.D. Singh, Director National Institute of Hydrology, Roorkee, for accepting my candidature for the project and providing tremendous organizational and intellectual assistance required within the time.

I am highly obliged and express my deep respect and gratitude to my guide Mr. C.P Kumar, Scientist 'G', Ground Water Hydrology Division, NIH and Dr. Surjeet Singh, Scientist 'D', NIH , without whom invaluable help and generous guidance this study would be impossible.

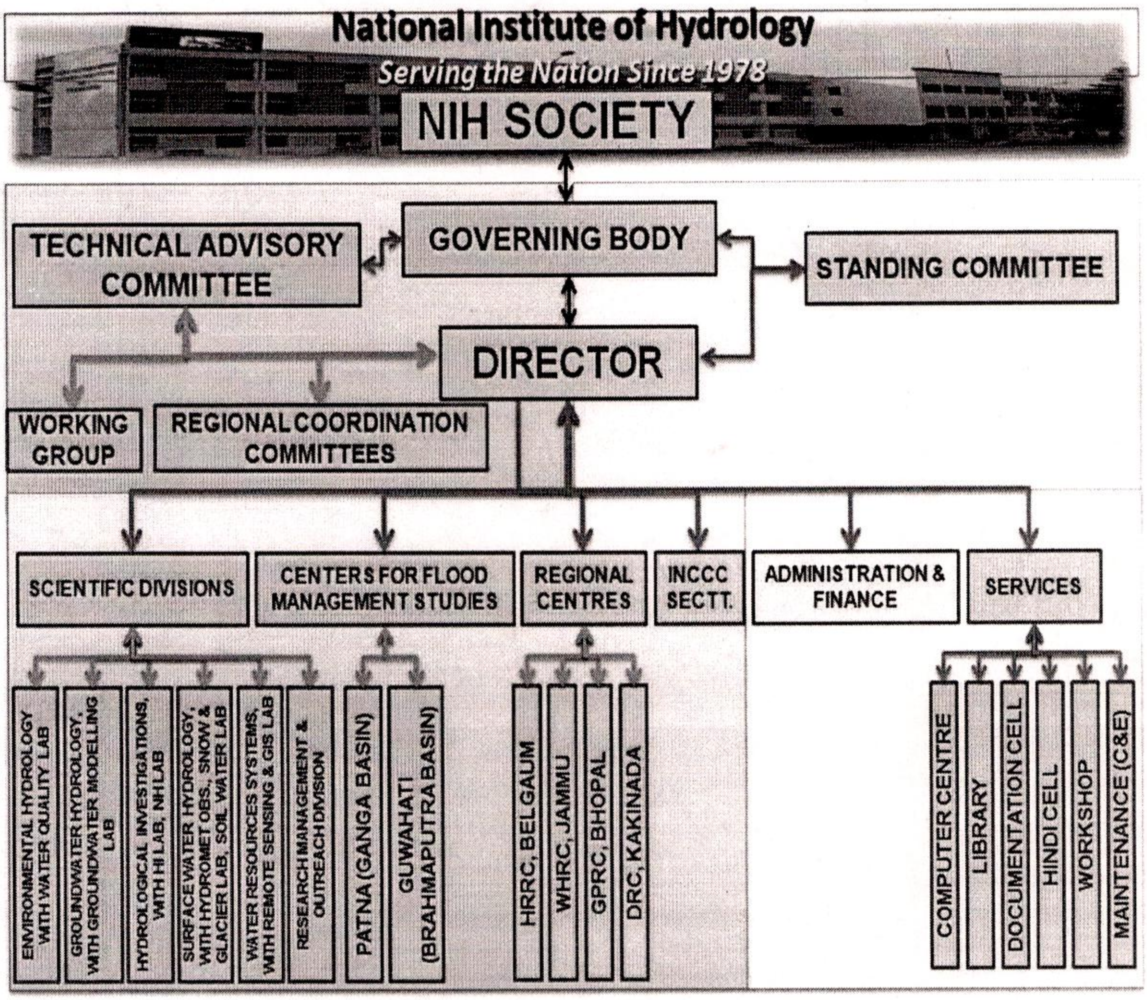
I would express thanks to Ms. Kausila Timsina and Mr. N.K. lakhera for their understanding, cooperation and encouragement from time to time, as I have learned a great deal from each of them, all of which I can remember now, during my project work.

At last but not least, I am highly obliged and grateful to my dear Parents without whose blessing, love and support, while I decided to be a professional for a while, the work would not have been converted from a ray hope to reality.

NATIONAL INSTITUTE OF HYDROLOGY (NIH)

INTRODUCTION

NATIONAL INSTITUTE OF HYDROLOGY, the premier Institute in the area of hydrology and water resources in India. The Institute was established in 1978 (Ministry of Water Resources, RD & GR, Govt. of India) with the main objective of undertaking, aiding, promoting and coordinating systematic and scientific work in all aspects of hydrology. The Institute has its Headquarter at Roorkee (Uttarakhand), four regional centres at Belgaum, Jammu, Kakinada and Bhopal and two centres for Flood Management Studies at Guwahati and Patna. The Institute is well equipped to carry out computer, laboratory & field oriented studies.



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1.0 INTRODUCTION AND TERMINOLOGY

1.0 INTRODUCTION

Background

The zone between ground surface and groundwater table is defined as the unsaturated zone or the vadose zone which contains in addition to solid soil particles, air and water. The unsaturated zone acts as a filter for the aquifers by removing unwanted substances that might come from the ground surface such as hazardous wastes, fertilizers and pesticides. This is, could be attributed to the high contents of organic matters and clay, which motivates biological degradation, transformation of contaminants and sorption. Therefore, the vadose can be considered as a buffer zone protecting the groundwater. Thus, the hydrogeological properties of this zone are of great concern for the groundwater pollution (Selker, et al., 1999, Stephens, 1996).

Many chemical and physical processes occur in the soil horizon. These processes are attributed to different soil phases, due to the existence of solid particles, water and air. In order to be able to model water and solute transport in the unsaturated zone and provide acceptable outputs concerning water and solute solution profiles, it is required to make some simplifications and assumptions due to the heterogeneous and complex nature of soil (Selker, et al., 1999).

From hydrologic point of view, the transmission of water to aquifers, water on the surface, and atmosphere is greatly controlled by the processes in unsaturated zone. For these reasons the study and modeling of water flow and solutes transport in the unsaturated zone is becoming an issue of major concern, generally, in terms of water resources planning and management, and especially in terms of water quality management and groundwater contamination (Rumynin, 2011).

A large number of models have been developed during the past several decades to evaluate the computations of water flow and solute transfer in the vadose zone. In general, they are either analytical or numerical models for predicting water and solute movement between the soil surface and the groundwater table. Amongst the most commonly used ones are the Richards equation for variably saturated flow, and the Fickian-based convection-dispersion equation (CDE) for solute transport (Šimůnek, et al., 2009). These two equations are solved numerically using finite difference or finite element methods (Arampatzis, et al., 2001, Šimůnek, et al., 2009), which requires an iterative implicit technique (Damodhara Rao, et al., 2006). HYDRUS is one of the computer codes which simulating water, heat, and solutes transport in one, two, and three dimensional variably saturated porous media on the basis of the finite element method. The Richards's equation for variably-saturated water flow and advection-dispersion type equations (CDE) for heat and solute transport are solved deterministically (Šimůnek, et al., 2009).

In this study, HYDRUS-1D version 4.14 is used as a tool to simulate water and solute movement in the vadose zone to develop our understanding of downward movement of solutes under variable boundary conditions. The software is originally developed and released by the United States.

Salinity Laboratory in cooperation with the International Groundwater Modeling Center (IGWMC), the University of California Riverside, and PC-Progress, Inc.

1.1 GROUNDWATER

Study of subsurface flow is equally important since about 22% of the world's Fresh water resources exist in the form of groundwater. Further, the subsurface water forms a critical input for the sustenance of life and vegetation in and zones. Because of its importance as a significant source of water supply, various aspects of groundwater dealing with the exploration, development and utilization have been extensively studied by workers from different disciplines, such as geology, geophysics, geochemistry, agricultural engineering, fluid mechanics and civil engineering and excellent treatises are available.

1.2 SOURCES OF GROUNDWATER

Groundwater is derived from precipitation and recharge from surface water. It is the water that has infiltrated into the earth directly from precipitation, recharge from streams and other natural water bodies and artificial recharge due to action of man.

Infiltration and further downward percolation from sources like rain, melting of snow and ice, rivers and streams, lakes, reservoirs, canals and other watercourses are the usual main sources that contribute to the groundwater of a region.

1.3 FORMS OF SUBSURFACE WATER

Water in the soil mantle is called subsurface water and is considered in two zones (Fig.1.1), saturated zones and Aeration zones.

1.3.1 Saturated Zone

This zone, also known as groundwater zone is the space in which all the pores of the soil are filled with water. The water table forms its upper limit and marks a free surface, i.e. a surface having atmospheric pressure.

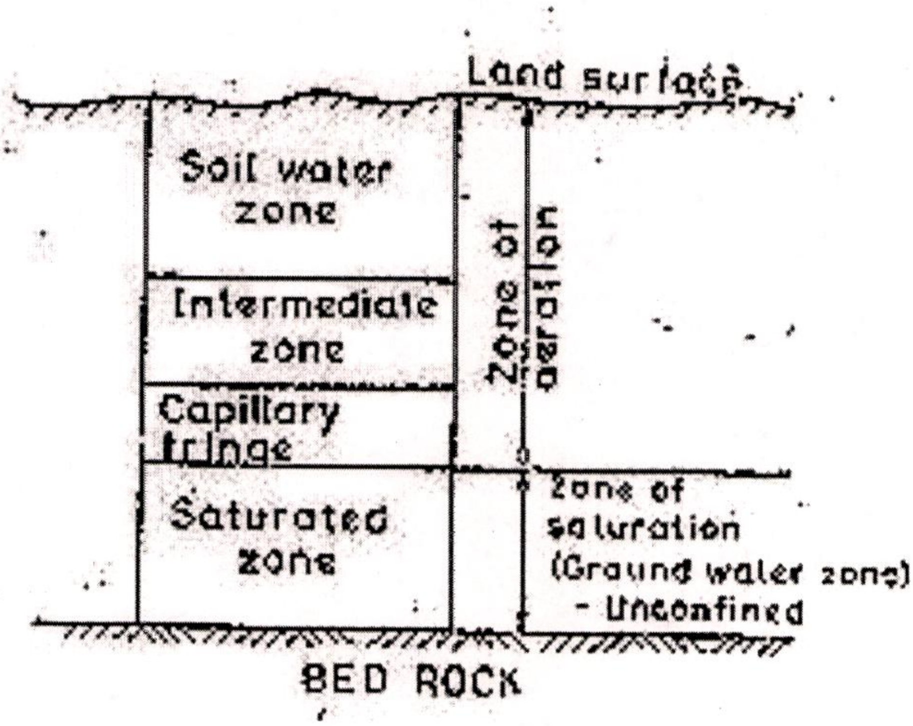


Fig 1.1: Classification of subsurface water

1.3.2 Zone of Aeration

In this zone the soil pores are only partially saturated with water. The space between the land surface and the water table marks the extent of this zone. Further, the zone of aeration has three subzones:

1.3.2.1 Soil Water Zone

This lies close to the ground surface in the major root band of the vegetation from which the water is lost to the atmosphere by evapotranspiration.

1.3.2.2 Capillary Fringe

In this the water is held by capillary action. This zone extends from the water table upwards to the limit of the capillary rise.

1.3.2.3 Intermediate Zone

This lies between the soil water zone and the capillary fringe. The thickness of the zone of aeration and its constituents subzones depend upon the soil texture and moisture content and vary from region to region. The soil moisture in the zone of aeration is of importance in agricultural practice and irrigation engineering.

All earth materials, from soils to rocks have pores spaces. Although these pores are completely saturated with water below the water table, from the groundwater utilization aspect only such material through which water moves easily and hence can be extracted with ease are significant. On this basis the saturated formations are classified into four categories:

1.4 AQUIFER

An aquifer is a saturated formation of earth material which not only stores water but yields it in sufficient quantity. Thus an aquifer transmits water relatively easily due to its high permeability. Unconsolidated deposits of sand and gravel form good aquifers.

1.4.1 AQUITARD

It is a formation through which only seepage is possible and thus the yield is insignificant compared to an aquifer. It is partly permeable.

1.4.2 AQUICLUDE

It is a geological formation which is essentially impermeable to the flow of water. It may be considered as closed to water movement even though it may contain large amounts of water due to its high porosity. Clay is an example of an aquiclude.

1.4.3 AQUIFUGE

It is a formation which has no interconnected openings and hence cannot absorb or transmit water. It is neither porous nor permeable.

Aquifers play the role of both a transmission conduct and a storage. Aquifers are classified as unconfined aquifers and confined aquifers on the basis of their occurrence and field situation.

- **UNCONFINED AQUIFERS**

  An unconfined aquifer is also known as water table aquifer. It is one in which free surface, i.e. a water table exists. Only the saturated zone of this aquifer is of importance in groundwater studies. Recharge of this aquifer takes place through infiltration of precipitation from the ground surface.

- **CONFINED AQUIFERS**

  A confined aquifer, known as artesian aquifer, is an aquifer which is confined between two impervious beds such as aquiclude or aquifuges. Recharge of this aquifer takes place only in the area where it is exposed at ground surface. The water in the confined aquifer will be under pressure and hence the piezo-metric level will be much higher than the top level of the aquifer.

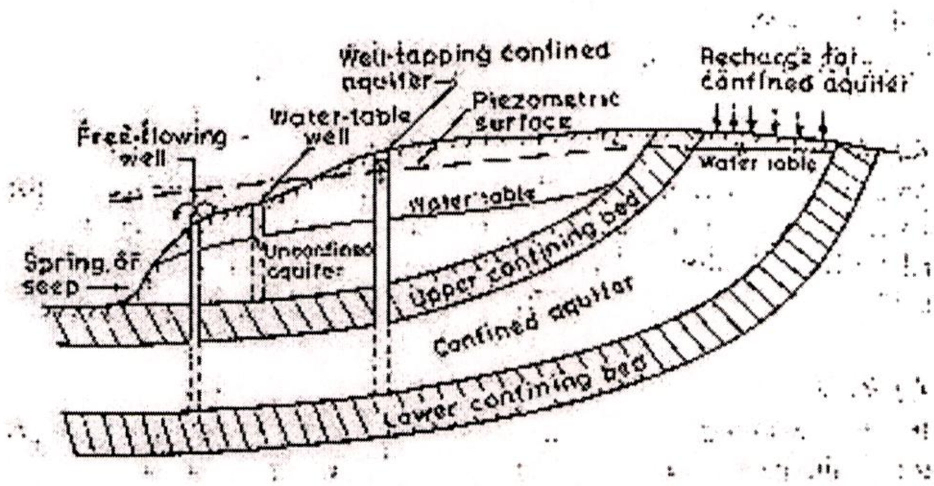


Fig 1.2: confined and unconfined aquifers

1.5 WATER TABLE

A water table is the free water surface is an unconfined aquifer. The static level of a well penetrating an unconfined aquifer indicated the level of the water table at that point.

The position of water table relative to the water level in a stream determines whether the stream contributes water to the groundwater storage or the other way about. If the bed of the stream is below the groundwater table, during periods of low flows in the stream, the water surface may go down below the general water table elevation and the groundwater contributes to the flow in the stream. Such stream which receive groundwater flow are called effluent streams (gaining streams). Perennial rivers and streams are of this kind. If, however, the water table is below the bed of the stream, the stream-water percolates to the groundwater storage and a hump is formed in the groundwater table. Such stream which contribute to the groundwater are known as influent streams (losing streams).

1.6 AQUIFER PROPERTIES

1.6.1 POROSITY

The amount of pores space per unit volume of the aquifer material is called porosity. It is expressed as

$n = v_v / v_o$

Where n= porosity,

V_v= volume of voids,

V_O= volume of the porous medium

1.7 INFILTRATION PROCESS

It is well-known that when water is applied to the surface of a soil, a part of it seeps into the soil. This movement of water through the soil surface is known as Infiltration and plays a very significant role in the runoff process by affecting the timing, distribution and magnitude of the surface runoff. Further, infiltration is the primary step in the natural groundwater recharge.

Infiltration is the flow of water into the ground through the soil surface and the process can be easily understood through a simple analogy. Consider a small container covered with wire guage as in Fig. 1.3. If water is poured over the guage, a part of it will go in container and a part overflows. Further, the container can hold only a fixed quantity and when it is full no more flows into the container can take place. This analogy, though a highly simplified one, underscores two important aspects, viz., the maximum rate at which the ground can absorb water, the infiltration capacity and the volume of water that it can hold, the field capacity.

Since the infiltered water may contribute to groundwater discharge in addition to increasing the soil moisture, the process can be schematically modelled as in Fig. 1.3. This figure considers two situations, viz. Low-intensity rainfall and high intensity rainfall, and is self-explanatory.

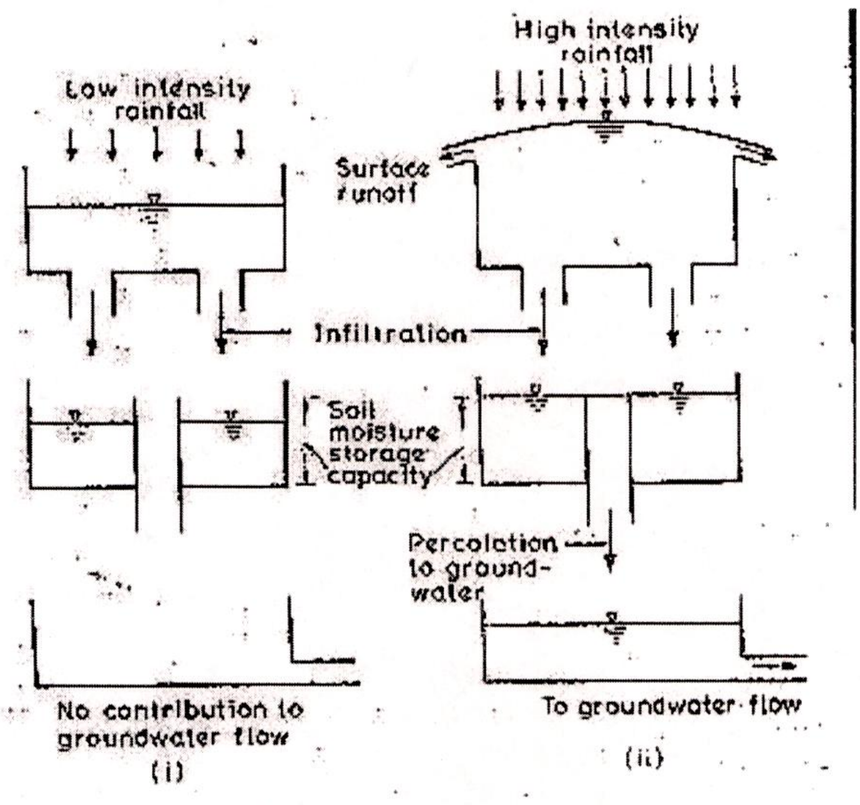


Fig 1.3: An infiltration model

1.7.1 INFILTRATION CAPACITY

The maximum rate at which a given soil at a given time can absorb water is defined as the infiltration capacity. It is designated as fc and is expressed in units of cm/hr. The actual rate of infiltration f can be expressed as

$f = fc$ when $i > fc$

$f = i$ when $i < fc$

Where i= intensity of rainfall. The infiltration capacity of a soil is high at the beginning of a storm and has an exponential decay as the time elapses. The infiltration process is affected by a large number of factor and a few important ones affecting fc are described below.

2.0 GENERAL INTRODUCTION AND OVERVIEW OF HYDRUS-1D

Background Theory

Naturally surface water reaches groundwater in form of precipitation that fall down to the ground surface but also could be more artificial forms, for instance, irrigation, surface runoff, stream flow, lakes. Rainfall or irrigation may infiltrates to groundwater if their intensity is larger than the infiltration capacity of the soil (the maximum rate at which water absorbed by soil). Some precipitation or irrigation water may be intercepted by vegetation and then return to the atmosphere as evaporation from leave surfaces. Some infiltrated water may be taken up by plant roots and then given back to atmosphere as transpiration via leaves. The water that has not been lost through evapotranspiration (evaporation plus transpiration) has a chance to percolate downwards to a deeper vadose zone and eventually reach the groundwater table or saturated zone. If the groundwater table is shallow then groundwater may move upward to the root zone by vapor diffusion and by capillary rise. A schematic representation of the unsaturated zone is shown in Figure 2.1.

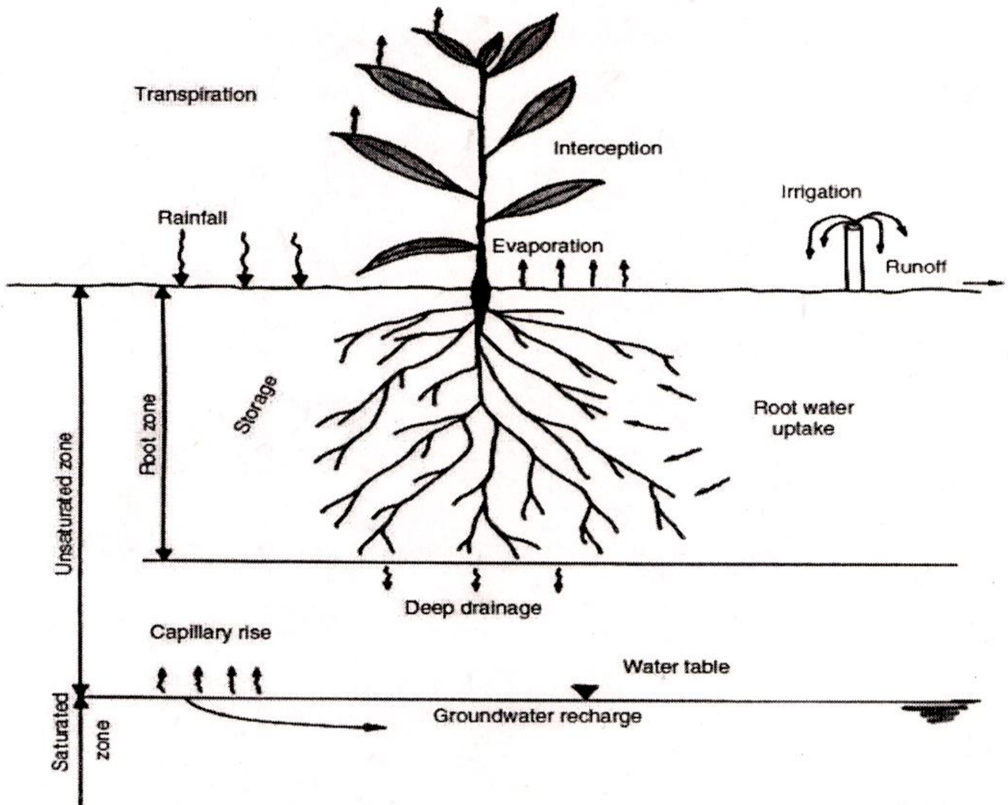


Fig 2.1: Schematic of water fluxes and various hydrologic components in the vadose zone (Simunek and Genuchten, 2006).

Infiltration is considered to be an extremely complex process. It is a function of not only soil hydro physical properties (soil water retention and hydraulic conductivity) and rainfall characteristics (intensity and duration) but also controlled by initial water content, surface sealing and crusting, vegetation cover and ionic composition of infiltrated water. Solute infiltration occurs in vadose zone or unsaturated zone or zone of aeration. In this zone pores usually are partially saturated with water, and those ones which are not filled with water filled with air instead. However in vadose zone may exist some saturated zones, for instance, perched water above impermeable soil layer (Simunek and Genuchten, 2006). Vadose zone play incredibly important role in water and solute transport, because it functioning as:

- a storage medium, where biosphere has immediate access;
- a buffer zone, which controls and could prevent transport of contaminants downward to ground water;
- a living environment, where varies physical and chemical processes take place, which can isolate and slowdown exchange of contaminants with other environments (Nimmo, 2006).

2.1 Water Flow in Unsaturated Zone

Water flow in vadose zone is usually described by a combination of continuity equation 2.1 and Darcy–Buckingham eq. 2.3. The continuity equation 4.1 states that change in water content in a given volume of soil, because of spatial changes in water fluxes and possible sources and sinks within that volume of soil:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_i}{\partial z_i} - S$$
eq. 2.1

Where θ is the volumetric water content, $[L^3L^{-3}]$, t is time [T], q is the volumetric flux density $[LT^{-1}]$, z_i is the spatial coordinate [L], and S is a general sink or source term $[L^3L^{-3}T^{-1}]$, for example, root water uptake.

Darcy (1856) made an experiment on the seepage of water through a pipe filled with sand. He proved that the flow rate Q through pipe filled with a sand was directly proportional to its cross-sectional area A and to the difference of hydraulic head h across the layer, and inversely proportional to the length of the pipe:

$$Q = -KA\frac{h_2 - h_1}{\Delta L}$$
eq. 2.2

Where coefficient of proportionality K is a hydraulic conductivity, $[LT^{-1}]$.

Firstly Darcy's law was implemented to the partly saturated flow by Buckingham (1907) and he found that in this case the hydraulic conductivity is a function of water content K=K (θ). This means that a small decrease in θ leads to a significant decrease in K. That is why for many soils the difference between hydraulic conductivities below and above water table might be great.

Normally it is assumed that unsaturated flow has virtually vertical direction in contrast to saturated flow below the water table, which usually is horizontal or in parallel to impervious layers. This because at interface, where soils with different hydraulic conductivities are meet "streamlines exhibit a pronounced refraction" (Brutsaert, 2005). Darcy's law was developed for an unsaturated medium:

$$q = -K(\theta)\frac{\partial h}{\partial z}$$

eq. 2.3

Where *h* is hydraulic head and defined as:

$$h = H(\theta) - z$$

eq. 2.4

Combination of equations 2.3 and 2.1 and is called Richards' equation and it describes vertical downward movement of water in unsaturated zone

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial H}{\partial z} - 1\right)\right] - S$$

eq. 2.5

Where *H* is soil water pressure head relative to atmospheric pressure ($H \leq 0$).
Richards' equation is partially differential and highly non-linear as θ-*H*-*K* has a non-linear relationship in nature, which also indicates its strongly physically based origin. Moreover boundary conditions at a soil surface are changing irregularly. That is why it might be solved analytically only for limited boundary conditions. If relationships between θ-*H*-*K* are known, numerical solutions may solve the equation for various top boundary conditions (Dam, et al., 2004).
In this study solute transport was numerically simulated by HYDRUS-1D. The software uses modified Richards' equation (2.6) and describes infiltration in vadose zone and modeling it as one dimensional vertical flow.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial H}{\partial z} - cos\alpha\right)\right] - S$$

eq. 2.6

Where H is the water pressure head [L], α is the angle between the flow direction and the vertical axis (i.e., α = *00* for vertical flow, *900* for horizontal flow, and *00* < α < *900* for inclined flow), and K is the unsaturated hydraulic conductivity [LT^{-1}] given by (Simunek, et al., 2005).

$$K(h,z) = K_s(r)\, K_r\, (h,z) \quad \text{eq. 2.7}$$

where Kr is the relative hydraulic conductivity [-] and Ks the saturated hydraulic conductivity [LT^{-1}].

2.1.1 Flow in single-porosity system

Water and solute movement in unsaturated zone was simulated by HYDRUS-1D using simple single porosity flow model (Figure 2.2). Single porosity model describes uniform flow in porous media while the other models are applied to simulate preferential flow or transport. In this case Richards' equation and Fickian-based convection-dispersion equation for solute transport are solved for the entire flow domain.

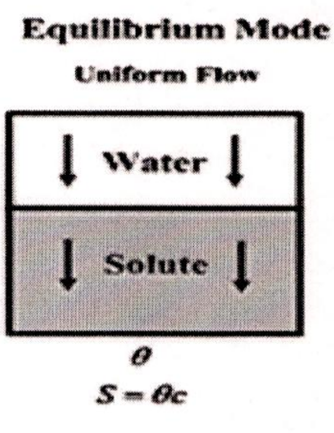


Fig 2.2: Conceptual physical equilibrium model for water flow and solute transport in a single-porosity system (Simunek et al., 2005).

2.2. The Unsaturated Soil Hydraulic Properties

The unsaturated soil hydraulic properties, θ (*h*) and *K* (*h*), in (2.1) are in general highly Nonlinear functions of the pressure head. HYDRUS permits the use of five different analytical Models for the hydraulic properties [*Brooks and Corey*, 1964; *van Genuchten*, 1980; *Vogel and Císlerová*, 1988; *Kosugi*, 1996; and *Durner*, 1994].

The soil water retention, θ (*h*), and hydraulic conductivity, *K* (*h*), functions according to *Brooks and Corey* [1964] are given by

$$S_e = \begin{cases} |\alpha h|^{-n} & h < -1/\alpha \\ 1 & h \geq -1/\alpha \end{cases}$$

$$K = K_s \, S_e^{2/n+l+2}$$

eq. 2.8

respectively, where *Se* is effective saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

eq. 2.9

in which θ*r* and θ*s* denote the residual and saturated water contents, respectively; *Ks* is the Saturated hydraulic conductivity, α is the inverse of the air-entry value (or bubbling pressure), *n* is a pore-size distribution index, and *l* is a pore-connectivity parameter assumed to be 2.0 in the original study of *Brooks and Corey* [1964]. The parameters α, *n* and *l* in HYDRUS are considered to be empirical coefficients affecting the shape of the hydraulic functions.

HYDRUS also implements the soil-hydraulic functions of *van Genuchten* [1980] who used the statistical pore-size distribution model of *Mualem* [1976] to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters.

The expressions of *van Genuchten* [1980] are given by

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases}$$

eq. 2.10

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2$$ eq. 2.11

where

$$m = 1 - 1/n \ , \quad n > 1$$ eq. 2.12

The above equations contain five independent parameters: θr, θs, α, n, and Ks. The pore connectivity parameter l in the hydraulic conductivity function was estimated [*Mualem*, 1976] to be about 0.5 as an average for many soils.

Application of Mualem's pore-size distribution model [*Mualem*, 1976] now leads to the following hydraulic conductivity function:

$$K = \begin{cases} K_s S_e^l \left\{ \frac{1}{2} erfc \left[\frac{\ln(h/\alpha)}{\sqrt{2}n} + n \right] \right\}^2 & (h < 0) \\ K_s & (h \geq 0) \end{cases}$$ eq. 2.13

Durner [1994] divided the porous medium into two (or more) overlapping regions and suggested to use for each of these regions a van Genuchten-Mualem type function [*van Genuchten*, 1980] of the soil hydraulic properties. Linear superposition of the functions for each particular region gives then the functions for the composite multimodal pore system [*Durner et al.*, 1999]:

$$S_e = w_1[1 + (\alpha_1 h)^{n_1}]^{-m_1} + w_2[1 + (\alpha_2 h)^{n_2}]^{-m_2}$$ eq. 2.13

Combining this retention model with *Mualem*'s [1976] pore-size distribution model leads now to:

$$K(S_e) = K_s \frac{\left(w_1 S_{e_1} + w_2 S_{e_2}\right)^l \left(w_1 \alpha_1 [1 - (1 - S_{e_1}^{1/m_1})^{m_1}] + w_2 \alpha_2 [1 - (1 - S_{e_2}^{1/m_2})^{m_2}]\right)^2}{\left(w_1 \alpha_1 + w_2 \alpha_2\right)^2}$$ eq. 2.14

where wi are the weighting factors for the two overlapping regions, and αi, ni, mi (=1-1/ni), and l are empirical parameters of the separate hydraulic functions (i=1,2).

2.3. Initial and Boundary Conditions

The solution of Eq. (eq. 2.6) requires knowledge of the initial distribution of the pressure head within the flow domain:

$h\ (x,y) = hi(x) \qquad t = t0 \qquad$ eq. 2.15

where hi [L] is a prescribed function of x, and to is the time when the simulation begins.

2.3.1. System-Independent Boundary Conditions

One of the following boundary conditions must be specified at the soil surface (x=L) or at the bottom of the soil profile (x=0):

$$h(x,t) = h_0(t) \qquad \text{at } x = 0 \text{ or } x = L$$

$$-K(\frac{\partial h}{\partial x} + \cos\alpha) = q_0(t) \qquad \text{at } x = 0 \text{ or } x = L$$

$$\frac{\partial h}{\partial x} = 0 \qquad \text{at } x = 0$$

eq. 2.16

where $h0$ [L] and $q0$ [LT^{-1}] are the prescribed values of the pressure head and the soil water flux at the boundary, respectively.

2.3.2. *System-Dependent Boundary Conditions*

In addition to the system-independent boundary conditions given by (2.15), we consider two system-dependent boundary conditions, which cannot be defined a priori. One of these involves the soil-air interface, which is exposed to atmospheric conditions. The potential fluid flux across this interface is controlled exclusively by external conditions. However, the actual flux depends also on the prevailing (transient) soil moisture conditions near the surface. The soil surface boundary condition may change from a prescribed flux to a prescribed head type condition (and vice-versa). The numerical solution of (2.6) is obtained by limiting the absolute value of the surface flux by the following two conditions [*Neuman et al.*, 1974]:

$$|-K\frac{\partial h}{\partial x}-K|\leq E \quad \text{at } x=L$$

eq. 2.17

And

$$h_A \leq h \leq h_S \quad \text{at } x=L$$

eq. 2.18

where E is the maximum potential rate of infiltration or evaporation under the current atmospheric conditions [LT^{-1}], and hA and hS are, respectively, minimum and maximum pressure head at the soil surface allowed under the prevailing soil conditions [L]. The value for hA is determined from the equilibrium conditions between soil water and atmospheric water vapor, whereas hS is usually set equal to zero; if positive, hS represents a small layer of water ponded which can form on top of the soil surface during heavy rains before initiation of runoff. One options in HYDRUS is to assume that any excess water on the soil surface above zero will be immediately removed. When one of the end points of (2.16) is reached, a prescribed head boundary condition will be used to calculate the actual surface flux. Methods of calculating E and hA on the basis of atmospheric data have been discussed by *Feddes et al.* [1974].

Another option in HYDRUS is to permit water to build up on the surface. If surface ponding is expected, a "surface reservoir" boundary condition of the type [*Mls*, 1982]

$$-K(\frac{\partial h}{\partial z}+\cos\alpha)=q_0(t)-\frac{dh}{dt} \quad \text{at } x=L$$

eq. 2.18

may be applied. The flux $q0$ in this equation is the net infiltration rate, i.e., the difference between precipitation and evaporation. Equation (4.18) shows that the height h (L, t) of the surface water layer increases due to precipitation, and reduces because of infiltration and evaporation.

A third system-dependent type boundary condition considered in HYDRUS is a seepage face at the bottom of the soil profile through which water can leave the saturated part of the flow domain. This type of boundary condition assumes that a zero-flux boundary condition applies as long as the local pressure head at the bottom of the soil profile ($x = 0$) is negative. However, a zero pressure head will be used as soon as the bottom of the profile becomes saturated. This type of boundary condition often applies to finite lysimeter that are allowed to drain under gravity.

Another system-dependent boundary condition, which can be used at the bottom of the soil profile involves flow to a horizontal subsurface tile drains. HYDRUS-1D permits two different analytical solutions to be used to approximate tile drainage. The first solution is known as the Hooghoudt equation [*Houghoudt*, 1940; *van Hoorn*, 1998; *van Dam et al.*, 1997]: where *qdrain* is the drain discharge rate per unit surface area [LT^{-1}], *KhTop* and *KhBot* are the horizontal saturated hydraulic conductivities above and below the drain system [LT^{-1}],

$$q_{drain} = \frac{8K_{hBot}D_{eq}h_{dr} + 4K_{hTop}h_{dr}^2}{L_{dr}^2} + \frac{h_{dr}}{\gamma_{entr}}$$

eq. 2.19

respectively; *hdr* is the water table height above the drain at the midpoint between the drains, i.e., the hydraulic head needed for calculating subsurface flow into the drains [L], *Ldr* is the drain spacing [L], *γentr* is the entrance resistance into the drains [T], and *Deq* is the equivalent depth [L].

The equivalent depth as introduced by Hooghoudt is a function of *Ldr*, the depth to an impervious layer, and the drain radius. HYDRUS-1D adopts a numerical scheme as used in the SWAT model [*van Dam et al.*, 1997]. When the drains are located in a homogeneous soil profile just above an impervious layer, (2.19) simplifies as follows:

$$q_{drain} = \frac{4K_h h_{dr}^2}{L_{dr}^2} + \frac{h_{dr}}{\gamma_{entr}}$$

eq. 2.20

where *Kh* is the horizontal saturated hydraulic conductivity [LT^{-1}].

3.0 Objectives

- The main aim of this research is to study Soil Moisture flow in the vadose zone in NIH through investigating downward movement of water.
- Examination of temporal variability in precipitation and implications of precipitation patterns on Soil Water Storage and the downward movement of water in different types of soils
- Estimation of Hydrological Soil Properties.

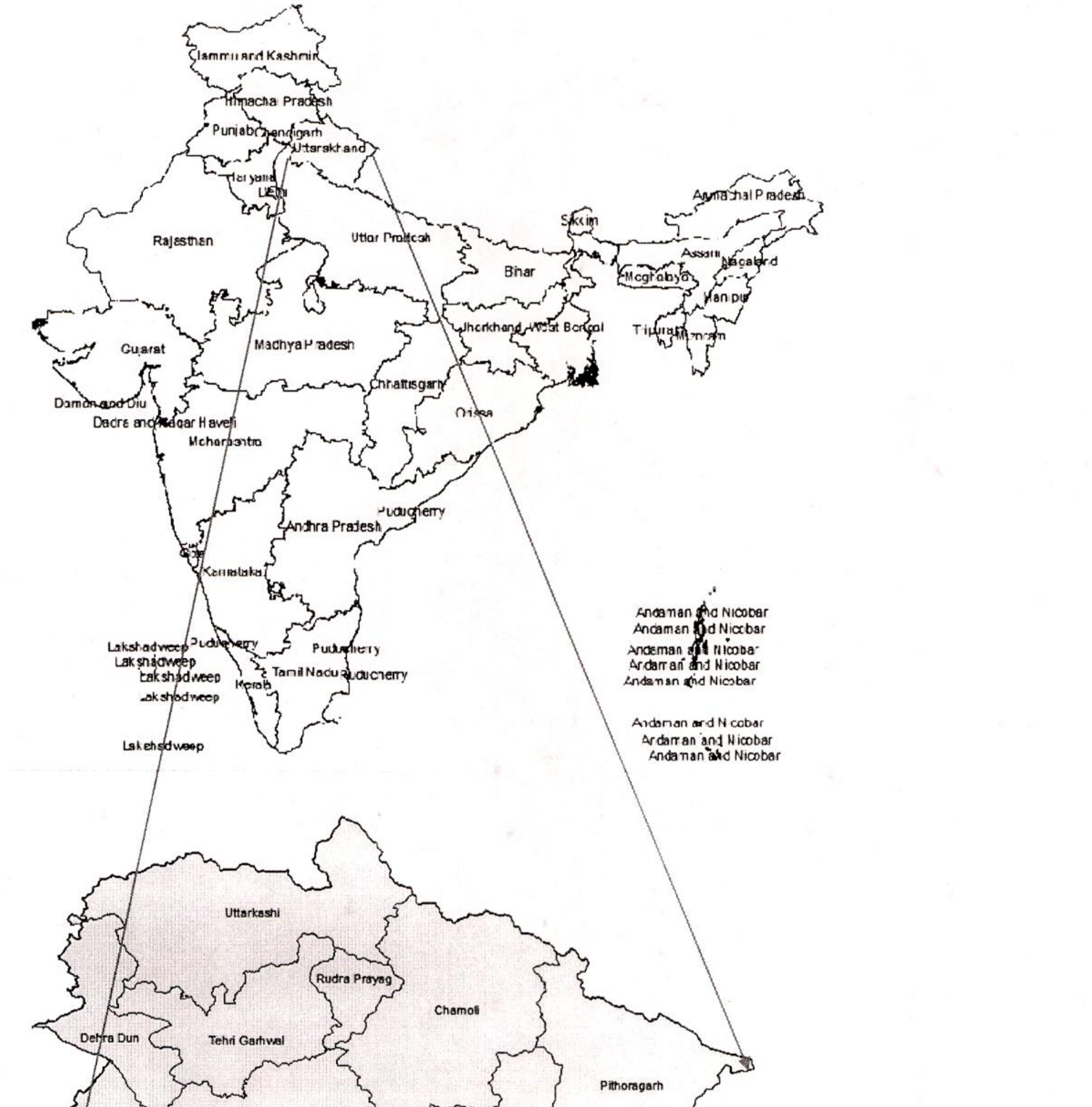
4.0 LOCATION OF STUDY AREA:

The site i.e. within the boundary of NIH main building near NIH observatory was selected.

TABLE 4.1: LIST OF EXPERIMENTAL SITE.

Sr no.	Name of the site
1	NIH, Roorkee

The location of study area may be well understood by the following maps:



4.1 DESCRIPTION OF STUDY AREA:

4.1.1 Topography

The study area is located near the NIH observatory in an open garden within the NIH boundary in Roorkee.

The study area is a part of the Indo-Gangetic alluvium, located in the district Haridwar of Uttarakhand within the latitudes and longitudes of 29° 50' 24" to 29° 54' 36" N and 77° 50' 24" to 77° 55' 48" E.

The town is situated on the right bank of the river Solani, a tributary of the river Ganga, and skirted in the north by a piedmont zone of Siwalik foothills. The Upper Ganga Canal, which was built in 1854, originates at Haridwar and is branched into Deoband branch, Muhammadpur and Basera distributaries. The main canal is 230 km long and is disserted with many cross drainage structure. Most of the area gets benefited from these canal systems, which somehow, neutralize the lowering trend of the water table. Its flow through the Roorkee town divides the town into two parts.

4.1.2 Climate and Rainfall

The study area has a moderate to sub-tropical monsoon. The rainy season (monsoon) extends from 15th June to 15th September. The average annual rainfall is about 1000 mm of which 85% is received during the monsoon season. Out of this amount, only around 200 mm percolates through the soil layer to recharge the aquifers.

4.1.3 Temperature

The region experiences higher temperature during the months of May and June, with average maximum of 40° C and minimum of 5° C.

4.1.4 Soil

In general, the subsurface geological formations, as evident from the geological sections and individual lithologs, are composed of top soil made up of surface clay underlain by strata composed of sandy horizons, occasionally mixed with gravel beds and clay beds often, characterized with the present of Kankar.

The roorkee town is mainly an urbanized area within its city limits. The drinking water demand of the city rests almost completely on its groundwater resources.

5.0 Literature review

1. Introduction

Rising economies population pressure makes planning and management of water resource very crucial. The study of water resource management has essentially gained importance in the research arena owing to its concerned depletion. "During the last several decades, the study of the movement of water and solutes in the unsaturated zone has become an issue of great significance due to profound effects of the physical and chemical processes occurring in this zone on the quality of both surface and subsurface waters"(Saifadeen and Gladnyeva 2011). It is generally known that the Studies have focused to find ways in which water accessibility and use are matched, and seek out to develop alternative sources and water allocation strategies. Subsequently various methods of water resource studies involving field based procedures along with the use of various software based studies have evolved over time to not only study the surface water but the ground water as well. Ground water studies involving the study of the process of precipitation, runoff, infiltration subsequent movement of water and the evaporation, transpiration contributes greatly in the availability of water.

2. Understanding Groundwater Studies

Nielsen (1986) gives an account of the current conceptual understanding of the basic processes of water flow and chemical transport in the unsaturated (vadose) zone and of various deterministic mathematical models that are being used to describe these processes. During the past few decades, tremendous effort has been directed toward unravelling the complexities of various interactive physical, chemical, and microbiological mechanisms affecting unsaturated flow and transport, with contributions being made by soil scientists, geochemists, hydrologists, soil microbiologists, and others. Thus a more unified and interdisciplinary approach is needed that considers the most pertinent physical, chemical, and biological processes operative in the unsaturated zone.

Challenges for both fundamental and applied researchers to reveal the intricacies of the zone and to integrate these with currently known concepts are numerous, as is the urgency for progress inasmuch as our soil and ground water resources are increasingly subjected to the dangers of long-term pollution. Specific research areas in need of future investigation are outlined.

Vadose zone flow processes have rarely been properly represented in hydrologic models (Ward, 2002; Scanlon, 2002; Keese et al., 2005). For example, models that simulate surface and near-surface hydrology usually oversimplify the impact of vadose zone flow processes and rarely consider three-dimensional regional groundwater flow. Similarly, regional-scale groundwater models often simplify vadose zone flow processes by calculating groundwater recharge externally without proper consideration of changes in groundwater levels (e.g., Lorenz and Delin, 2007; Shah et al., 2007; Uddameri and Kuchanur, 2007). To overcome this frequent simplification, there is an urgent need for methods that can effectively simulate water flow through the vadose zone in large-scale hydrologic models (Winter et al., 1998). This issue is especially important for groundwater models.

Genuchten (2007) states that accurate process-based modeling of nonequilibrium water flow and solute transport remains a major challenge in vadose zone hydrology. Our objective here was to describe a wide range of nonequilibrium flow and transport modeling approaches available within the latest version of the HYDRUS-1D software package. The formulations range from classical models simulating uniform flow and transport, to relatively traditional mobile-immobile water physical and two-site chemical nonequilibrium models, to more complex dual-permeability models that consider both physical and chemical nonequilibrium. The models are divided into three groups: (i) physical nonequilibrium transport models, (ii) chemical nonequilibrium transport models, and (iii) physical and chemical nonequilibrium transport models. Physical nonequilibrium models include the Mobile-Immobile Water Model, Dual-Porosity Model, Dual-Permeability Model, and Dual-Permeability Model with Immobile Water. Chemical nonequilibrium models include the One Kinetic Site Model, the Two-Site Model, and the Two Kinetic Sites Model Finally, physical and chemical nonequilibrium transport models include the Dual-Porosity Model with One Kinetic Site and the Dual-Permeability Model with Two-Site Sorption. Example calculations using the different types of nonequilibrium models are presented. Implications for the formulation of the inverse problem are also discussed. The many different models that have been developed over the years for nonequilibrium flow and transport reflect the multitude of often simultaneous processes that can govern nonequilibrium and preferential flow at the field scale.

The rainfall of Korea in the summer monsoon period occupies more than 50% of the annual precipitation in most areas, and thus groundwater recharge to shallow aquifers is dominantly controlled by the amount and the pattern of monsoon precipitation. An infiltration model is presented for analyzing variability of precipitation recharge in relation to the monsoon rainfall. The model simulates the unsaturated flow from time series data of precipitation and pan evaporation, assuming immediate removal of surface ponding, a linear relationship between the evaporation rate and the soil water content, and a static water table. Numerical simulations were performed for three soil textural groups by using 20-year meteorological data. The results demonstrate that the annual recharge is linearly proportional to the annual precipitation with varying degrees of the correlation coefficient depending on soil types. Sensitivity analyses show that the uncertainties in evaporation-related model parameters significantly affect the model results with controlling tradeoff between recharge and evaporation estimates (Koo et. al 2008).

Modelling solute transport through the vadose zone is difficult due to the complicated networks of interconnected pathways in the soil which can transmit water and its solutes at varying velocities. Preferred pathways resulting from biological and geological activity may transmit water (and its solutes) at very much higher rates than those predicted by

Darcy's theory. Therefore, current transport models for water and solutes based on the assumption of Darcian flux, eg. Richards' equation and the Convective-Dispersive equation may significantly under-estimate the risk to groundwater supplies because they do not consider explicitly preferential flow paths but model the bulk flow in an "average" path. A preferential solute transport model developed by us simulates the effects of natural heterogeneities in the soil layer by identifying paths responsible for the transport of water and solutes. The soil-water hydraulic conductivity function is used to identify these paths and the interaction between these paths are described by mixing functions. This paper discusses the nature of preferential flow and illustrates application of the model to several field experiments (Parlange 1996).

Mohanasundaram et. al (2013) made an attempt has been made to model fluid flow through a geological unit consisting of sandy-clay and clayey soil with significant macro pores. Considering such a geological formation using a single-continuum approach may not always be justified as the porosity and permeability contrast between the soil matrix and macro pore vary by several orders of magnitude and not by a scale factor. Under such circumstances, deducing the mean values of parameters such as porosity and permeability using conventional Representative Elementary Volume from a single continuum becomes nearly impossible. For this purpose, a numerical model has been developed to investigate the consequences of applying both equilibrium model or Single-Porosity Medium (SPM) and non-equilibrium model or Dual-Porosity Medium (DPM) approaches for the same soil types. Numerical results suggest that the depths associated with soil moisture fronts are significantly different by applying a dual continuum approach with reference to the conventional single-continuum approach.

Lewandowska (2004) in the study focuses on the "Multi-scale, multi-components, multi phases" being the key words that characterize the double porosity media, like fissured rocks or aggregated soils, subject to geo-environmental conditions. An integrated upscaling approach to the modelling of unsaturated water flow in double porosity media. This approach combines three issues: theoretical, numerical and experimental. Schmalz et. al. (2003) states that a realistic, physically based simulation of water and solute movement in the unsaturated soil zone requires reasonable estimates of the water retention and unsaturated hydraulic conductivity functions. A variety of studies have revealed the importance of how these unsaturated soil parameters are assessed and subsequently distributed over the numerical mesh on modeling outcome. This study was initiated to acquire experimental data about the water flow characteristics of sandy soils to serve as a base for numerical analyses. Specific objectives were to clarify the effects of

(i) The invoked procedure for estimating the soil hydraulic parameters and

(ii) Using increasingly refined spatial definitions of the hydraulic properties on simulated two dimensional water content and flow velocity distributions. Weeks (2004) paper considers the two-dimensional saturated and unsaturated flow of water through inclined porous media, namely a waste dump or hill slope. Since the partial differential equation governing this water flow transforms from being parabolic to elliptic as the water flow varies from unsaturated to saturated, an iterative, finite differencing scheme is used to develop a numerical solution. The model can be used to investigate the effects that hill slope angle, depth of soil cover and hilltop width have on water accumulation in the dump and the time required for saturation to occur at different areas in the dump domain. The accuracy and reliability of the computer based solution is tested for two different boundary conditions –

(1) No flow on all boundaries (i.e., the internal redistribution of soil moisture to steady state) and

(2) A constant rainfall flux on the dump surface. Numerical studies then show the effects of changing the hill slope angle, depth of layer, and dump geometry on the flow characteristics in the dump.

3. Use of HYDRUD-1D model

Numerical models have become much more efficient, making their application to problems increasingly widespread. User-friendly interfaces make the setup of a model much easier and more intuitive while increased computer speed can solve difficult problems in a matter of minutes. Modeling and Applications demonstrates one- and two-dimensional simulations and computer animations of numerical models using the HYDRUS software. This volume includes numerous examples and homework problems. It provides students with access to the HYDRUS-1D program as well as the Rosseta Module, which contains large volumes of information on the hydraulic properties of soils. The HYDRUS-1D is used for problems that demonstrate infiltration, evaporation, and percolation of water through soils of different textures and layered soils. It also shows heat flow and solute transport in these systems, including the effect of physical and chemical nonequilibrium conditions (Radcliffe et. al 2010).

In a study, a broad methodology was developed to assess the outcome of soil water hysteresis, and temporal variability in precipitation and evaporation input data on the transport of solutes in soils. To complete this aim, three objective functions were examined, movement of center of mass of solutes, masses into groundwater, and depth to a limit concentration. A one-dimensional unsaturated transport model was used to simulate non-reactive transport of solutes. Simulations were conducted in HYDRUS-1D code using measured precipitation data. Water and solutes movement in the unsaturated zone is extremely complex process due to the varied nature of soil and variable atmospheric boundary conditions at both the soil surface over short time periods. Despite all the simplifications which were made, HYDRUS-1D was discovered to be a powerful tool to simulate the movement of water and solutes in partially saturated porous media different water flow and solute transport boundary conditions. However, to be able to validate the model performance, more data collection and measurements are needed which in turn means more cost-effective sampling and analysis methodologies must be developed (Saifadeen 2011).

Leão and Gentry (2010) did an accurate estimation of hydraulic fluxes in the vadose zone is essential for the prediction of water, nutrient and contaminant transport in natural systems. The objective of this study was to simulate the effect of variation of boundary conditions on the estimation of hydraulic properties (i.e. Water content, effective unsaturated hydraulic conductivity and hydraulic flux) in a one-dimensional unsaturated flow model domain. Unsaturated one-dimensional vertical water flow was simulated in a pure phase clay loam profile and in clay loam interlayered with silt loam distributed according to the third iteration of the Cantor Bar fractal object Simulations were performed using the numerical model Hydrus 1D. There was an increase in water contents, fluxes and hydraulic conductivities with the increase in head difference between boundary conditions. Variation in boundary conditions in the pure phase and interlayered one- dimensional profiles caused significant deviations in fluxes, water contents and hydraulic conductivities compared to the simplest case (a head difference between the upper and lower constant head boundaries of 10 cm in the wetter range and 100 cm in the drier range).

Few other studies like modeling the transport and concentration of major soluble ions in and below the root zone is a requisite for predicting groundwater quality as well as for managing irrigation and fertilization practices (Suarez and Simunek 1997). Few studies have investigated spatiotemporal variations of surface water (SW) – groundwater (GW) interactions (including both hydrologic and nutrient) in the central
U.S. Therefore, understanding of riparian zone and stream connectivity is limited in that region (Chinnasamy 2012).

6.0 Methodology

6.1 Field Experiments

Field experiments consisted of the soil sampling conducted in the study area on January 1st, 2016.

6.1.1 Sampling

The soil sampling was carried out during the month of January 2016. Soil samples were collected layer by layer (30cm sections) with the help of a hand auger of 2" diameter starting from ground surface to about 210 cm. The soil samples were carefully collected and packed in properly scaled Polyethylene bags so that there was no exchange of the moisture with the atmosphere and brought to the laboratory for the analysis.

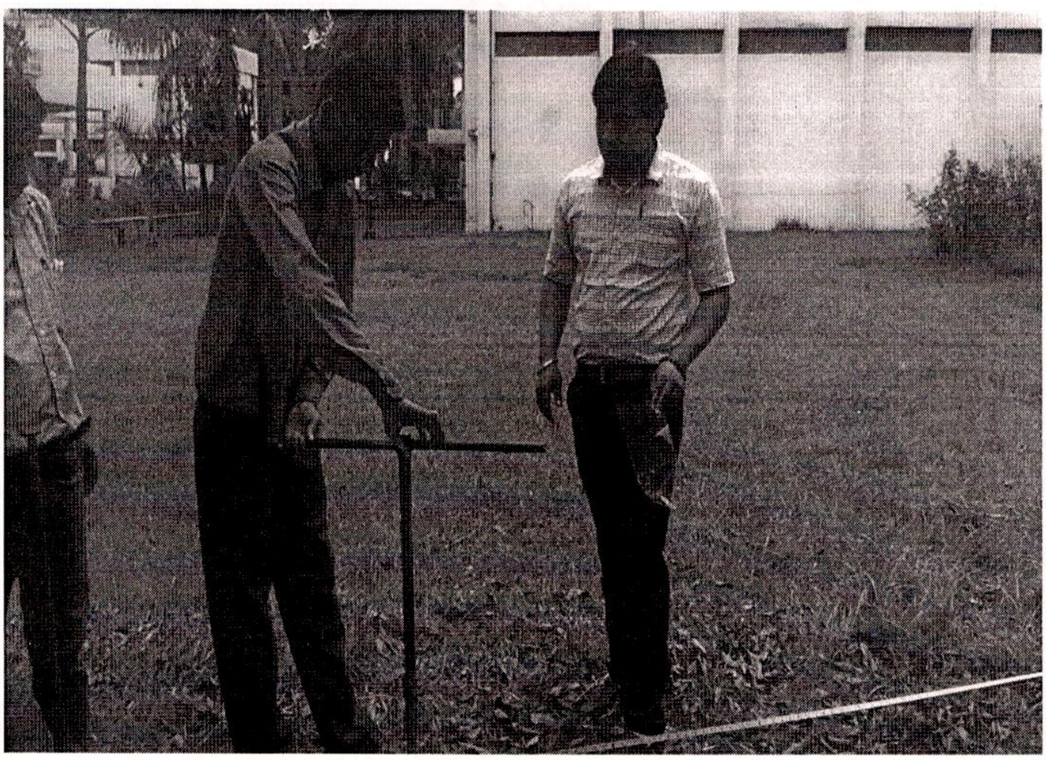


Fig 6.1: Sampling

6.1.2 Field saturated hydraulic conductivity

The constant head Guelph Permeameter device was used to determine the field saturated hydraulic conductivity, matrix flux potential and soil sorpitivity in the field.

Hydraulic conductivity: hydraulic conductivity is the measure of the ability of a soil to conduct water under a unit hydraulic potential gradient.

Field saturated hydraulic conductivity: it refers to the saturated hydraulic conductivity of soil containing entrapped air.

Matrix flux potential: it is a measure of the soil's ability to pull the water by capillary force through a unit cross sectional area in a unit time.

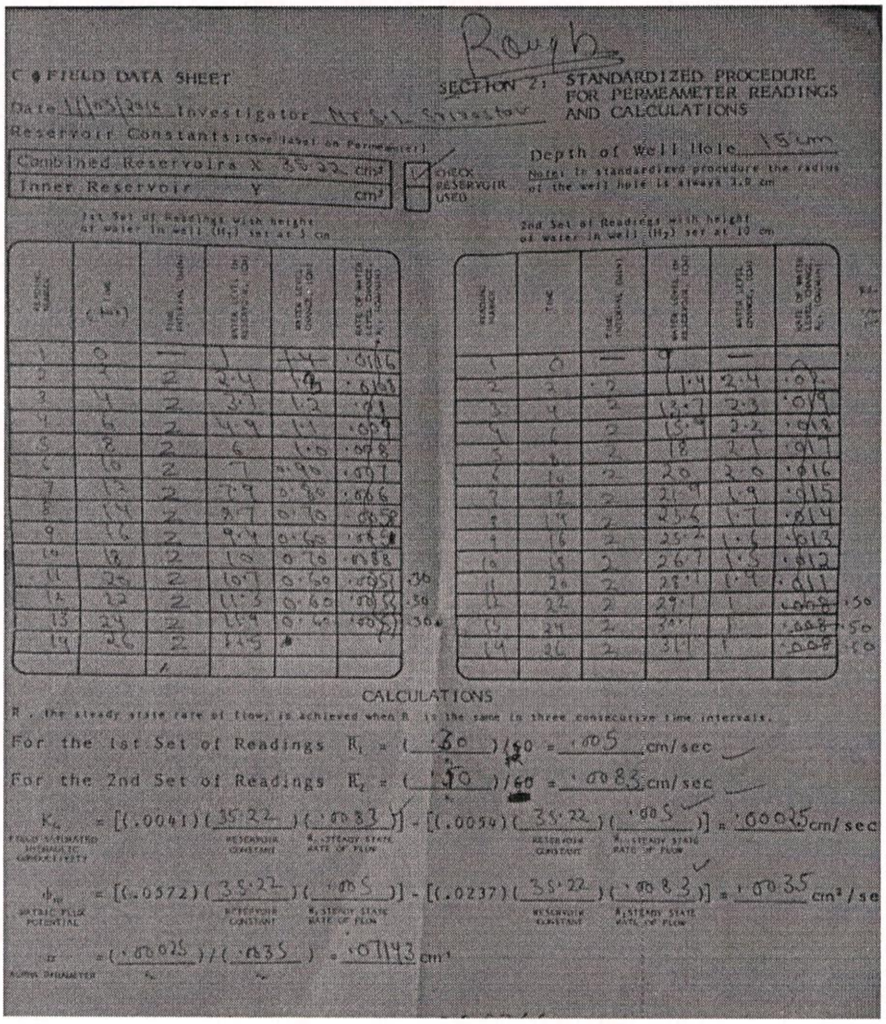
Sorpitivity: it is a measure of the ability of a soil to absorb a wetting liquid.

Fig 6.2: Field saturated hydraulic conductivity using Guelph Permeameter.

Results: Table 6.1

S.NO	DEPTH	K_{fs}	a
	cm	CM/day	CM^{-1}
1	30	52.14	0.00860
2	60	77.4	0.00610
3	90	74.95	0.00650
4	120	97.09	0.00620
5	150	72.45	0.0087
6	180	41.34	0.0105
7	210	46.75	0.0075

Calculations:


Rough

FIELD DATA SHEET

SECTION 2: STANDARDIZED PROCEDURE FOR PERMEAMETER READINGS AND CALCULATIONS

Date 11/03/2016 Investigator [illegible]

Reservoir Constants: (See label on Permeameter)

Combined Reservoirs X 35.22 cm²

Inner Reservoir Y cm²

CHECK RESERVOIR USED

Depth of Well Hole 15 cm

Note: In standardized procedure the radius of the well hole is always 3.0 cm

1st Set of Readings with height of water in well (H_1) set at 5 cm

1	0	—	1	1.4	.0116
2	2	2	2.4	1.3	.0108
3	4	2	3.7	1.2	.01
4	6	2	4.9	1.1	.009
5	8	2	6	1.0	.008
6	10	2	7	0.90	.007
7	12	2	7.9	0.80	.0066
8	14	2	8.7	0.70	.0058
9	16	2	9.4	0.60	.005
10	18	2	10	0.70	.0058
11	20	2	10.7	0.60	.0051 .30
12	22	2	11.3	0.60	.0050 .30
13	24	2	11.9	0.60	.0050 .30
14	26	2	12.5		

2nd Set of Readings with height of water in well (H_2) set at 10 cm

1	0	—	9	—	
2	2	2	11.4	2.4	.02
3	4	2	13.7	2.3	.019
4	6	2	15.9	2.2	.018
5	8	2	18	2.1	.017
6	10	2	20	2.0	.016
7	12	2	21.9	1.9	.015
8	14	2	23.6	1.7	.014
9	16	2	25.2	1.6	.013
10	18	2	26.7	1.5	.012
11	20	2	28.1	1.4	.011
12	22	2	29.1	1	.008 .50
13	24	2	30.1	1	.008 .50
14	26	2	31.1	1	.008 .50

CALCULATIONS

R, the steady state rate of flow, is achieved when R is the same in three consecutive time intervals.

For the 1st Set of Readings R_1 = (.30)/60 = .005 cm/sec

For the 2nd Set of Readings R_2 = (.50)/60 = .0083 cm/sec

K_{fs} = [(.0041)(35.22)(.0083)] - [(.0054)(35.22)(.005)] = .00025 cm/sec

ϕ_m = [(.0572)(35.22)(.005)] - [(.0237)(35.22)(.0083)] = .0035 cm²/sec

α = (.00025)/(.0035) = .07143 cm⁻¹

6.2 Laboratory Experiments

6.2.1 Soil moisture content

The moisture content of the soil samples on wet weight basic was estimated by gravimetric method.

The soil moisture content may be expressed by weight as the ratio of the mass of water present to the dry soil weight of the soil sample, or by volume as ratio of the volume of water to the total volume of the soil sample. To determine any of these ratios for a particular soil samples, the water mass must be determined by drying the soil to constant weight and measuring the soil sample mass after and before drying. The water mass is the difference between the weights of the wet and oven dry samples.

Wet weight of each soil sample was determined by weighting the sampling using electronic balance. After that the soil sample was kept in oven at temperature 100-110 degree Celsius for 24 hours. Next day the dry weight of each samples was determined.

Bulk density for each sample was determined by dividing the wet weight of the sample by the volume of each sample, which was equivalent to the volume of hand auger of known diameter for a particular depth of soil column.

Volumetric moisture content for each soil sample was estimated by multiplying the moisture content obtained on wet weight basis and bulk density of the soil. The values of volumetric moisture content are tabulated in table

Table 6.2. Soil moisture content

	Soil Sample weight		bulk density	wt of	q_d	water density	bulk density/water density	volumetric water content
Depth (cm)	Wet weight (gm)	Dry weight (gm)	g/c.cm	water	(wt of water/ wt of dry soil)	(g/cubic.cm)		q_{vd}
15-30	109	104.05	1.4	4.95	0.047573	1	1.4	0.0666
30-60	89.94	81.86	1.3	8.08	0.098705	1	1.3	0.1283
60-90	134.78	118.05	1.3	16.7	0.141720	1	1.3	0.1842
90-120	119.25	102.66	1.15	16.6	0.161601	1	1.15	0.1858
120-150	90.899	72.94	1.15	18	0.246216	1	1.15	0.2831
150-180	93.05	76.33	1.3	16.7	0.219049	1	1.3	0.2848
180-210	144.5	118.58	1.3	25.9	0.218587	1	1.3	0.2842

6.2.2 Particle size analysis:

The samples collected from the field were tested in the Soil and Groundwater laboratory, National Institute of Hydrology, for carrying out particle size distribution and texture analysis. Particle size distribution of the soil samples was carried out by sieve analysis and master sizer analysis. Soil samples were washed with distilled water to remove the soluble salts. The washed samples were separated into two fractions i.e. +75 micron and -75 micron through wet sieving. Sieve analysis was performed for the fraction of soil retained on 75 micron sieve (+75 micron). The portion passed through the 75 micron sieve (-75 micron) was analyzed by master sizer. The test results of the analysis are given in **Table 6.3**

Table 6.3. Particle size analysis

S.NO	Depth (cm)	ACTUAL SAND (%)	ACTUAL SILT (%)	ACTUAL CLAY (%)	TYPE OF SOIL
1	0-30	53.35	43.93	2.72	LOAM
2	30-60	28	67.14	4.86	SILTY LOAM
3	60-90	18.04	75.68	6.28	SILTY LOAM
4	90-120	11.85	81.37	6.78	SILTY
5	120-130	7.56	82.97	9.47	SILTY
6	150-180	11.36	78.68	9.96	SILTY LOAM
7	180-210	15.26	75.27	9.47	SILTY LOAM

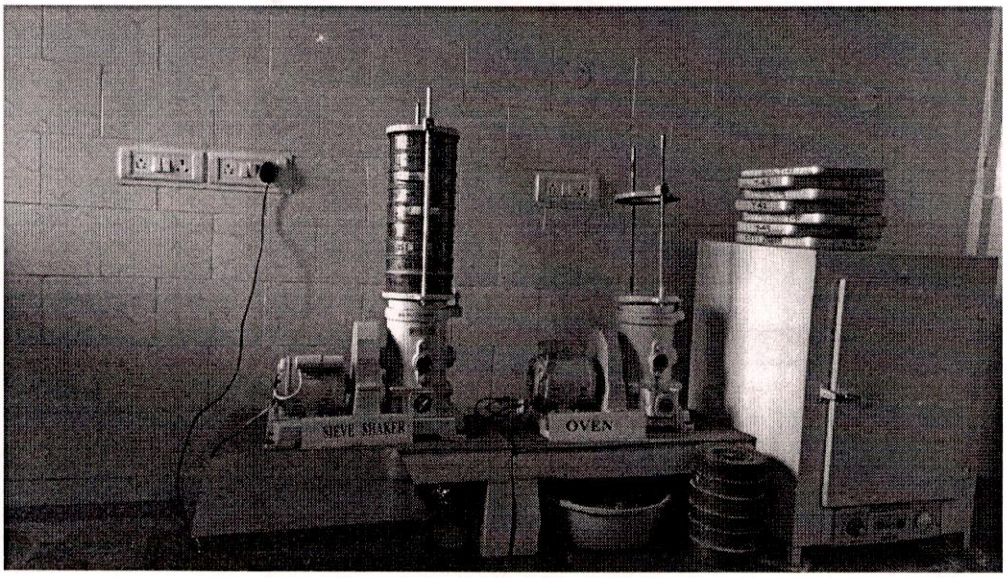


Fig 6.3: Sieve shaker

6.2.3 Pressure Plates Apparatus

This is a standard method for obtaining the soil moisture retention curve. Pressure plate apparatus consists of a pressure chamber in which a saturated soil sample is placed on a porous ceramic plate through which the soil solution passes but no soil particle or air can pass. The soil solution which passes through the membrane is in contact with atmospheric pressure. As soon as the air pressure inside the chambers are raised above the atmospheric it takes excess water from the soil out of the chamber through the membrane outlet. Soil water will flow out from the soil sample until the metric potential of the unsaturated flow is same as the applied air pressure. The air pressure is then, released and the moisture content of the soil is gravimetrically determined.

The samples collected from the field were tested in the Soil and Groundwater laboratory, National Institute of Hydrology, for obtaining the soil moisture retention curve using Pressure plate apparatus. The results are given in **table 6.4**

Table 6.4. Soil Moisture Characteristic Curve

Soil Moisture Characteristic Curve								
AVERAGE MOISTURE CONTENT AT DIFFERENT PRESSURES								
S.NO	H (CM)	SITE-1	SITE-2	SITE-3	SITE-4	SITE-5	SITE-6	SITE-7
1	100	27.40	30.65	36.36	39.76	42.38	40.92	40.37
2	300	22.06	24.74	30.53	33.25	35.83	35.77	35.40
3	500	17.15	20.24	30.53	30.76	33.04	33.03	32.00
4	700	16.62	19.05	30.53	27.12	31.83	32.51	31.71
5	1000	11.50	13.05	16.19	19.53	27.79	27.81	26.32
6	3000	8.80	10.24	16.11	19.25	23.92	24.93	24.37
7	5000	7.28	8.33	13.10	16.96	22.44	22.93	21.67
8	7000	6.05	6.86	11.56	15.29	19.98	22.17	20.60
9	10000	5.57	6.28	10.28	14.63	18.94	20.80	18.65
10	15000	4.75	5.47	9.09	14.03	18.45	20.22	18.50

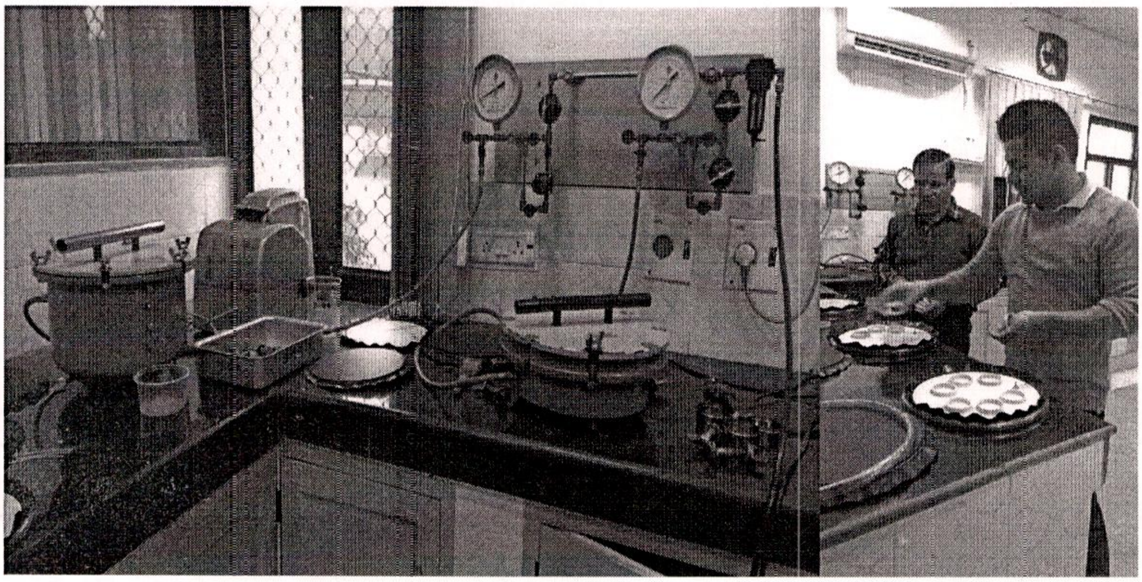


Fig 6.4: Pressure Plates Apparatus

6.3 Introduction to HYDRUS-1D

HYDRUS-1D, a computer software package, can be used in the simulation of movement of water, heat, and solutes in one-dimensional variably saturated porous media. The software can be also used in the simulation of carbon dioxide and major ion solute movement. Basically, it helps in solving the Richards equation numerically, for variably-saturated water flow and advection-dispersion type equations (CDE) for heat and solute transport. The variability in the soil properties is accounted by making modifications in the flow equation. This is done by introducing a sink term to account for water uptake by plant roots, and dual-porosity type flow or dual-permeability type flow to account for non-equilibrium flow.

The software can also work for different water flow and solutes transport boundary conditions (Šimůnek, et al., 2009).

In addition to HYDRUS computer code, the HYDRUS-1D software comes with an interactive graphics-based user interface module which consists of a project manager and a unit for preprocessing and post processing.

6.4 HYDRUS-1D model development

6.4.1 Input data

6.4.1.1 Meteorological data

Precipitation

Precipitation and evapotranspiration were given as an input for time variable boundary conditions in HYDRUS-1D. The study period for the input is 2016. The meteorological data used in the model was obtained from NIH observatory for the site under investigation i.e. within the NIH boundary. Initially the rainfall data were given in daily time resolution in order to investigate the effect of time resolution of the input on the model.

Table 6.5. Meteorological data

NIH Observatory,					
Roorkee	**Temp**	**Temp.**	**Temp,**	**Rain**	**Evp.**
date	**max**	**min.**	**mean**		
	(0C)	**(0C)**	**(0C)**	**(mm)**	**(mm)**
01-01-2016	**24.0**	**9.5**	16.8	0.0	1.1
02-01-2016	**22.0**	**9.5**	15.8	0,0	1.1

03-01-2016	**23.8**	**6.0**	14.9	0.0	0.8
04-01-2016	**23.5**	**7.1**	15.3	0.0	0.9
05-01-2016	**24.5**	**11.0**	17.8	0.0	1.0
06-01-2016	**25.2**	**10.0**	17.6	0.0	1.5
07-01-2016	**24.5**	**8.0**	16.3	0.0	1.0
08-01-2016	**24.0**	**10.0**	17.0	0.0	0.9
09-01-2016	**24.0**	**10.5**	17.3	0.0	1.5
10-01-2016	**21.0**	**10.0**	15.5	0.0	2.0
11-01-2016	**22.5**	**7.4**	15.0	0.0	1.0
12-01-2016	**23.0**	**8.2**	15.6	0.0	0.9
13-01-2016	**24.0**	**9.5**	16.8	0.0	1.1
14-01-2016	**24.0**	**9.2**	16.6	0.0	0.8
15-01-2016	**21.2**	**10.0**	15.6	0.0	0.4
16-01-2016	**15.0**	**10.0**	12.5	0.0	0.6
17-01-2016	**15.0**	**11.6**	13.3	0.0	0.6
18-01-2016	**21.0**	**7.0**	14.0	0.0	0.9
19-01-2016	**21.5**	**8.5**	15.0	0.0	1.1
20-01-2016	**18.0**	**8.5**	13.3	0.0	0.4
21-01-2016	**14.5**	**8.6**	11.6	0.0	0.6
22-01-2016	**11.0**	**8.4**	9.7	0.0	0.9
23-01-2016	**14.8**	**5.0**	9.9	0.0	1.0
24-01-2016	**20.0**	**5.0**	12.5	0.0	0.8
25-01-2016	**20.0**	**6.5**	13.3	0.0	1.0
26-01-2016	**18.0**	**7.1**	12.6	0.0	1.1
27-01-2016	**20.5**	**6.2**	13.4	0.0	0.9
28-01-2016	**22.0**	**6.7**	14.4	0.0	1.2
29-01-2016	**22.5**	**7.8**	15.2	0.0	0.9
30-01-2016	**23.6**	**12.0**	17.8	0.0	1.2
31-01-2016	**26.8**	**12.8**	19.8	0.0	1.4
Total	**655.4**	**267.6**	**461.5**	**0.0**	**30.6**
Mean	21.1	8.6	14.9	0.0	1.0
St.dev	3.762692	1.968991	2.334094	0	0.325312
01-02-2016	23.5	9.2	16.35	0.0	1.6
02-02-2016	23.4	8.0	15.7	0.0	2.0
03-02-2016	22.0	8.5	15.25	0.0	2.2
04-02-2016	23.0	8.4	15.7	0.0	2.4
05-02-2016	23.2	8.5	15.85	0.0	0.9
06-02-2016	25.0	10.0	17.5	0.0	1.5
07-02-2016	24.6	14.0	19.3	1.8	1.8

08-02-2016	17.0	9.5	13.25	5.2	1.2
09-02-2016	24.7	10.0	17.35	0.0	1.7
10-02-2016	26.2	9.8	18.0	0.0	2.0
11-02-2016	26.0	11.0	18.5	0.0	2.2
12-02-2016	25.0	9.6	17.3	0.0	2.0
13-02-2016	26.5	11.2	18.85	0.2	2.4
14-02-2016	15.0	10.0	12.5	1.8	0.7
15-02-2016	26.6	10.4	18.5	0.0	1.5
16-02-2016	25.5	11.0	18.25	0.0	2.0
17-02-2016	27.0	9.4	18.2	0.0	2.2
18-02-2016	28.8	15.8	22.3	0.0	2.3
19-02-2016	31.0	18.2	24.6	0.0	2.5
20-02-2016	26.0	19.0	22.5	0.0	1.2
21-02-2016	30.2	16.4	23.3	0.6	2.5
22-02-2016	26.2	13.0	19.6	0.0	2.9
23-02-2016	27.2	12.0	19.6	0.0	3.6
24-02-2016	29.0	13.0	21.0	0.0	2.6
25-02-2016	29.0	12.4	20.7	0.0	2.5
26-02-2016	29.8	12.5	21.15	0.0	2.7
27-02-2016	30.0	13.5	21.75	0.0	2.7
28-02-2016	30.0	13.6	21.8	0.0	2.7
29-02-2016	30.2	14.2	22.2	0.0	2.4
Total	**751.6**	**342.1**	**546.85**	**9.6**	**60.9**
Mean	**25.0**	**11.4**	**18.2**	**0.3**	**2.0**
Stdev	**5.414409**	**3.363325**	**4.180368**	**1.015662**	**0.717382**
01-03-2016	30.0	14.0	22.0	0.0	2.0
02-03-2016	29.5	14.5	22.0	0.0	2.8
03-03-2016	31.0	15.0	23.0	0.0	2.6
04-03-2016	31.8	16.0	23.9	0.0	2.9
05-03-2016	32.8	17.0	24.9	0.0	4.0
06-03-2016	28.0	15.4	21.7	1.4	2.1
07-03-2016	27.0	15.2	21.1	0.0	1.3
08-03-2016	31.8	17.0	24.4	0.0	2.9
09-03-2016	32.0	16.4	24.2	0.0	3.6
10-03-2016	30.0	16.5	23.3	0.0	3.6
11-03-2016	30.5	18.2	24.4	0.0	4.0
12-03-2016	31.0	18.4	24.7	3.6	5.0
13-03-2016	28.2	17.5	22.9	5.4	2.4
14-03-2016	28.0	15.4	21.7	8.8	3.2

15-03-2016	27.0	14.3	20.7	0.6	2.3
16-03-2016	29.0	15.2	22.1	0.0	4.0
17-03-2016	28.0	15.8	21.9	0.0	3.6
18-03-2016	29.0	20.0	24.5	0.0	2.2
19-03-2016	33.0	18.0	25.5	0.0	3.4
20-03-2016	33.0	20.2	26.6	0.0	4.0
21-03-2016	33.5	16.8	25.2	0.6	5.0
22-03-2016	31.5	14.5	23.0	0.0	6.5
23-03-2016	30.0	15.0	22.5	0.0	6.0
24-03-2016	32.0	15.5	23.8	0.0	4.0
25-03-2016	34.5	18.8	26.7	0.0	3.3
26-03-2016	34.5	21.5	28.0	0.0	3.6
27-03-2016	30.0	19.0	24.5	0.0	3.0
28-03-2016	32.0	18.4	25.2	0.0	4.0
29-03-2016	32.4	19.4	25.9	0.0	4.0
30-03-2016	32.2	18.4	25.3	0.0	3.4
31-03-2016	35.0	19.5	27.3	0.0	4.0

R.H (%) (0830hr)	Wind velocity (km/hr)	Wind dir. (0830 hr)	Weather	Sun shine hour
96	0.5	NW	Partly Cloudy	5.30
94	0.5	NE	Partly Cloudy	4.25
94	0.2	NE	Clear	6.50
96	0.3	NE	Clear	5.00
86	0.5	NE	Clear	4.30
95	0.1	NE	Clear	8.00
86	0.2	NE	Partly Cloudy	4.35
90	0.1	SW	Partly Cloudy	2.10
97	0.2	SW	Partly Cloudy	5.45
95	1.6	NW	Cloudy	4.30

95	0.3	**SW**	**Clear**	7.00
92	0.9	**SW**	**Clear**	6.00
90	0.3	**NE**	**Partly Cloudy**	6.30
100	0.2	**NW**	**Partly Cloudy**	4.05
100	1.0	**NW**	**Dark fog**	0.00
88	1.0	**SW**	**Dark fog**	0.00
83	1.1	**SW**	**Cloudy**	0.00
94	0.3	**SE**	**Partly Cloudy**	4.45
92	0.5	**NW**	**Cloudy**	6.20
98	1.0	**NW**	**Cloudy**	0.2:15
96	1.6	**NW**	**Dark fog**	0.00
92	1.5	**NW**	**Dark fog**	0.00
88	0.5	**SE**	**Partly Cloudy**	5.00
100	0.6	**NW**	**Dark fog**	5.45
99	1.0	**NW**	**Dark fog**	6.30
98	0.9	**NW**	**Fog**	3.40
94	0.3	**NW**	**Cloudy**	4.55
95	0.2	NW	**Clear**	7.00
88	0.4	**SW**	**Partly Cloudy**	4.25
88	0.5	**SE**	**Partly Cloudy**	0.00
91	0.5	**SW**	**Partly Cloudy**	6.25
2890.0	**18.6**			
93.2	0.6			
4.53659	0.442357			
98	1.75	NW	Cloudy	6.10

86	1.5	NW	**Partly Cloudy**	7.48
94	1.6	NW	Clear	7.55
91	2.0	NW	Clear	7.40
92	0.3	SE	Partly Cloudy	3.45
85	0.4	SE	Partly Cloudy	7.25
98	0.8	NW	Cloudy	4.15
83	1.2	NW	Partly Cloudy	0.00
90	0.5	NW	Clear	8.30
98	0.6	NW	Fog in morning	9.05
78	0.3	SW	Clear	8.18
75	0.8	NW	Partly Cloudy	6.30
73	0.9	NW	Cloudy	8.00
63	1.0	NW	Cloudy	0.00
95	0.3	SE	Partly Cloudy	8.55
86	0.4	NW	Partly Cloudy	4.50
78	0.6	NW	Clear	9.02
63	1.7	NW	Partly Cloudy	8.50
77	1.6	NW	Cloudy	5.20
75	0.8	NW	Cloudy	0.00
91	1.3	NW	Cloudy	5.30
84	3.0	NW	Partly Cloudy	6.30
88	2.3	NW	Clear	9.00
84	0.3	NE	Clear	8.40
78	0.8	NW	Clear	8.30
72	0.7	NW	Clear	9.12
78	0.3	SW	Clear	8.40
77	0.3	SW	Clear	6.35
77	0.4	SE	Clear	6.15

2407	**28.2**			
80.8	**0.9**			
17.04393	**0.683883**			
85	0.3	NW	Partly cloudy	4.00
82	0.7	SE	Clear	7.40
82	0.5	SE	Partly cloudy	5.40
83	0.3	NW	Dark fog in morning	8.34
74	1.9	NE	Partly cloudy	8.10
76	2.2	SE	Cloudy	3.00
65	1.1	NW	Cloudy	5.15
81	1.0	NW	Clear	8.58
84	1.0	NW	Clear	9.15
79	1.5	NW	Clear	8.35
74	1.0	SW	Cloudy in night	8.10
76	1.0	NE	Cloudy	2.35
66	1.9	NW	Cloudy	2.40
70	1.5	NW	Cloudy	7.05
78	0.6	NW	Cloudy	5.00
80	0.8	NW	Clear	9.55
75	0.6	SE	Partly cloudy	5.55
59	0.8	SE	Cloudy	4.00
74	0.8	NE	Cloudy	7.00
56	2.6	NW	Partly cloudy	9.25
58	3.0	NW	Clear	8.45
68	2.5	NW	Clear	9.35
73	2.0	NW	Clear	10.04
63	0.8	SE	Clear	9.55
71	2.0	SW	Partly cloudy	8.15
80	1.0	SW	Cloudy	7.35
74	2.2	NE	Partly cloudy	0.55

68	1.5	NW	Clear	8.05
66	2.0	NW	Partly cloudy	9.10
68	1.3	SW	Partly cloudy	6.32
60	1.0	SE	Clear	9.08

Solar radiation

Solar radiation values were obtained by using software CROPWAT 4.16.0110.

Table 6.6. Solar radiation values were obtained by using software CROPWAT 4.16.0110.

Rad
MJ/m?/day
10.5
9.5
11.8
10.3
9.6
13.4
9.7
7.4
10.9
9.7
12.6
11.6
11.9
9.6
5.4
5.4
5.5
10.2
12.1
7.8
5.6
5.6
11
11.6
12.6
9.5
10.8

13.5
10.6
5.9
12.9
15
16.9
17
17
12
17
13
7.6
18.6
19.7
18.6
16.2
18.6
7.9
19.5
14.1
20.3
19.7
15.2
8.2
15.5
17
20.8
20
20
21.2
20.3
17.4
17.3
15.6
20.7
17.8
22.1
21.8
14.3

17.6
22.6
23.5
22.2
22
13.5
13.5
20.4
17.4
24.3
18.2
16
20.5
23.9
22.6
23.9
25
24.4
22.3
21
11
22.2
23.7
19.5
23.7

6.4.1.2 Soil hydraulic properties

In the study, water flow movement were examined for different climatic conditions and for the soils having different physical properties. Soil samples were collected layer by layer (30 cm sections) with the help of a hand auger of 2" diameter starting from ground surface to about 210 cm. 210 cm deep multi layered soil profiles were used as input data for HYDRUS-1D for sites of interest.

For calculating the volumetric water content for the soil, van Genuchten formula was used. The hydrodynamic parameters θr and θs in the Van Genuchten formula were predicted by Hydrus-1D from the particle size distribution and bulk density of the soils.

Table 6.6. The hydrodynamic parameters θr and θs in the Van Genuchten formula were predicted by Hydrus-1D from the particle size distribution and bulk density of the soils.

Soil profile	Θr	θs
1	0.0193	0.3598
2	0.0224	0.3752
3	0.0318	0.3983
4	0.0503	0.4653
5	0.0688	0.4945
6	0.0729	0.4665
7	0.0672	0.4572

6.4.1.3 Main process: the main process dialog window lists down the processes that can be simulated in HYDRUS such as water flow, solute and heat transport, root water uptake, and root growth. For our study, only water flow tabs were selected and simulated.

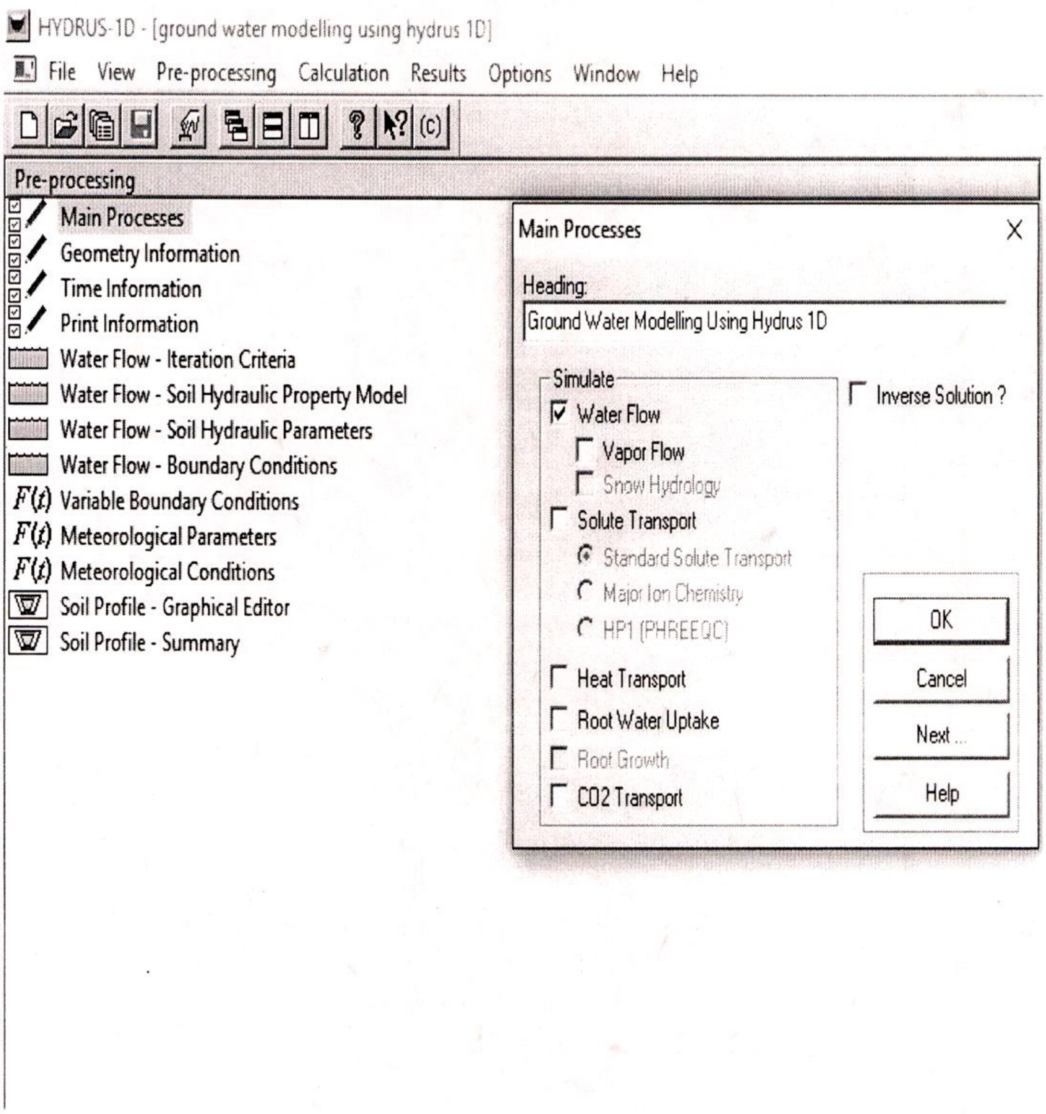


Fig 6.5: The main process dialog window

6.4.1.4 Geometry information

The geometry of the model can be defined in HYDRUS-1D Firstly, in the geometry information dialog box, the number of soil types, the total depth of soil profile, and length units can be set. Finally, the finite element model can be constructed by subdividing each region into linear elements by using soil profile graphical editor or soil profile summary dialog windows.

For this study, seven different kinds of soil profiles were used. The total depth of each soil profile is 30 cm.

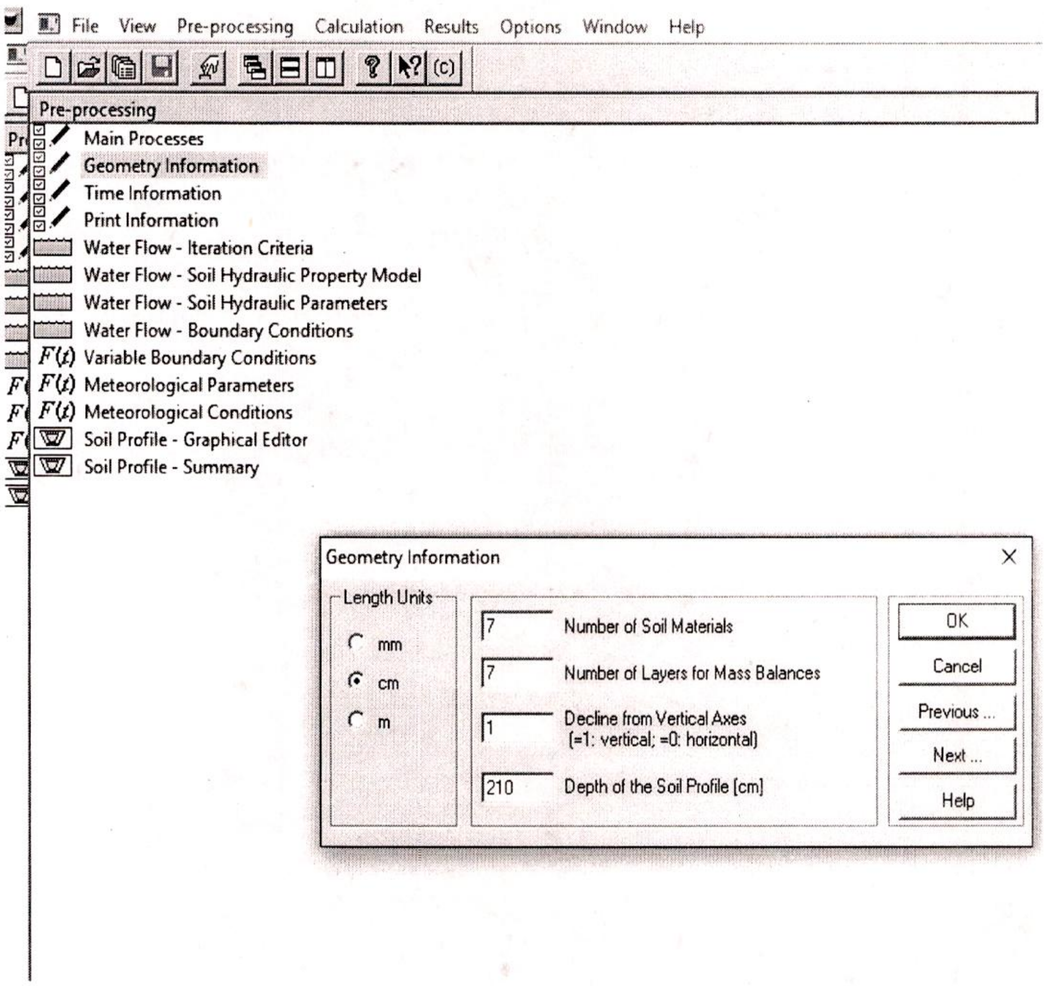


Fig 6.6: Geometry information

6.4.1.5 Time information

Under this section, time units, time discretization, and time-variable boundary conditions can be defined. The unit of time was selected in days and the period 1st of March -25th of September was used for simulation purposes (91 days).

In HYDRUS-1D code, the maximum number of time variable records is 91; therefore, 91 days are chosen as simulation period, which consequently means having 91 records when using daily precipitation and evaporation input data.

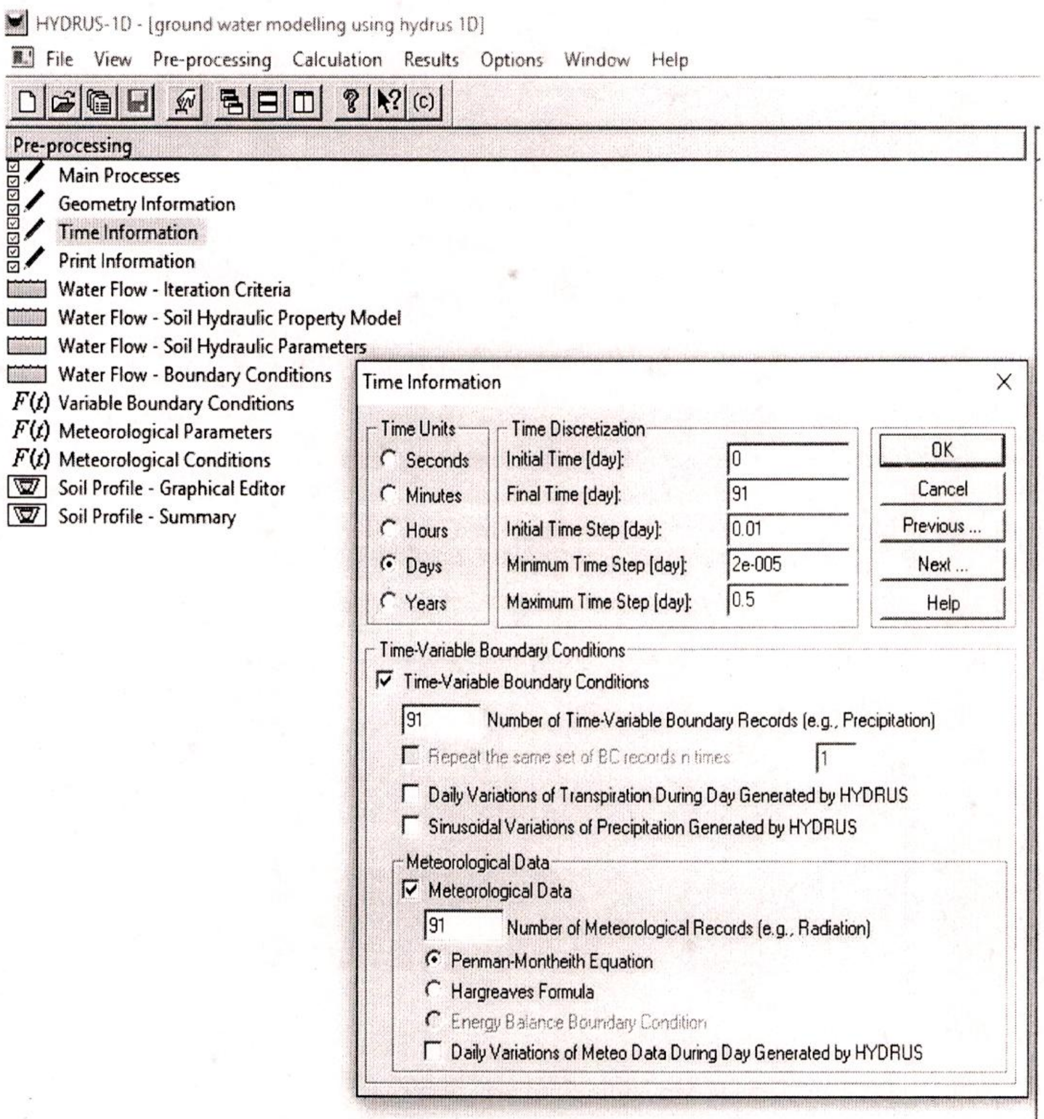


Fig 6.7: Time information

6.4.1.6 Water flow

6.4.1.6.1 *Soil hydraulic property model*

The hydraulic model and hysteresis can be defined, within this command window. There are various hydraulic models that can be used; however, in this research, ***van Genuchten-Mualem single porosity model*** was used without hysteresis.

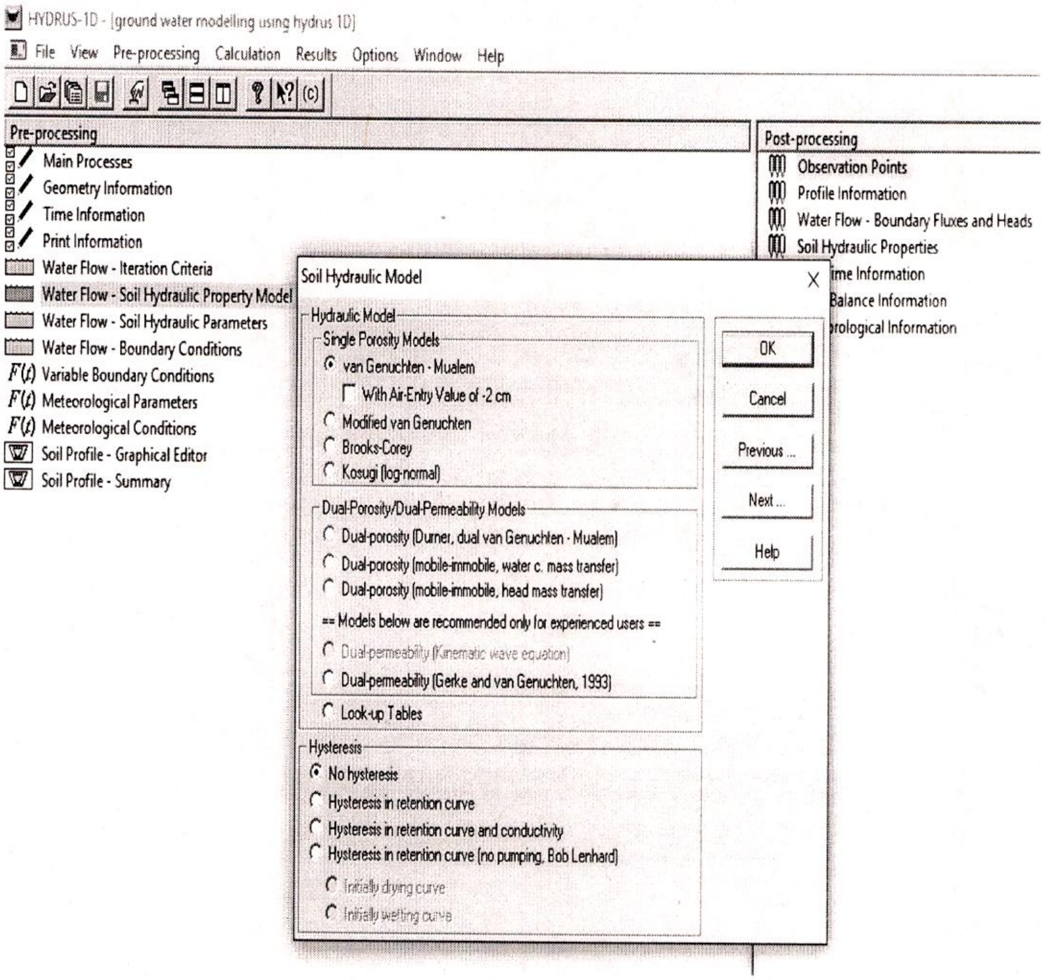


Fig 6.8: Soil hydraulic property model

6.4.1.6.2 Soil hydraulic parameters

All the parameters needed for various soil hydraulic models are mentioned under this section. The required parameters are residual and saturated water contents, saturated hydraulic conductivity, pore connectivity parameter, and empirical coefficients Alpha and n. To predict the values of these parameters, HYDRUS-1D uses Rosetta DLL (Dynamically Linked Library), by Marcel Schaap (Šimůnek, et al., 2009).

The Rosetta model can be used to estimate water retention parameters, saturated hydraulic conductivity, and unsaturated hydraulic conductivity parameters, as per van Genuchten (1980) and Mualem (1976).

To achieve this, a database of measured water retention and other properties for a wide variety of media has been used in order to operate the model. A retention curve with a good statistical comparability can be estimated by the model for a given medium's particle-size distribution and other soil properties. . This helps in predicting the retention curves of other media with similar physical properties (Nimmo, 2006).

The percentage of sand, silt, and clay together with the bulk density for different soil layers were used to get values of all the parameters needed.

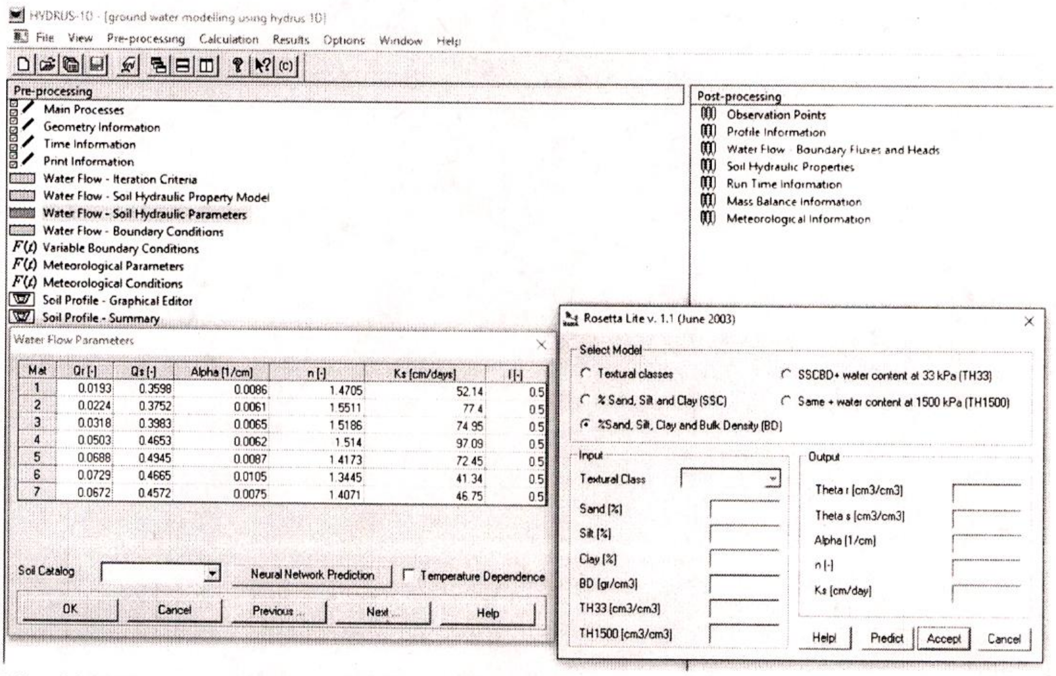


Fig 6.9: The water flow parameters dialog window.

6.4.1.6.3 Flow boundary conditions

Water flow boundary conditions are selected under this section. The window contains upper and lower boundaries. For 1D modelling purpose, the lower boundary condition was assumed to have a free drainage and the upper boundary condition was taken as the atmospheric boundary condition with the surface runoff.

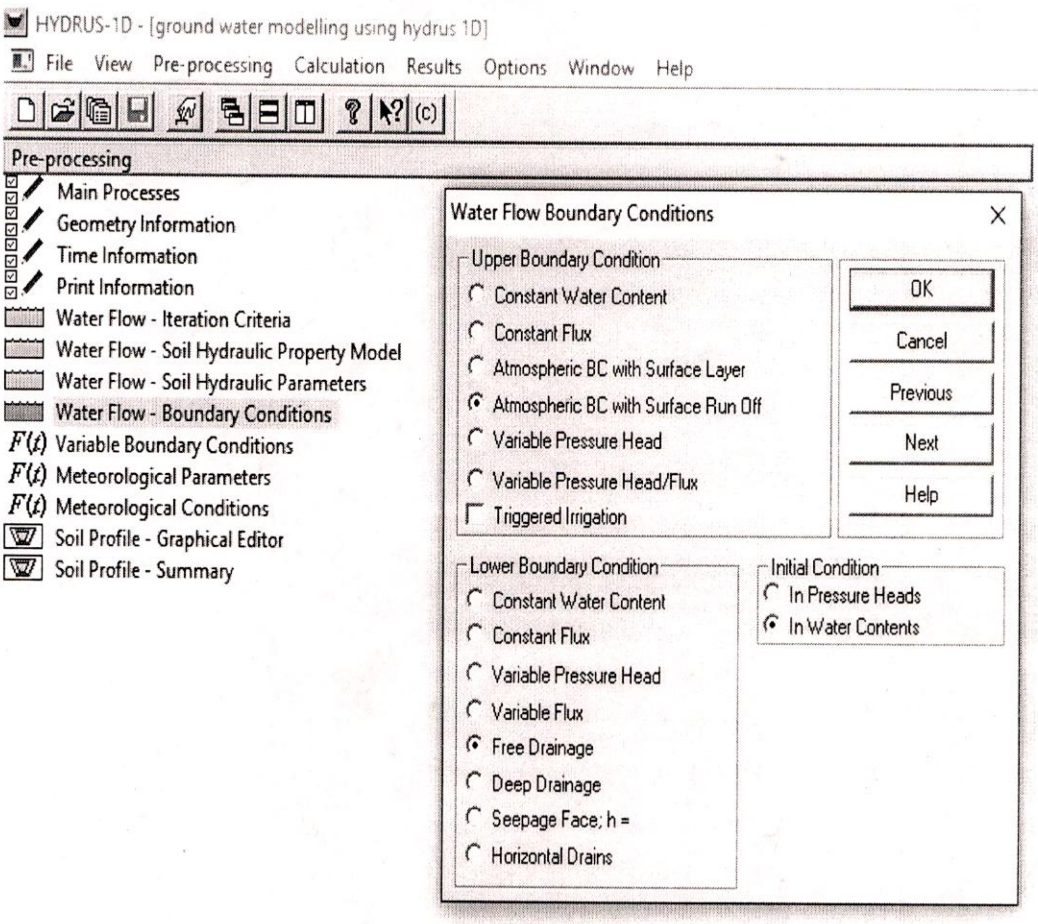


Fig 6.10: Flow boundary conditions

6.4.1.6 Variable Boundary Condition

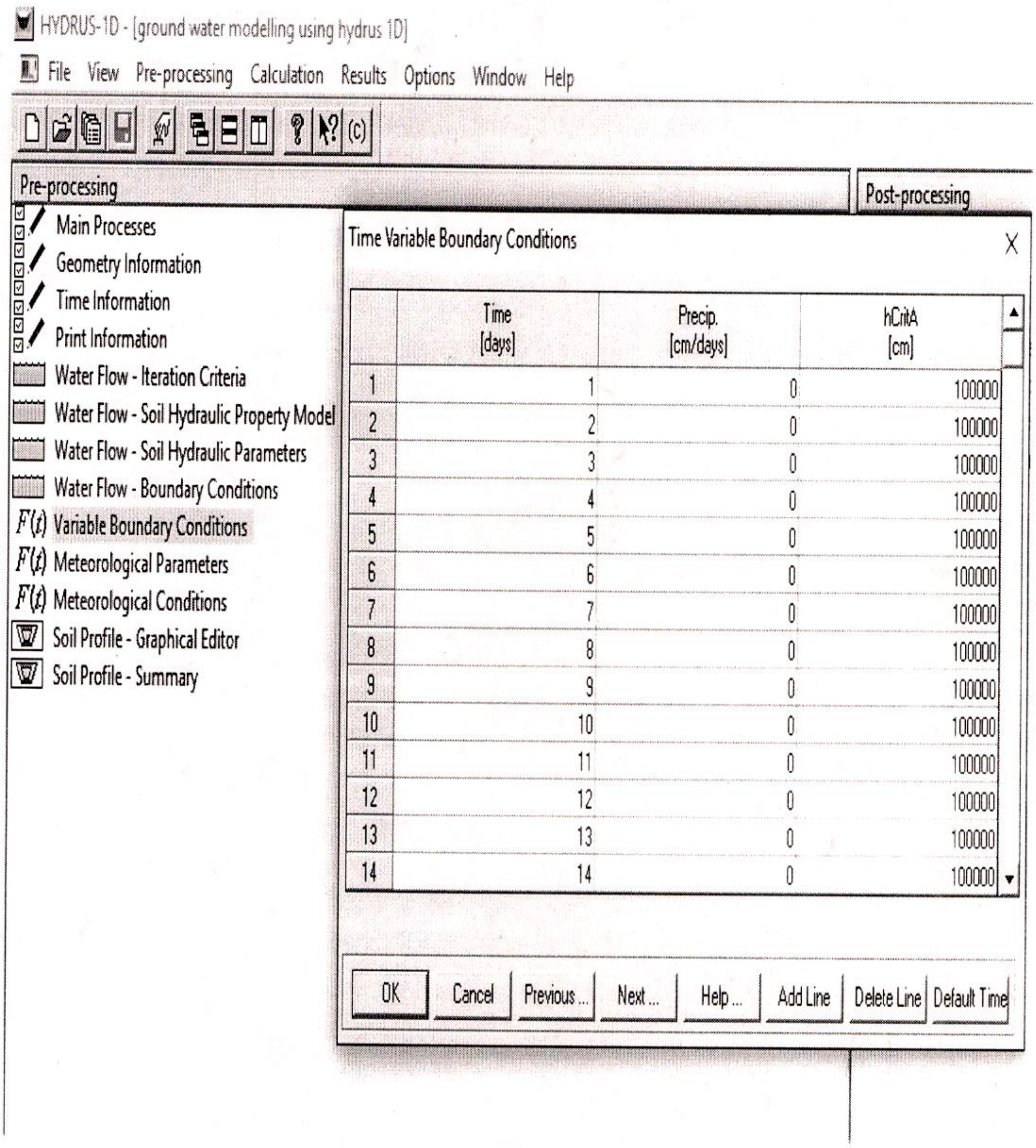


Fig 6.11: Variable Boundary Condition

6.4.1.7 Meteorological Parameters (Pre-Processing Menu)

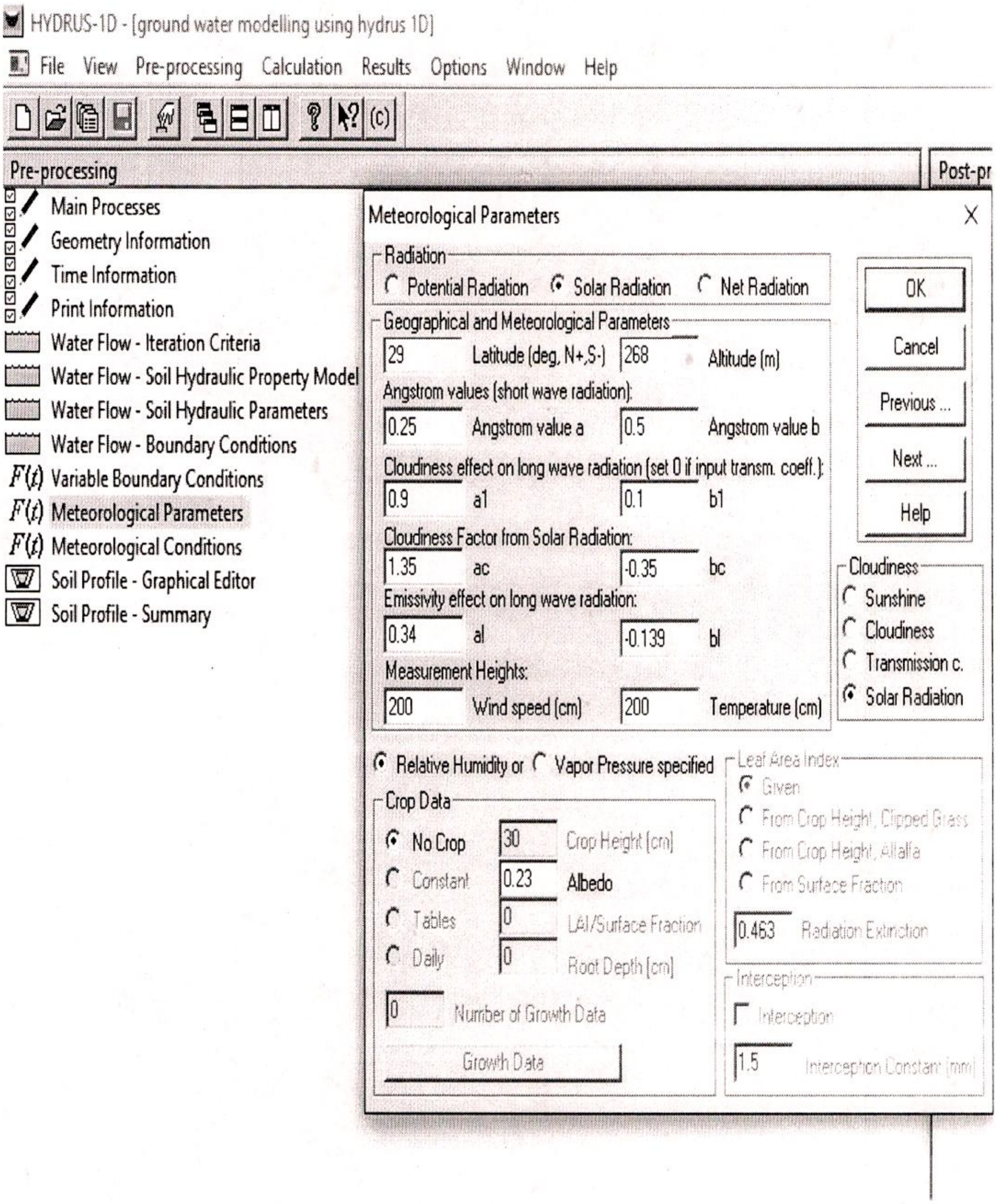
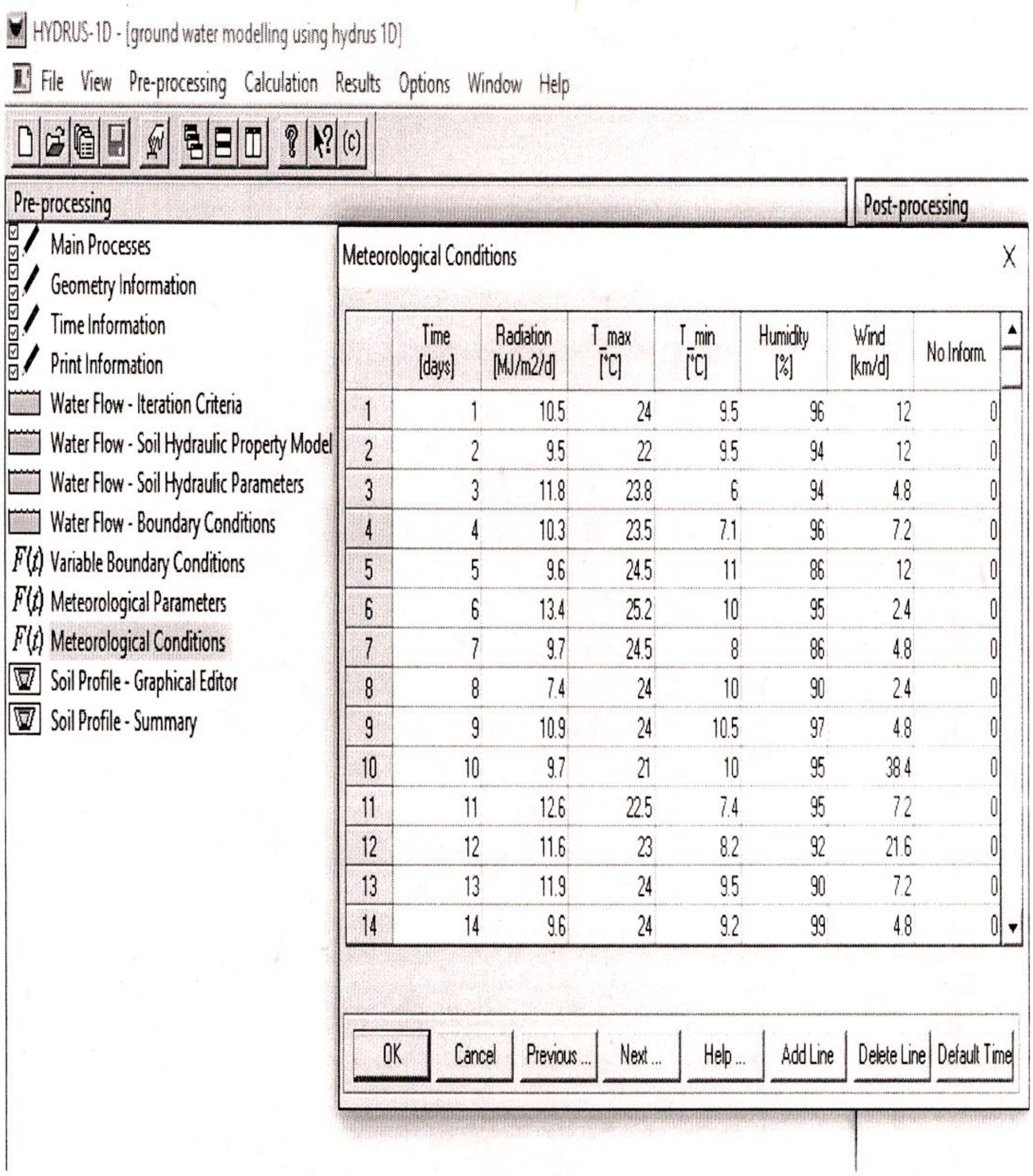


Fig 6.12: Meteorological Parameters

6.4.1.8 Meteorological Conditions



	Time [days]	Radiation [MJ/m2/d]	T_max [°C]	T_min [°C]	Humidity [%]	Wind [km/d]	No Inform.
1	1	10.5	24	9.5	96	12	0
2	2	9.5	22	9.5	94	12	0
3	3	11.8	23.8	6	94	4.8	0
4	4	10.3	23.5	7.1	96	7.2	0
5	5	9.6	24.5	11	86	12	0
6	6	13.4	25.2	10	95	2.4	0
7	7	9.7	24.5	8	86	4.8	0
8	8	7.4	24	10	90	2.4	0
9	9	10.9	24	10.5	97	4.8	0
10	10	9.7	21	10	95	38.4	0
11	11	12.6	22.5	7.4	95	7.2	0
12	12	11.6	23	8.2	92	21.6	0
13	13	11.9	24	9.5	90	7.2	0
14	14	9.6	24	9.2	99	4.8	0

Fig 6.13: Meteorological Conditions

6.4.1.7 Profile Information (Pre-Processing Menu)

The following properties are specified in the PROFILE module.

Initial conditions are specified for the pressure head, temperature, and/or the solution, and adsorbed concentrations.

The following properties of the flow domain specified in the PROFILE module:

- Material distribution of soil types with different hydraulic and solute transport properties.
- Subregion distribution used for calculating water and solute mass balances
- Observation nodes nodes for which a continuous record of the pressure head, water content, and temperature will be saved.

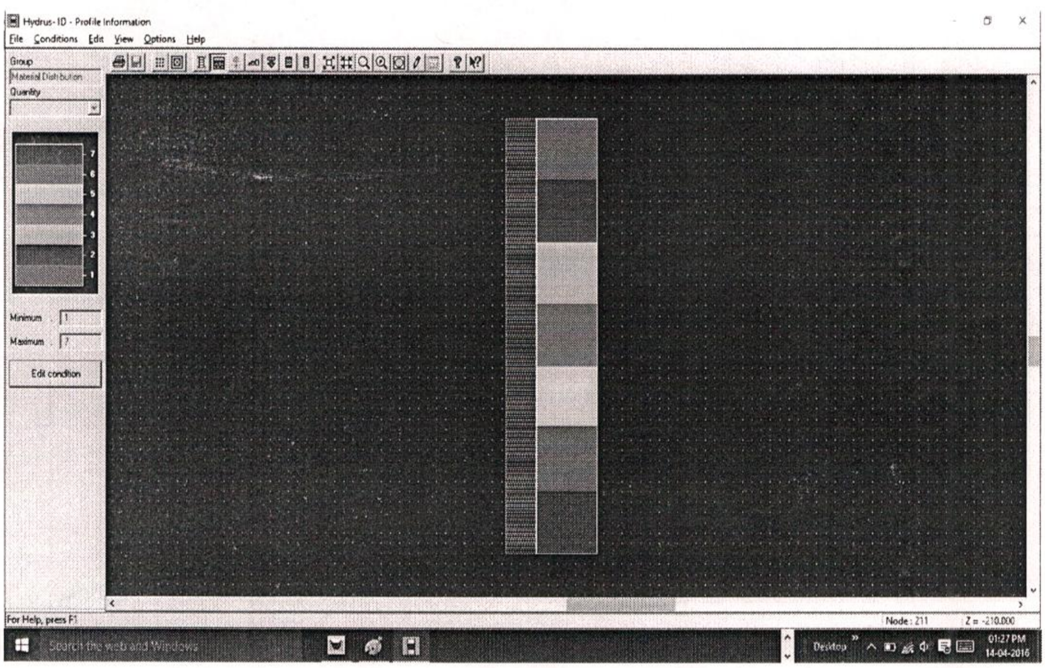
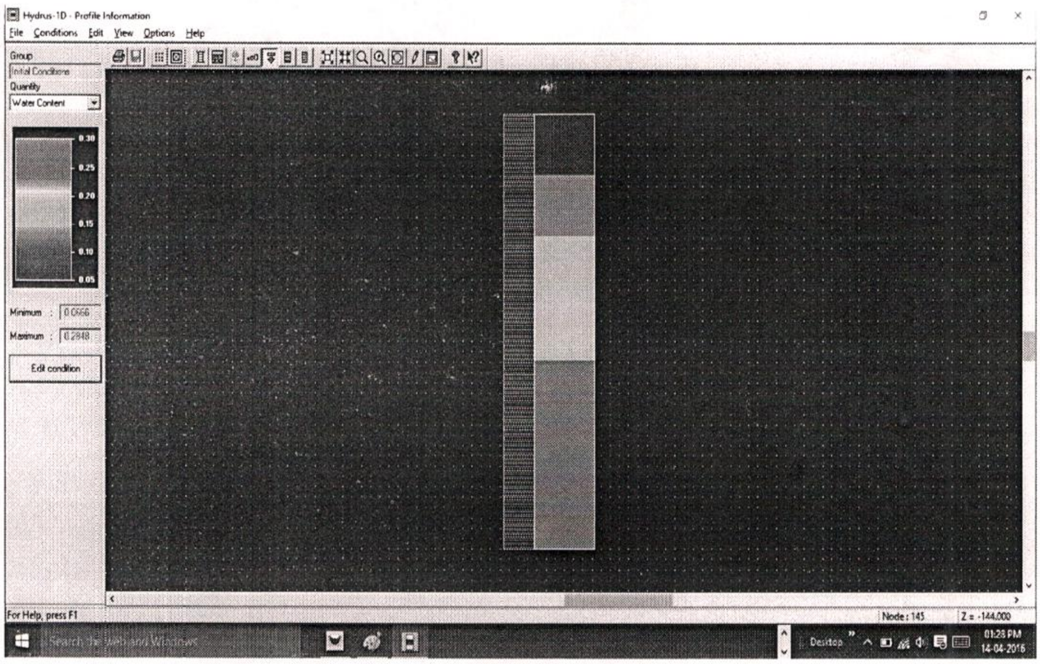


Fig 6.14: Material distribution of soil types

Fig 6.15: Subregion distribution used for calculating water and solute mass balances



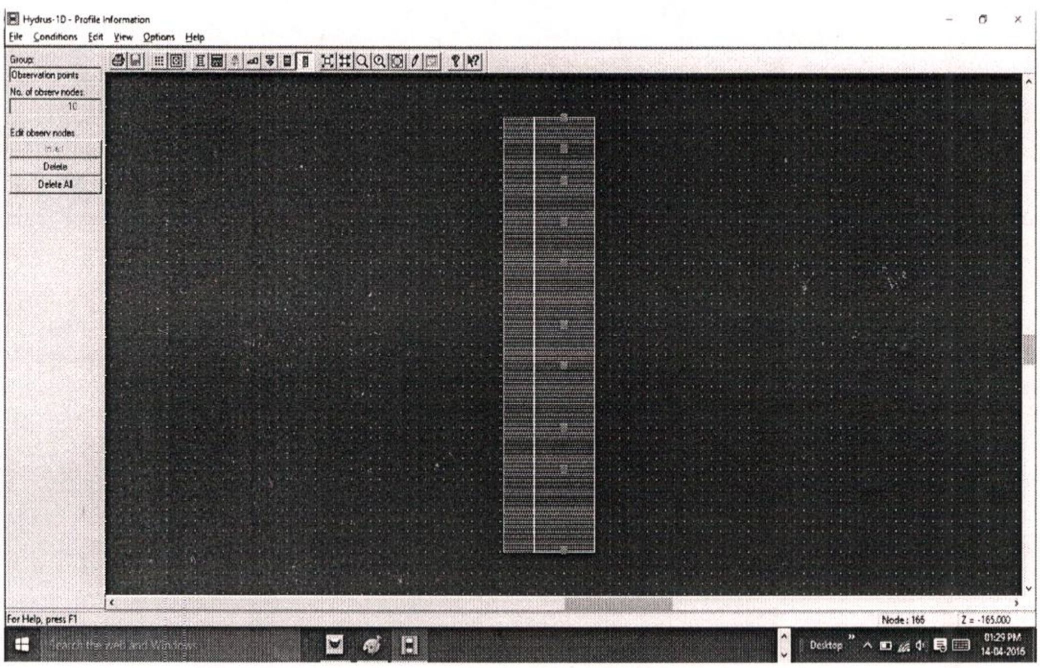
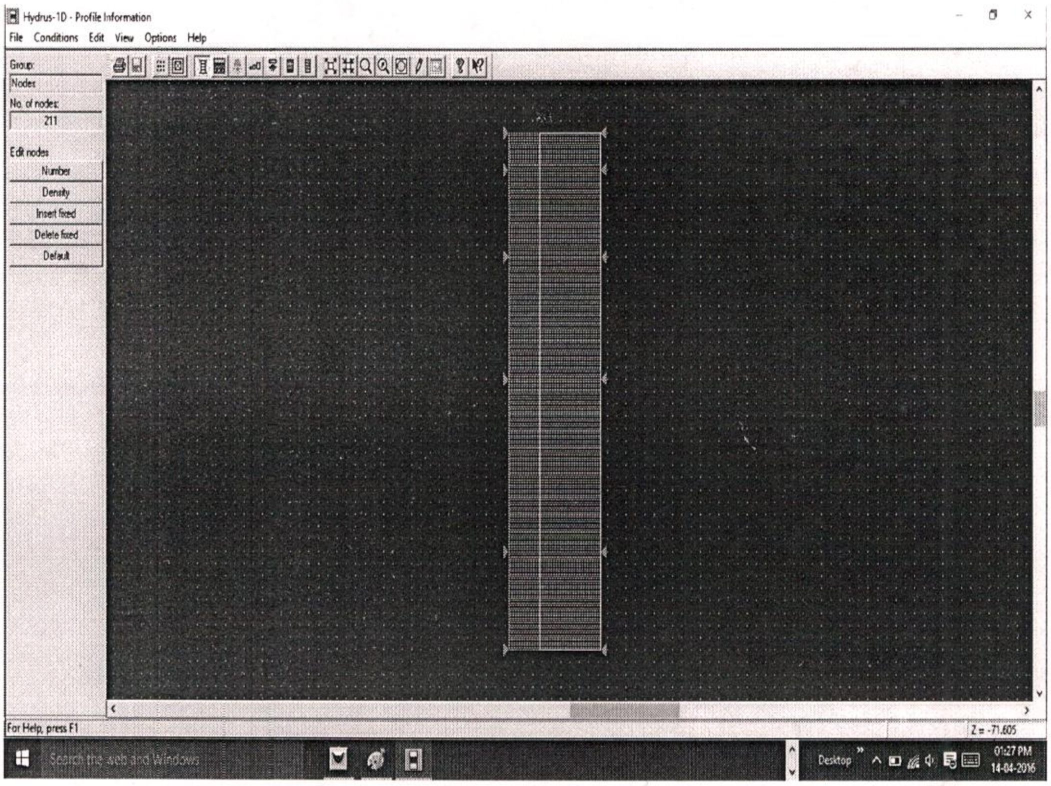


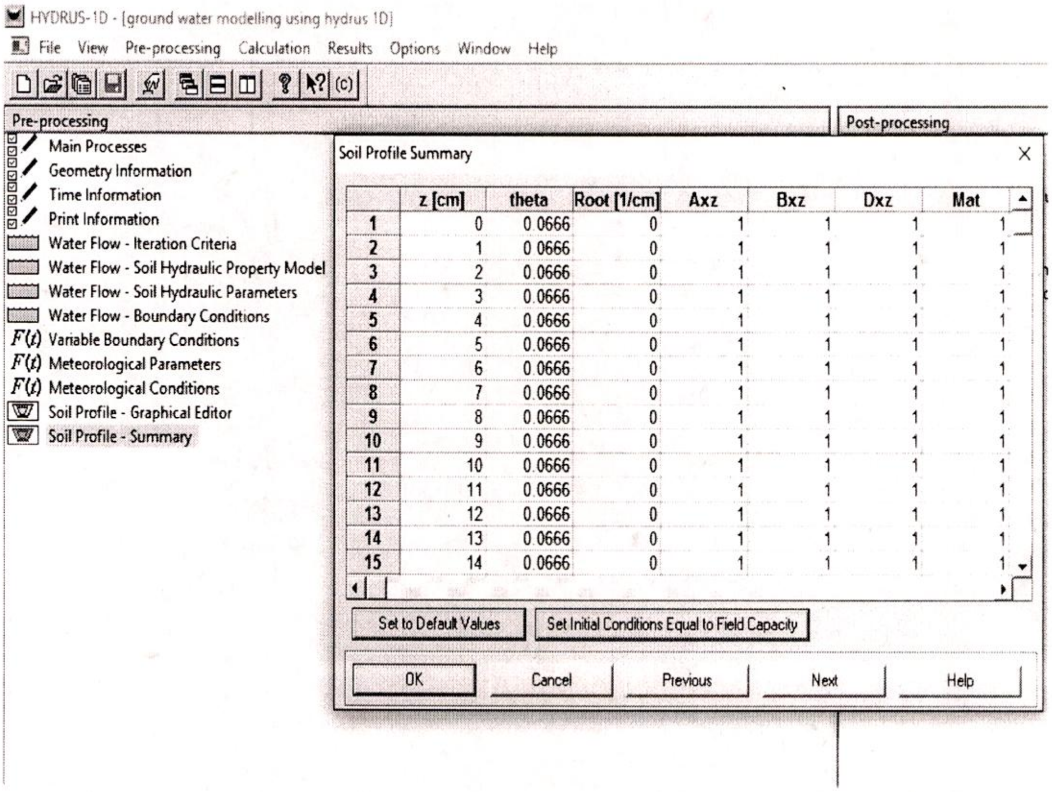
Fig 6.16: Observation nodes for which a continuous record of the pressure head, water content, and temperature will be saved.

Fig 6.17: Nodes and density: No of nodes-211 and Density equals to 1 is defined for the entire soil profile.



6.4.1.8 Profile Summary (Pre-Processing Menu)

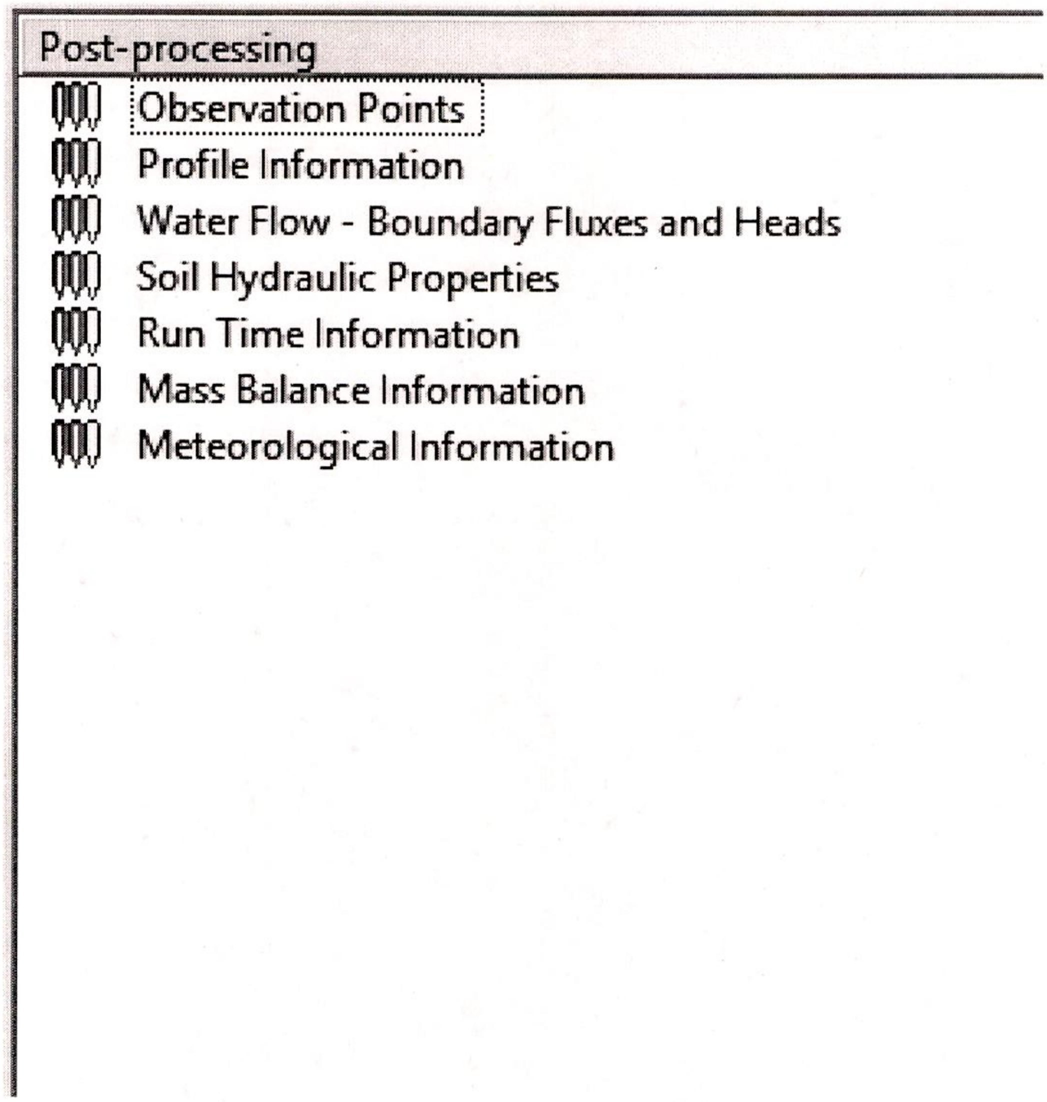
This command summarizes in tabular form the spatial discretization and spatial distribution of soil properties, initial conditions, and related information. It allows a user to summarize and modify the parameter set up in the external PROFILE module.



	z [cm]	theta	Root [1/cm]	Axz	Bxz	Dxz	Mat
1	0	0.0666	0	1	1	1	1
2	1	0.0666	0	1	1	1	1
3	2	0.0666	0	1	1	1	1
4	3	0.0666	0	1	1	1	1
5	4	0.0666	0	1	1	1	1
6	5	0.0666	0	1	1	1	1
7	6	0.0666	0	1	1	1	1
8	7	0.0666	0	1	1	1	1
9	8	0.0666	0	1	1	1	1
10	9	0.0666	0	1	1	1	1
11	10	0.0666	0	1	1	1	1
12	11	0.0666	0	1	1	1	1
13	12	0.0666	0	1	1	1	1
14	13	0.0666	0	1	1	1	1
15	14	0.0666	0	1	1	1	1

Fig 6.18: Profile Summary

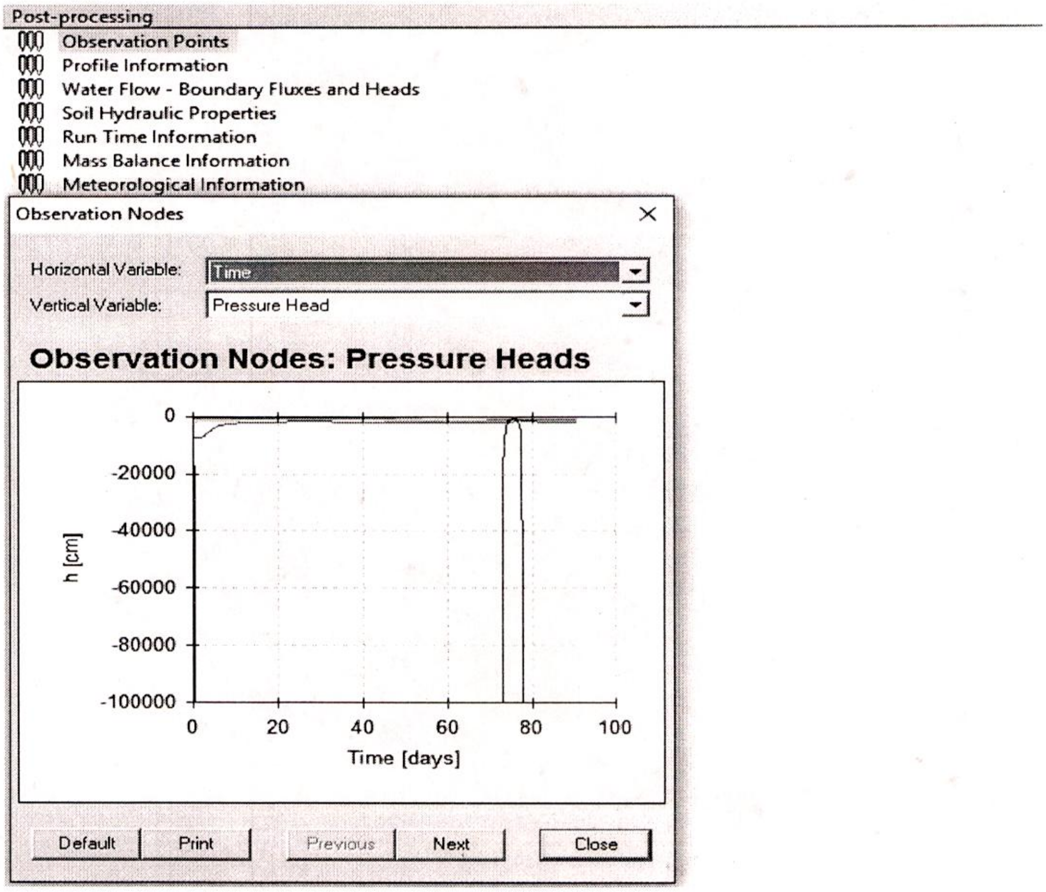
7.0 RESULTS AND DISCUSSION:

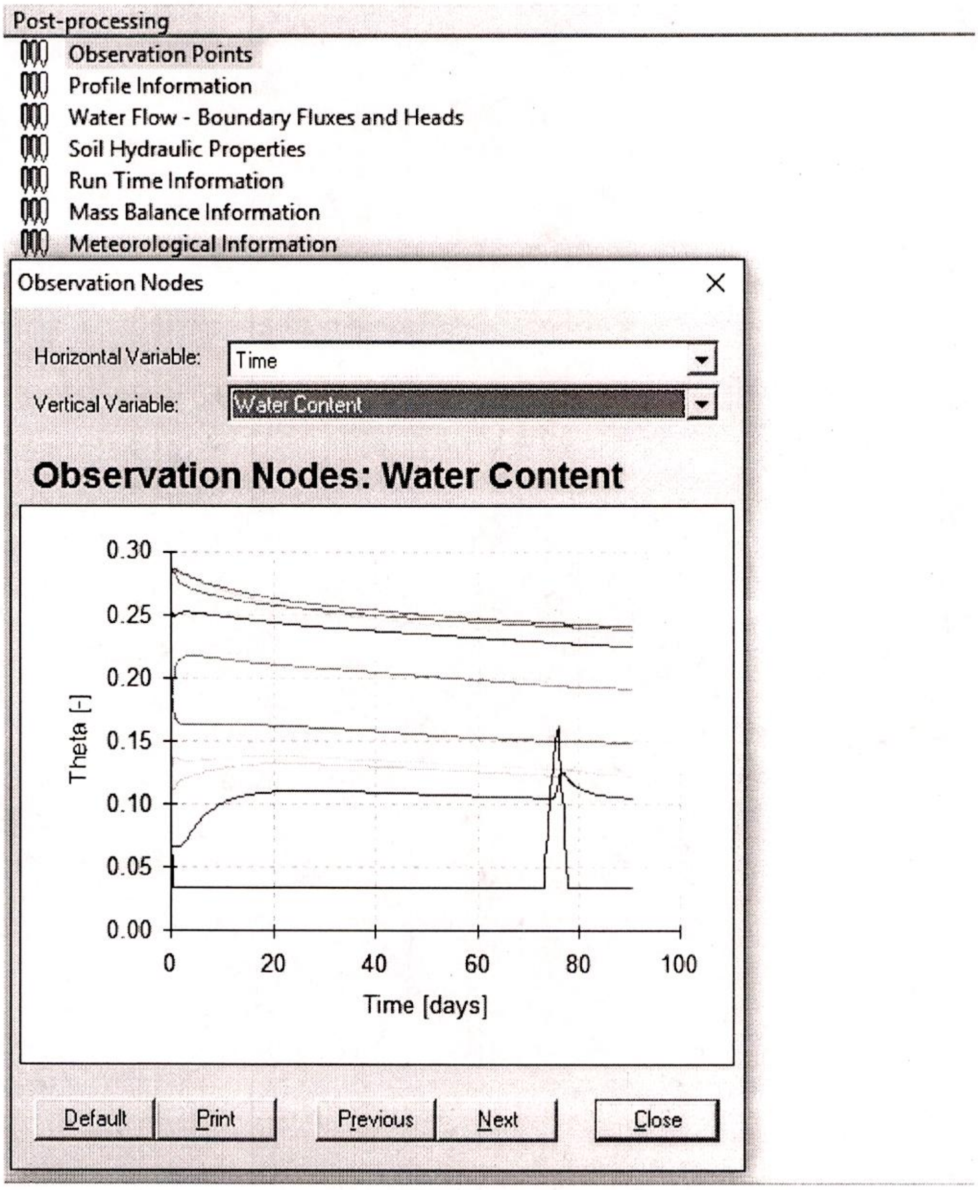


7.1 Observation Points (Results Menu)

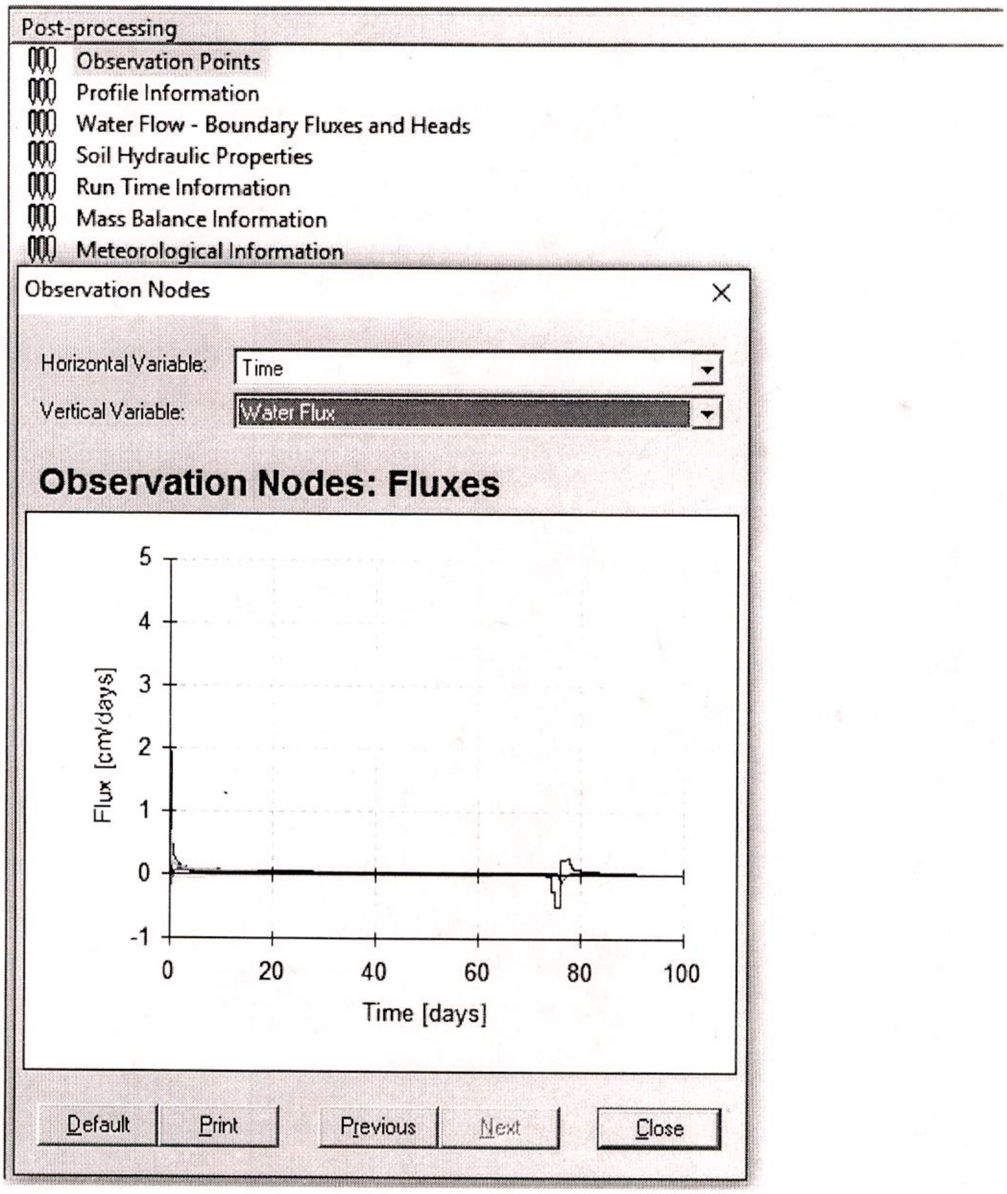
Graphical representation of changes in water content, pressure head, temperature and/or solution at specified observation nodes.

Fig 7.1: Graphical representation of changes in water content, pressure head, temperature and/or solution at specified observation nodes



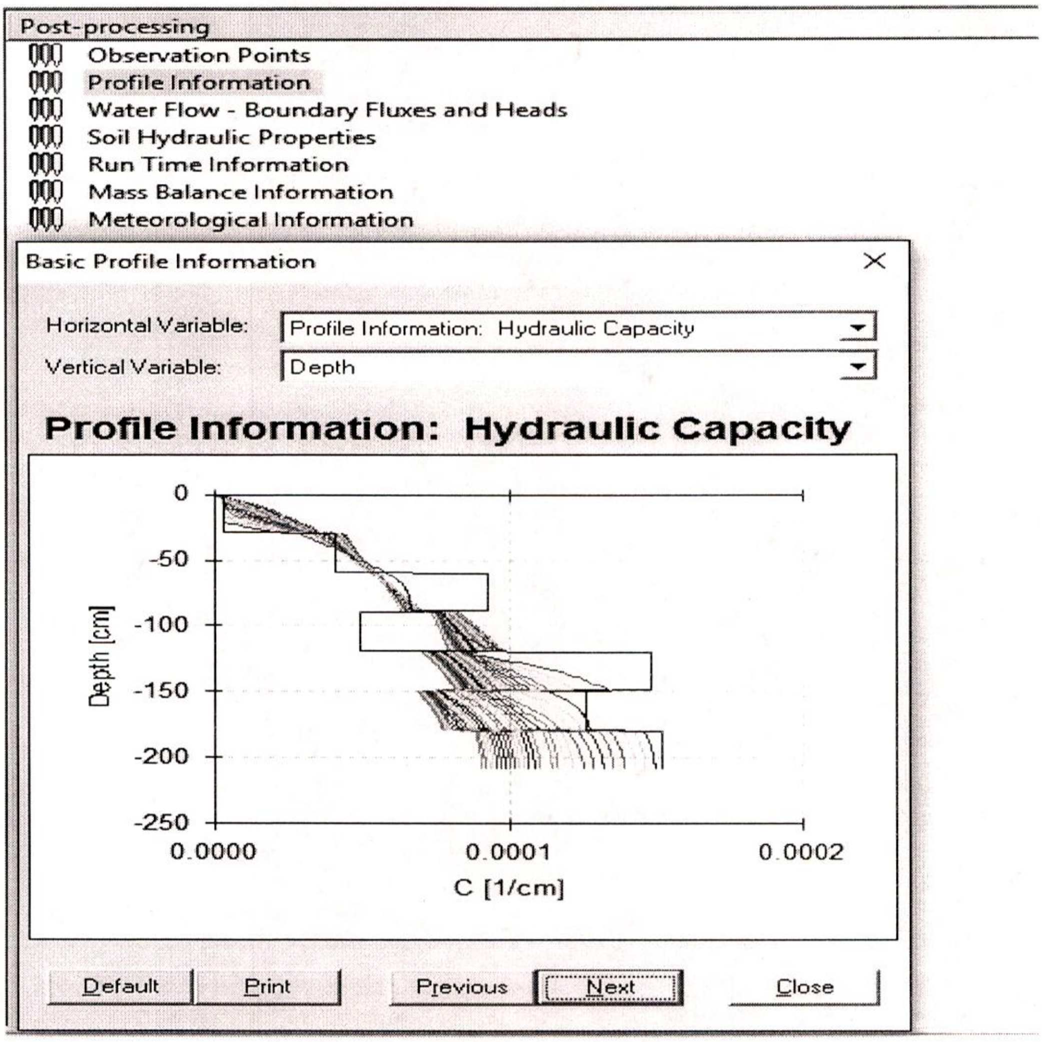


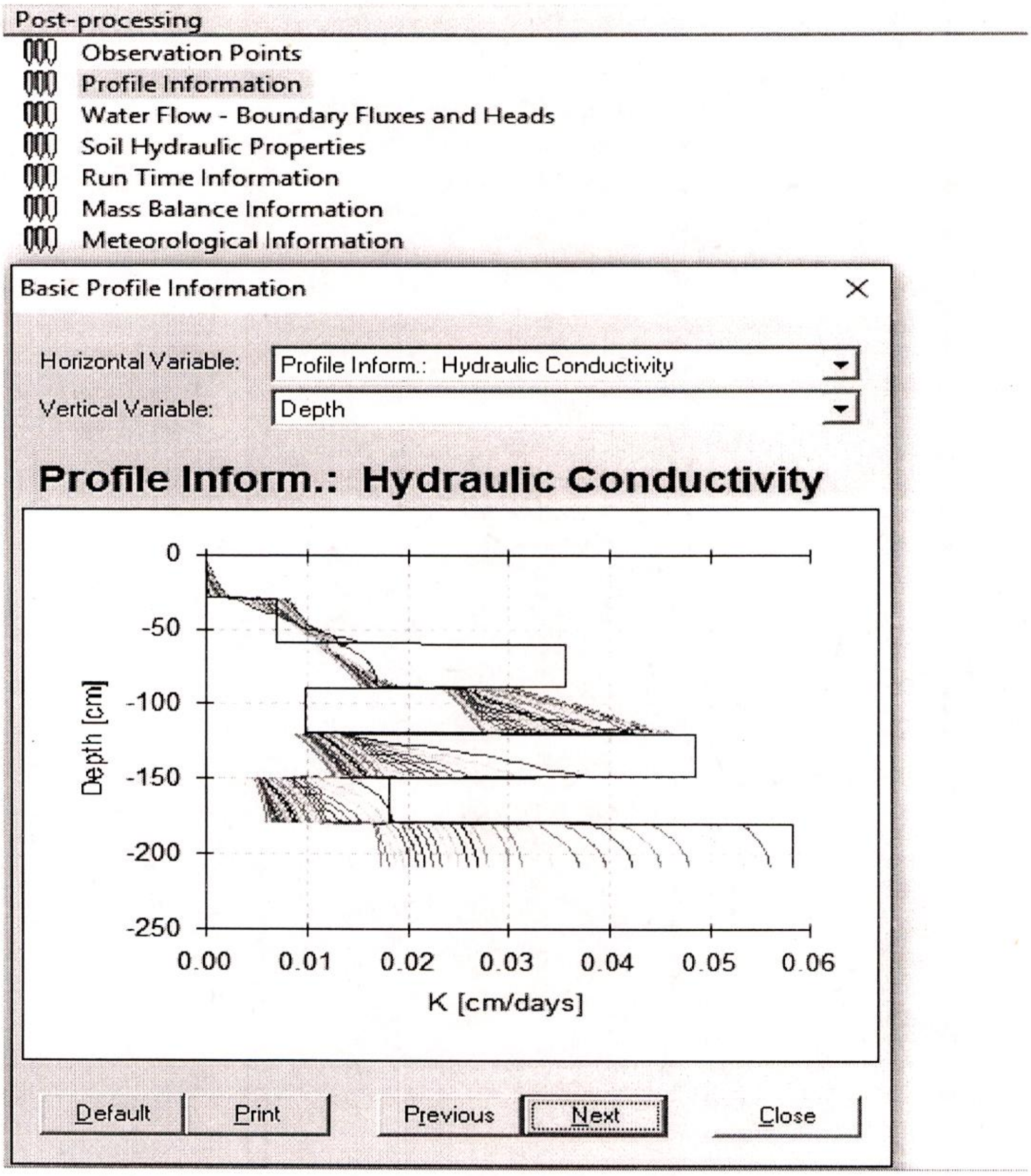
Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Observation Nodes
Horizontal Variable:
Time
Vertical Variable:
Water Content
Observation Nodes: Water Content
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Theta [-]
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Observation Nodes
Horizontal Variable:
Time
Vertical Variable:
Water Flux
Observation Nodes: Fluxes
Flux [cm/days]
Time [days]
Default
Print
Previous
Next
Close

7.1 Profile Information (Results Menu)

Fig 7.2: Graphical representation of changes in Hydraulic capacity, Hydraulic conductivity, Pressure head, Water content and Water flux.




Post-processing
Observation Points
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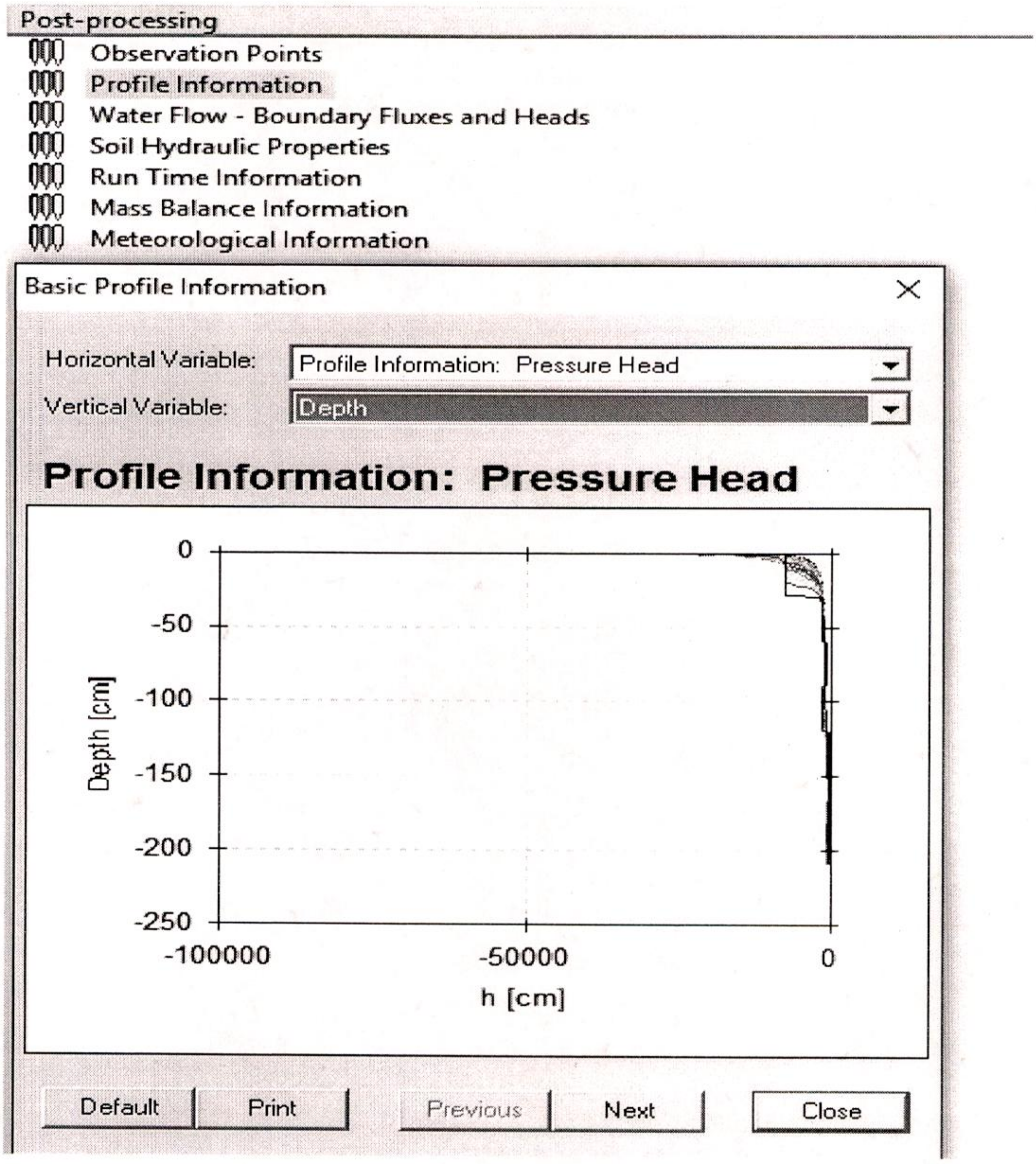
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Basic Profile Information
Horizontal Variable:
Profile Inform.: Hydraulic Conductivity
Vertical Variable:
Depth
Profile Inform.: Hydraulic Conductivity
Depth [cm]
0
-50
-100
-150
-200
-250
0.00
0.01
0.02
0.03
0.04
0.05
0.06
K [cm/days]
Default
Print
Previous
Next
Close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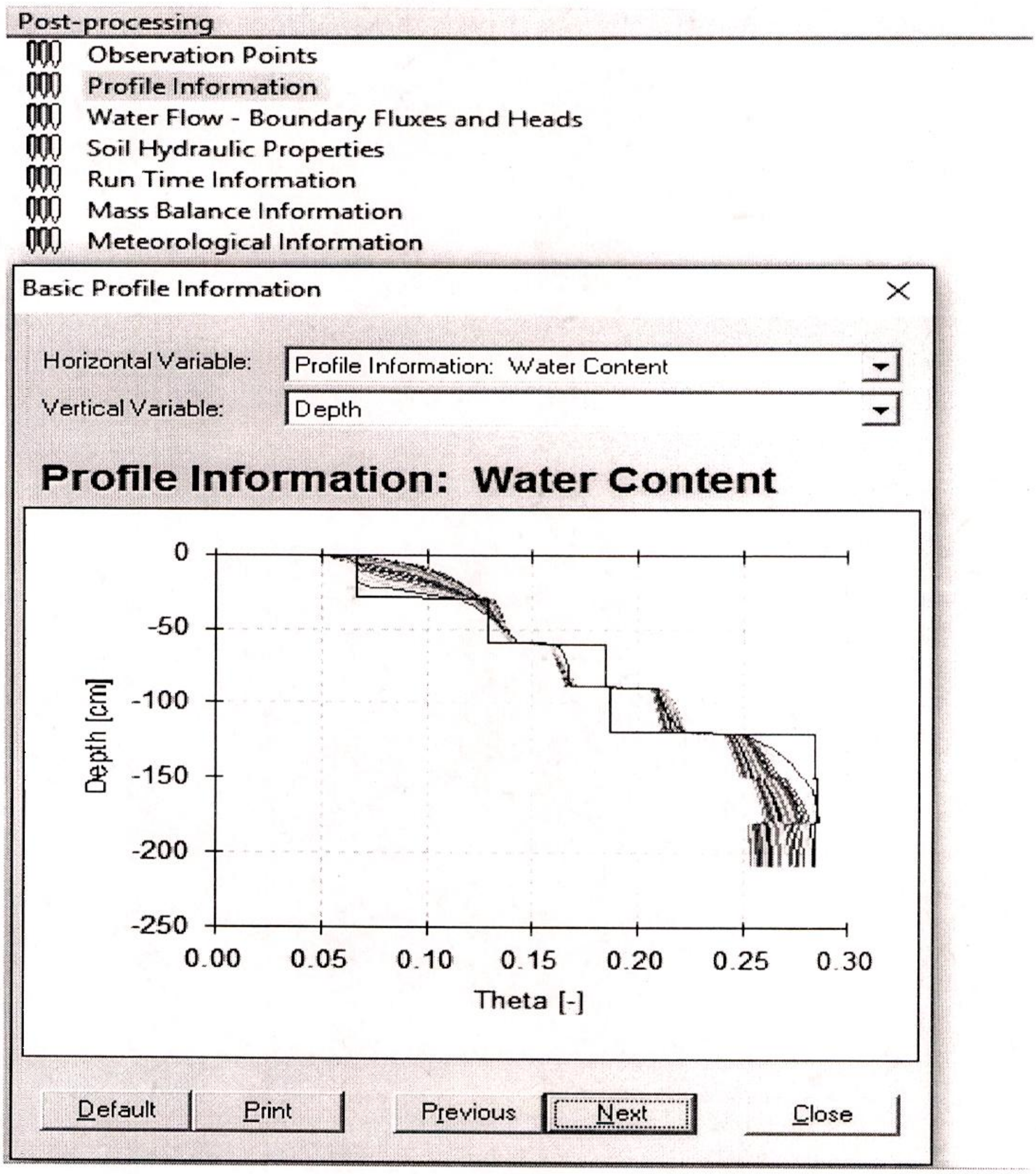
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Basic Profile Information
Horizontal Variable:
Profile Information: Pressure Head
Vertical Variable:
Depth
Profile Information: Pressure Head
0
-50
-100
-150
-200
-250
Depth [cm]
-100000
-50000
0
h [cm]
Default
Print
Previous
Next
Close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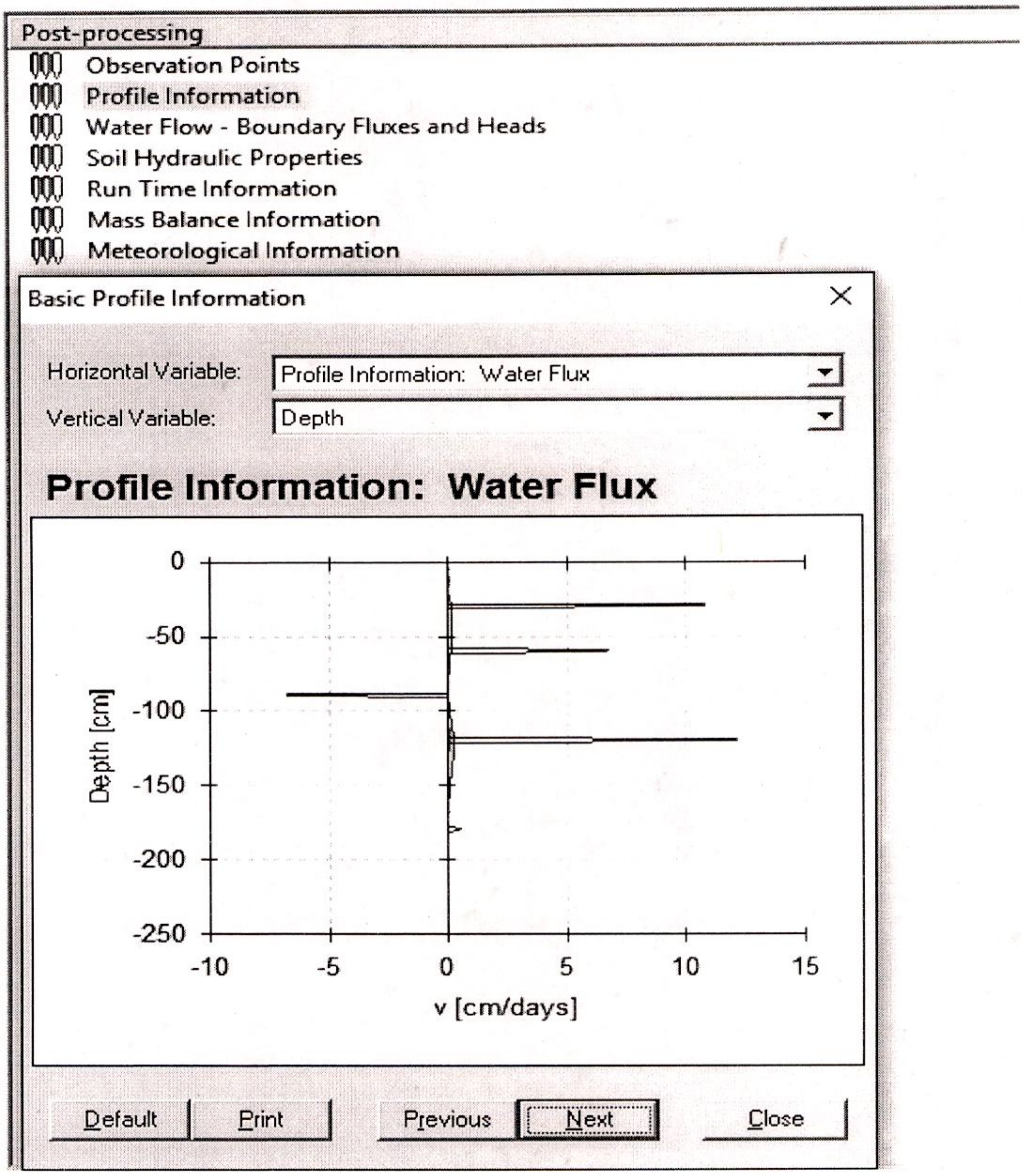
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Basic Profile Information
Horizontal Variable:
Profile Information: Water Content
Vertical Variable:
Depth
Profile Information: Water Content
Depth [cm]
0
-50
-100
-150
-200
-250
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Theta [-]
Default
Print
Previous
Next
Close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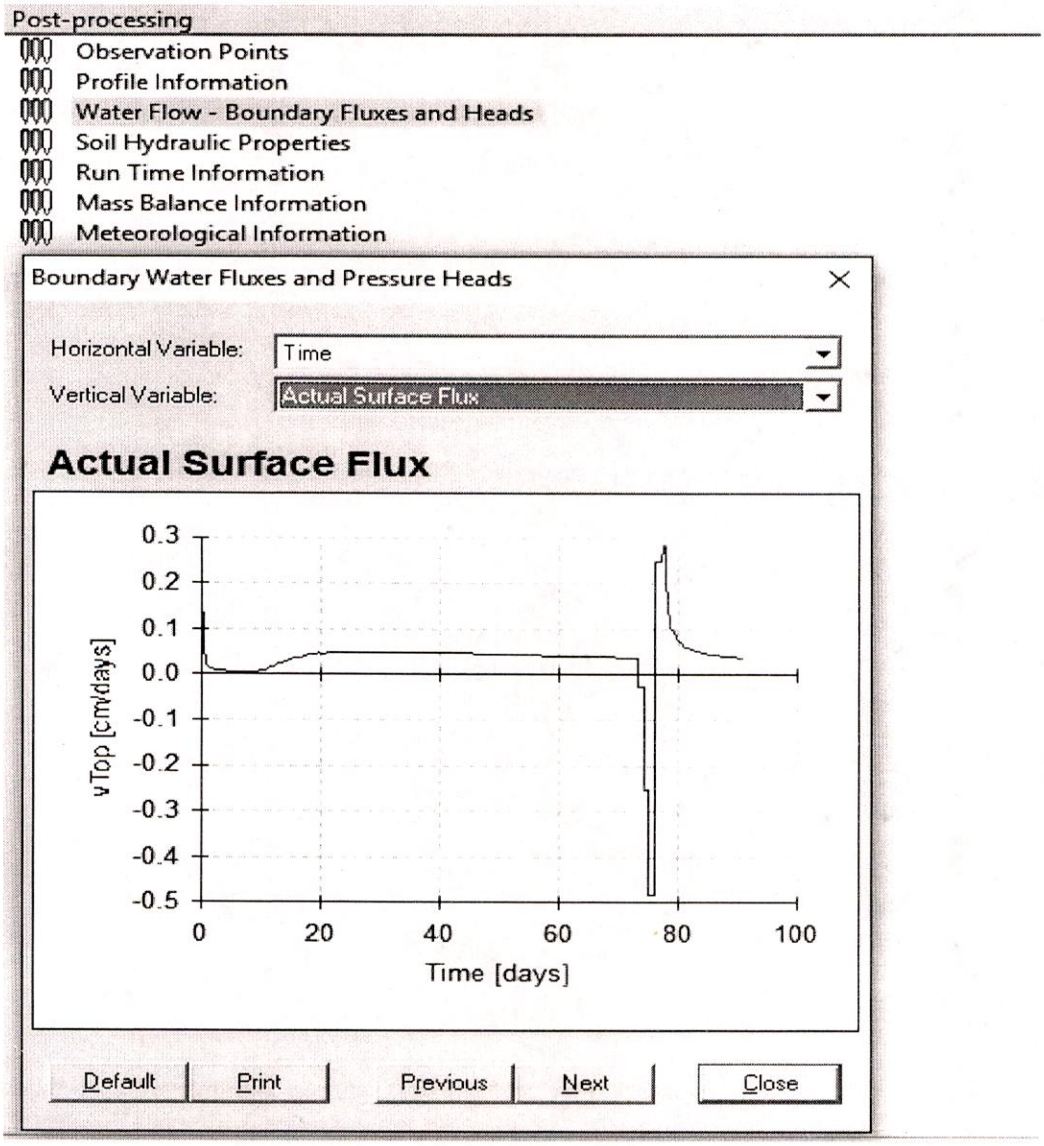
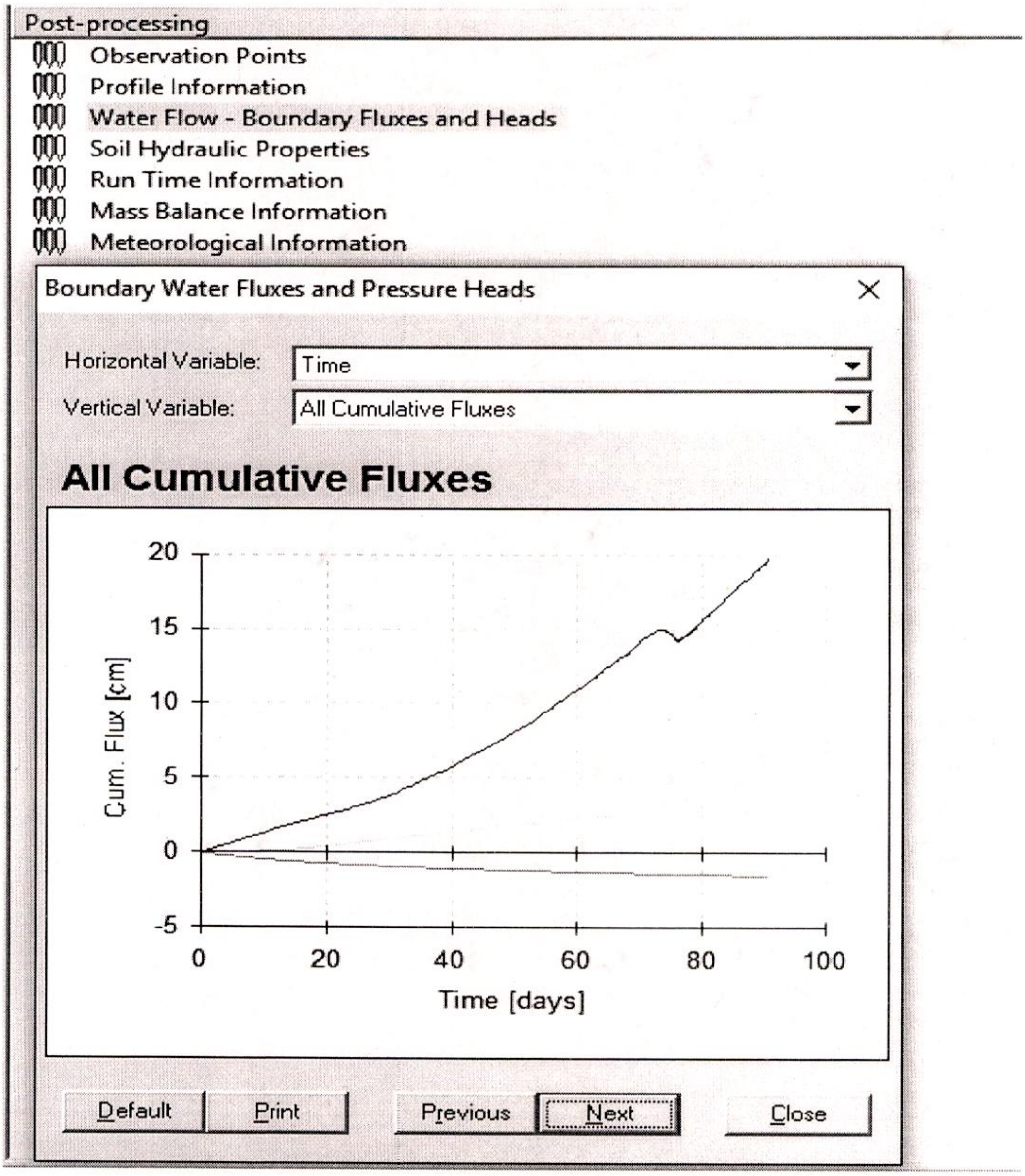
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Basic Profile Information
Horizontal Variable:
Profile Information: Water Flux
Vertical Variable:
Depth
Profile Information: Water Flux
Depth [cm]
v [cm/days]
Default
Print
Previous
Next
Close

7.2 Water Flow Fluxes (Results Menu, Boundary Information Submenu)

Graphs of temporal changes in actual and cumulative water fluxes and pressure heads across the upper and lower boundaries.

Fig 7.3: Graphical representation of changes in Actual surface flux, All Cumulative Fluxes, All Fluxes, All Pressure Heads, Bottom fluxes, Bottom Pressure Head, Cum. Actual surface flux, Cum. Actual Bottom flux, Cum. Evaporation, Cum. Infiltration, Cum. Potential Surface flux, Soil Water Storage and Surface Pressure Head.

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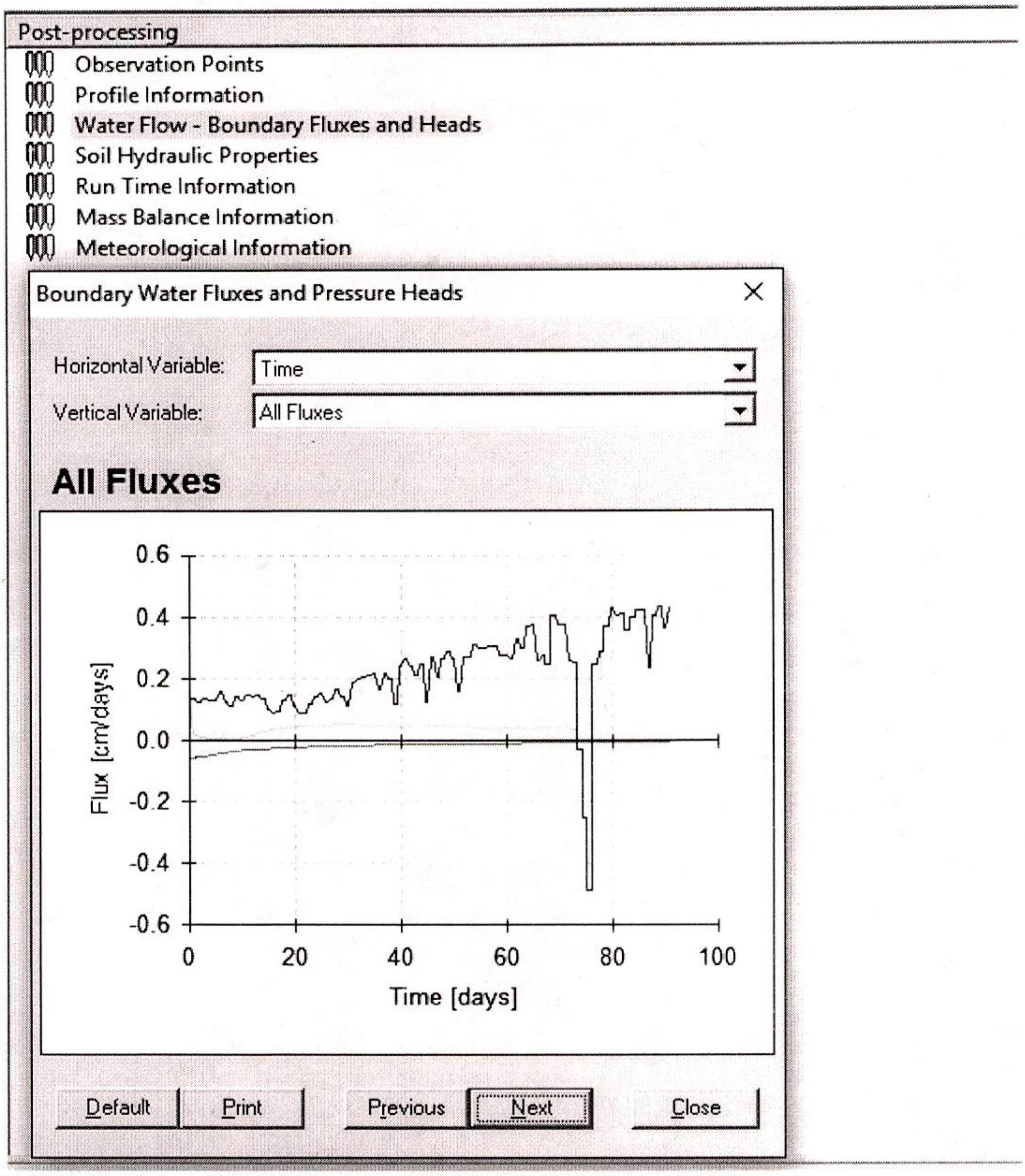
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
All Cumulative Fluxes
All Cumulative Fluxes
Cum. Flux [cm]
Time [days]
Default
Print
Previous
Next
Close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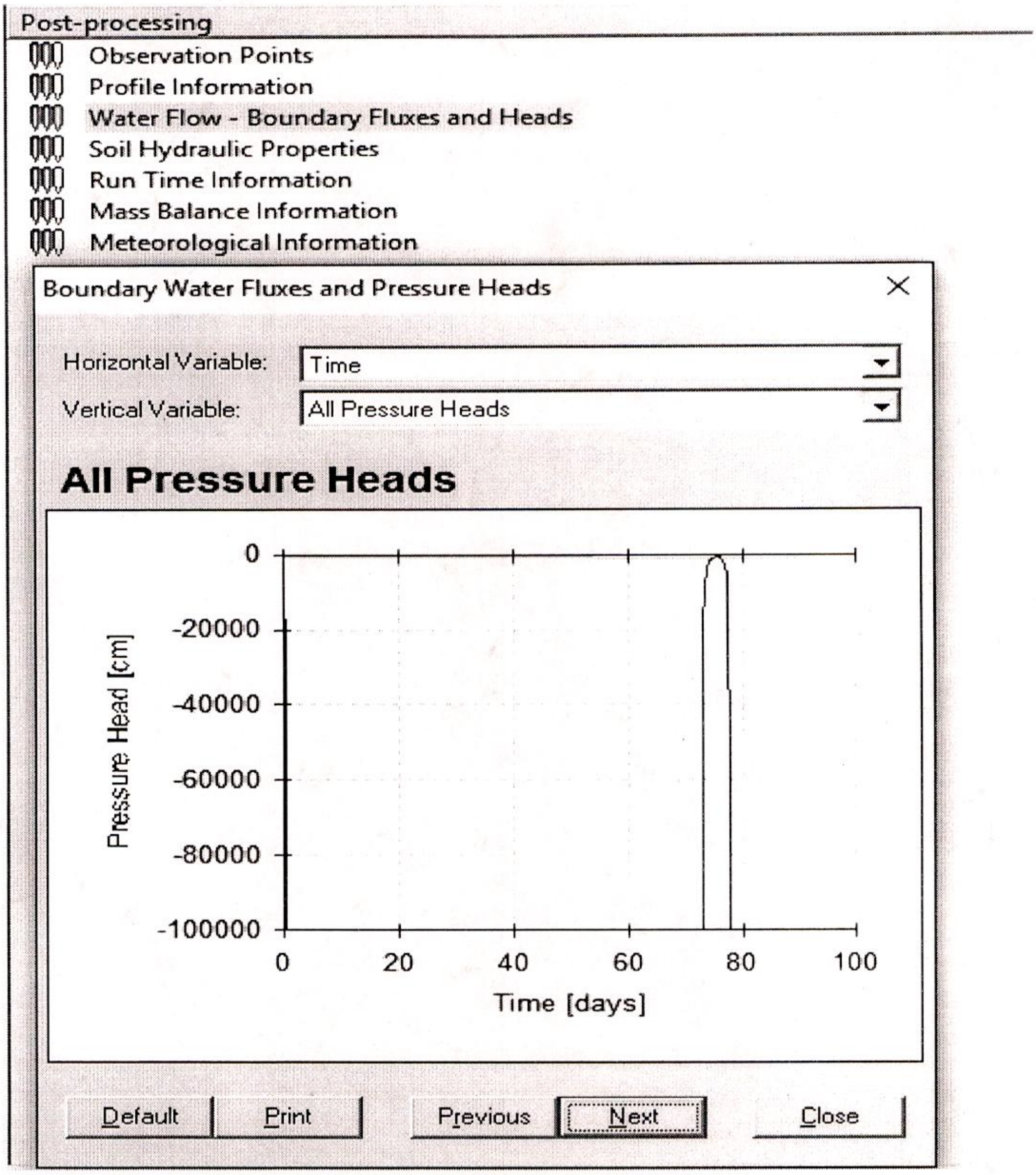
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
All Fluxes
All Fluxes
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Flux [cm/days]
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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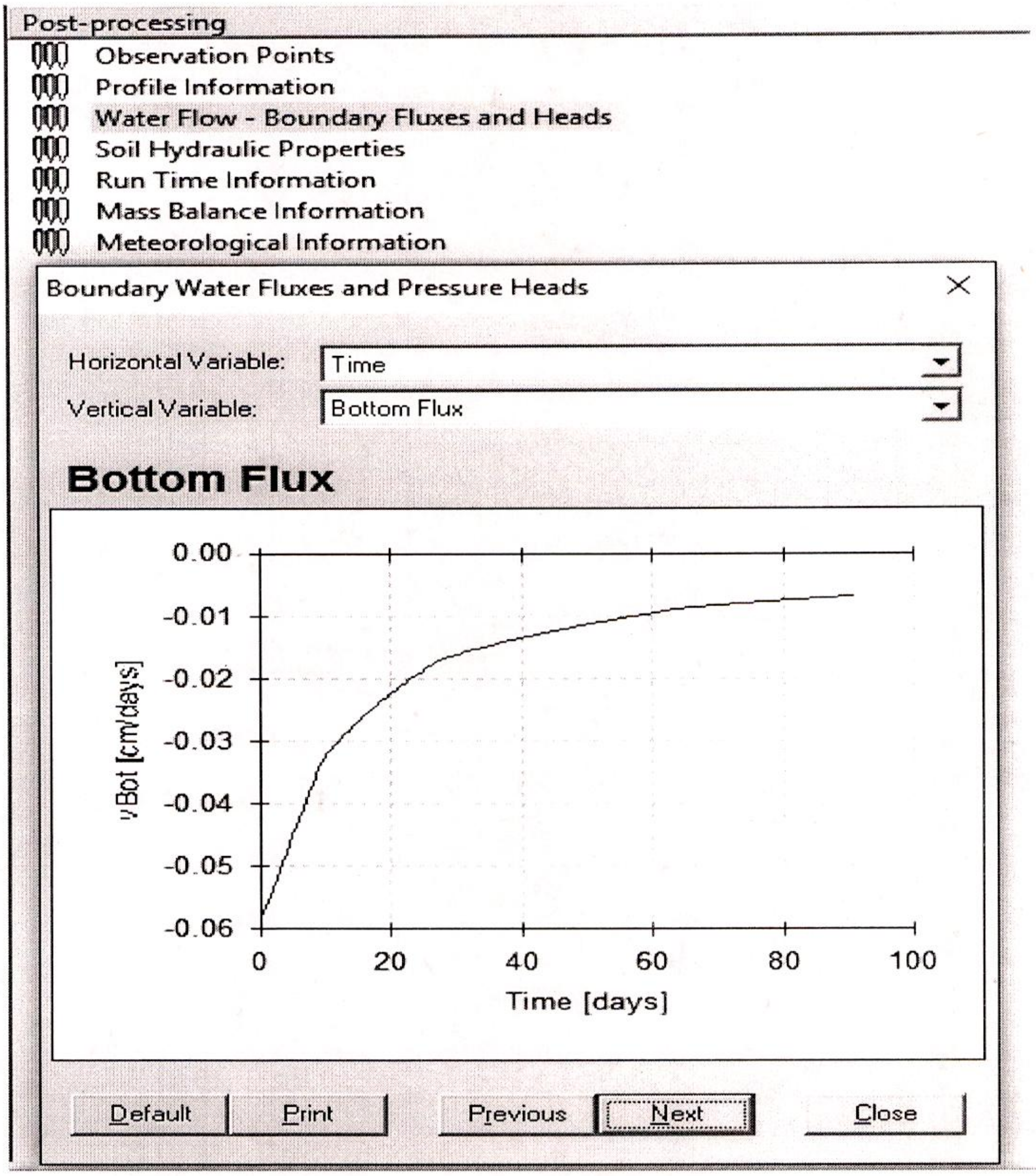
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
All Pressure Heads
All Pressure Heads
0
-20000
-40000
-60000
-80000
-100000
Pressure Head [cm]
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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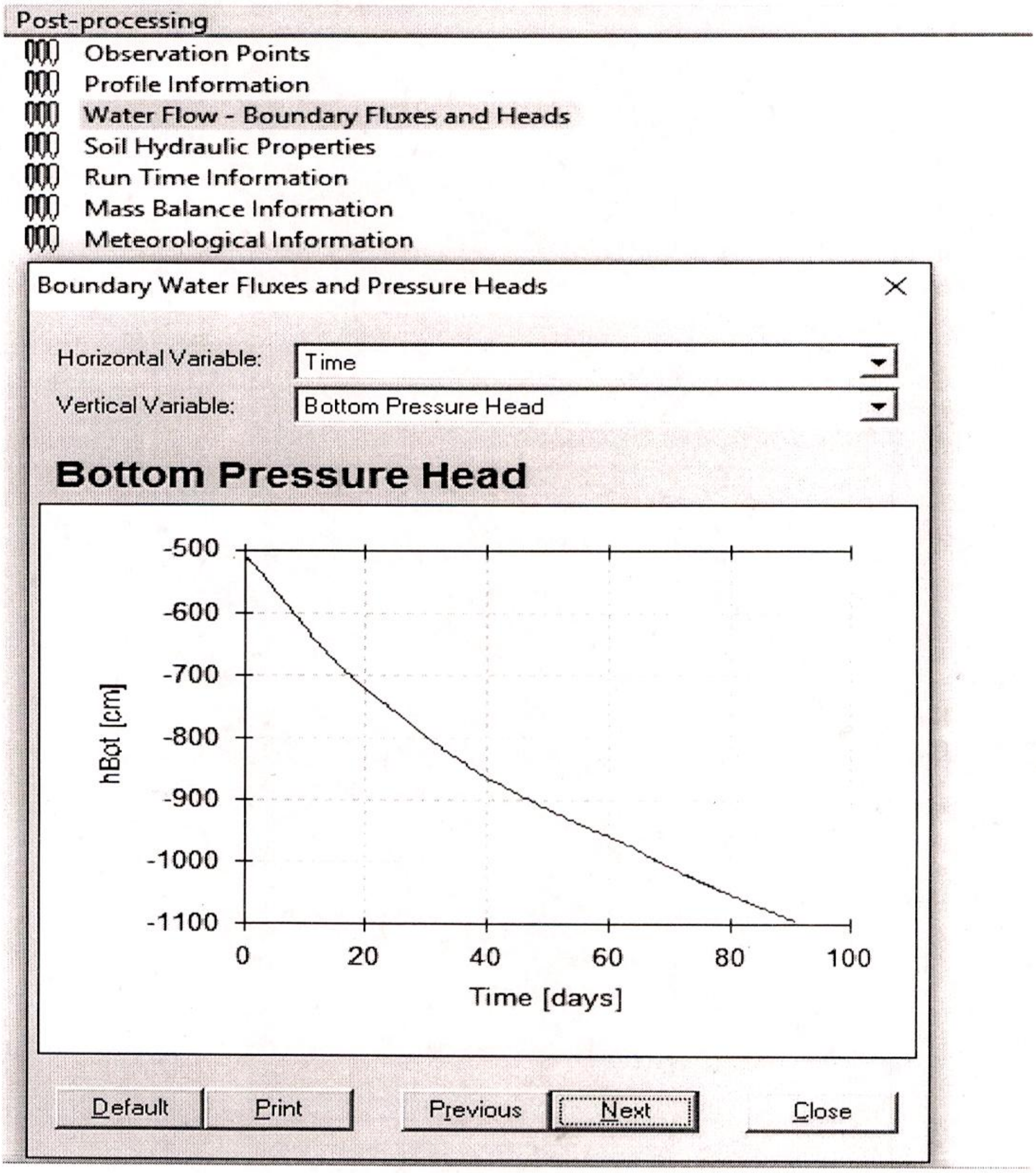
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable: Time
Vertical Variable: Bottom Flux
Bottom Flux
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
vBot [cm/days]
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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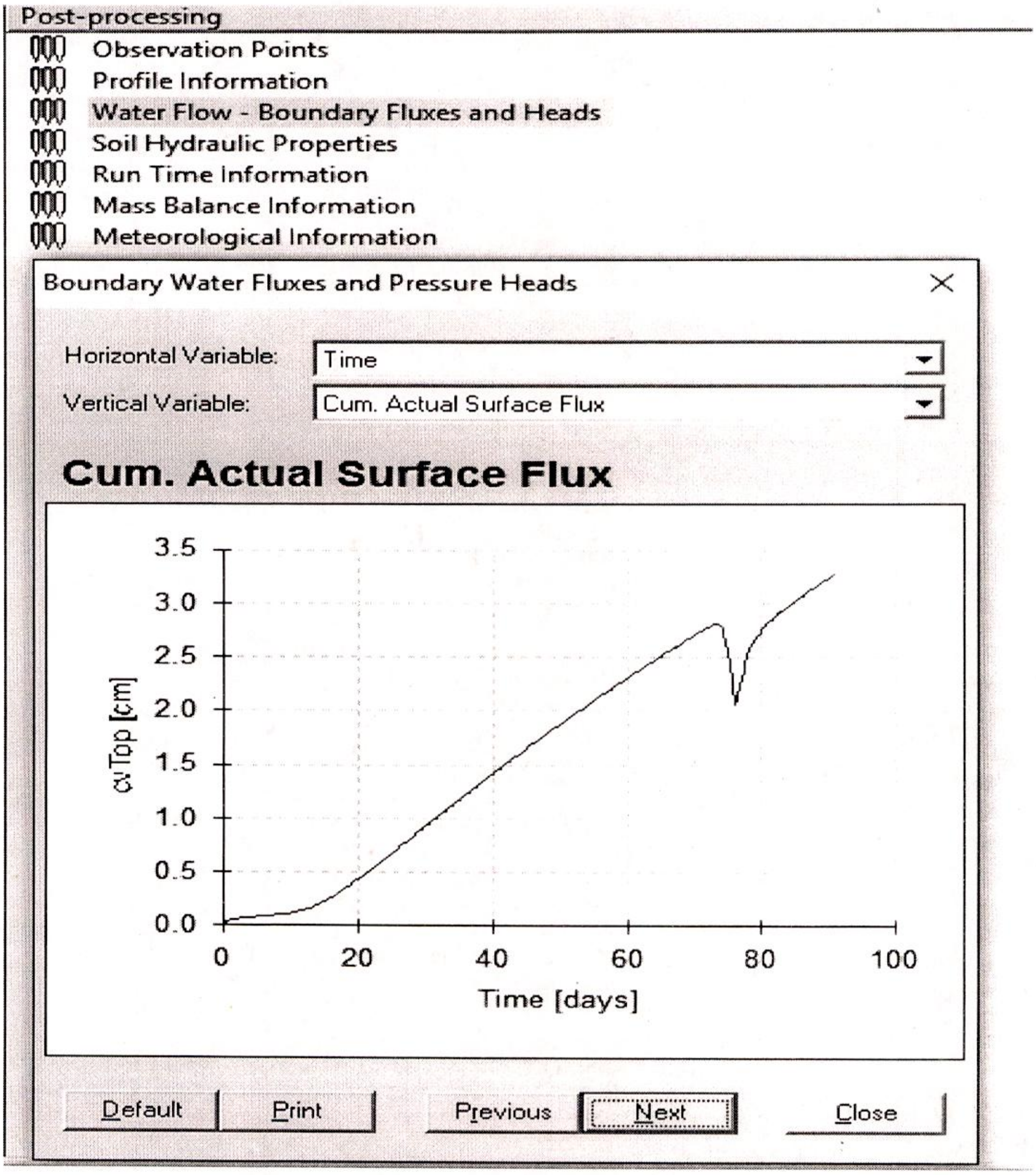
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Bottom Pressure Head
Bottom Pressure Head
hBot [cm]
-500
-600
-700
-800
-900
-1000
-1100
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Cum. Actual Surface Flux
Cum. Actual Surface Flux
cvTop [cm]
Time [days]
Default
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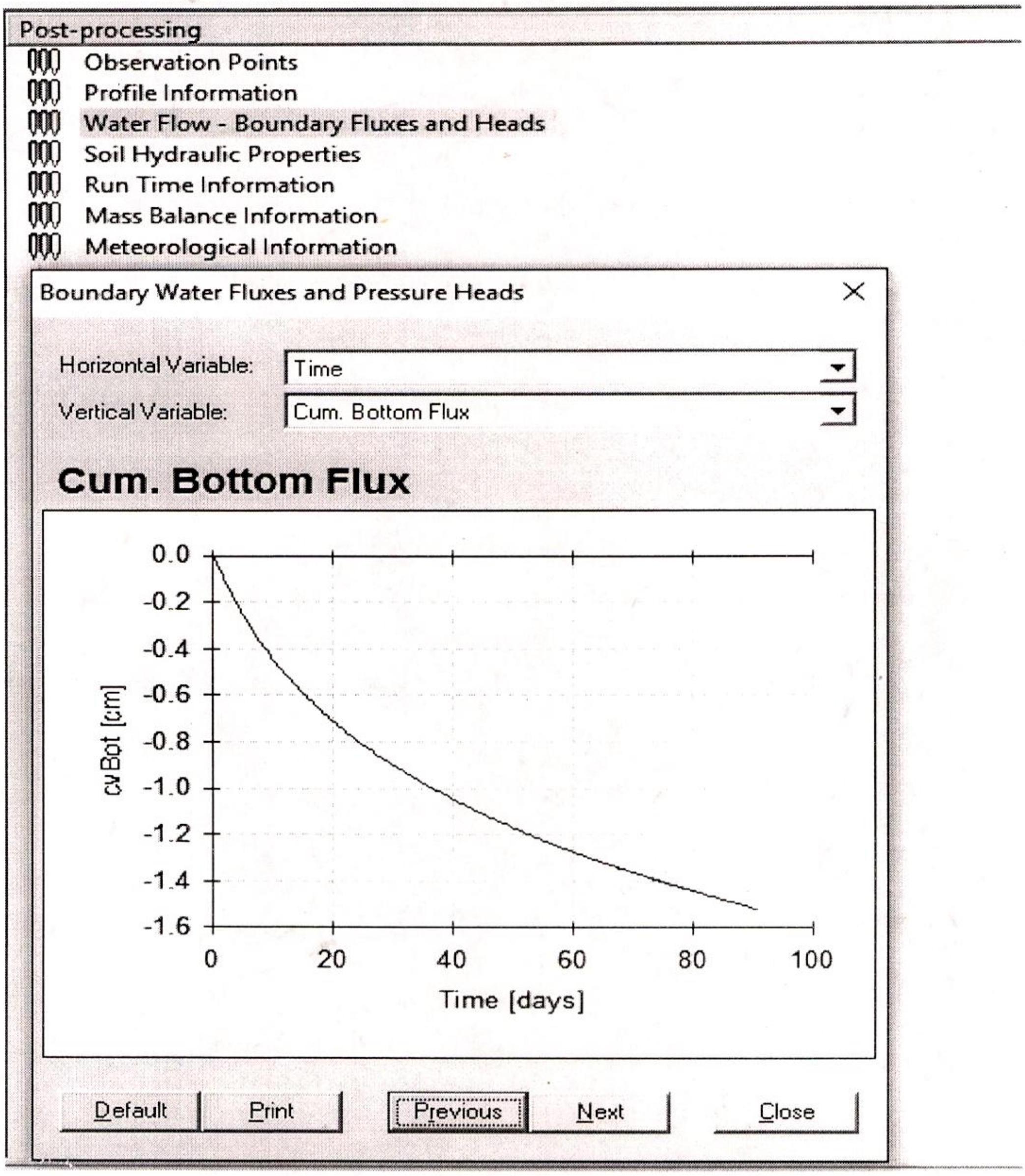
Previous
Next
Close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Observation Points
Profile Information
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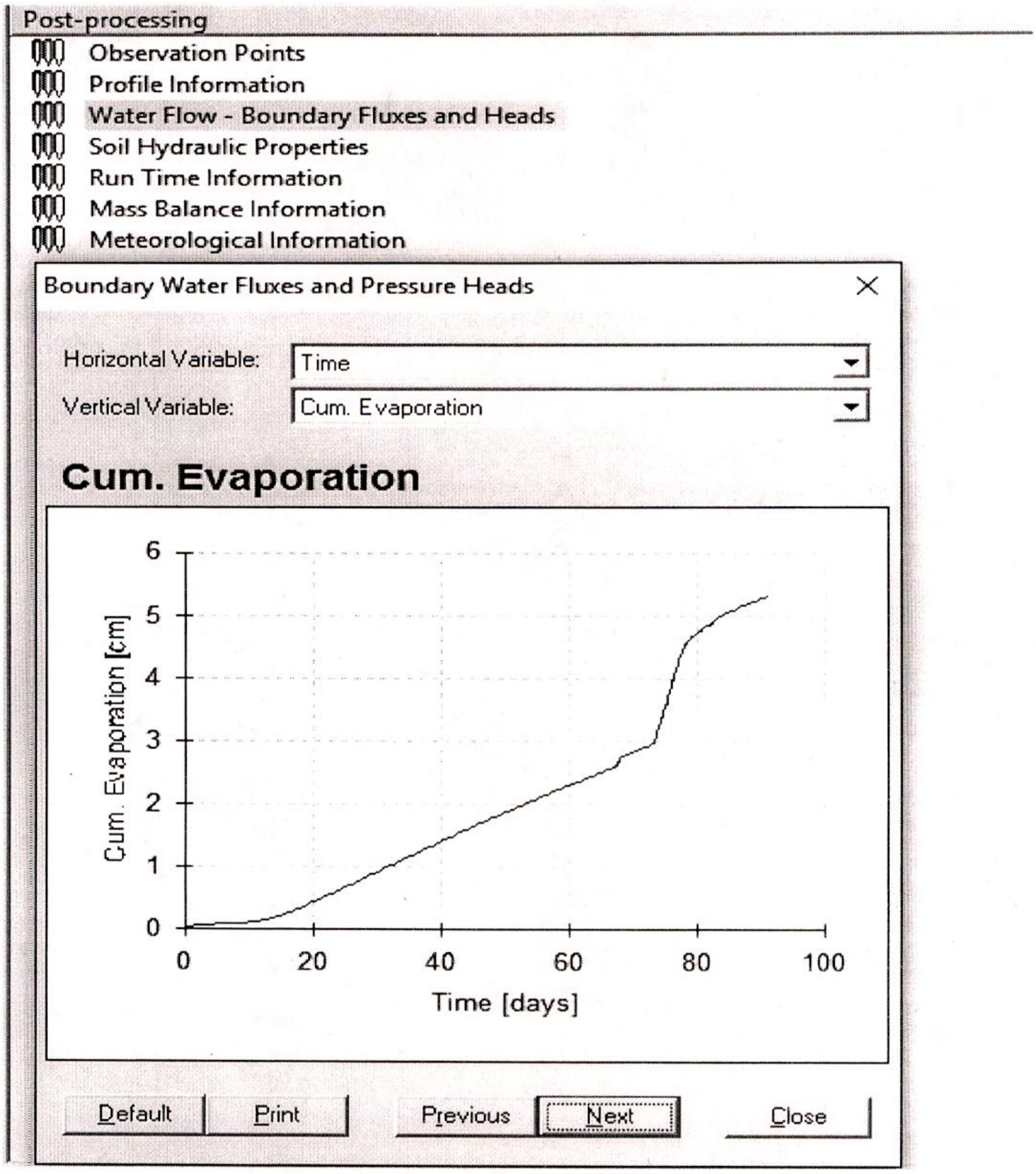
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Cum. Bottom Flux
Cum. Bottom Flux
cvBot [cm]
Time [days]
Default
Print
Previous
Next
Close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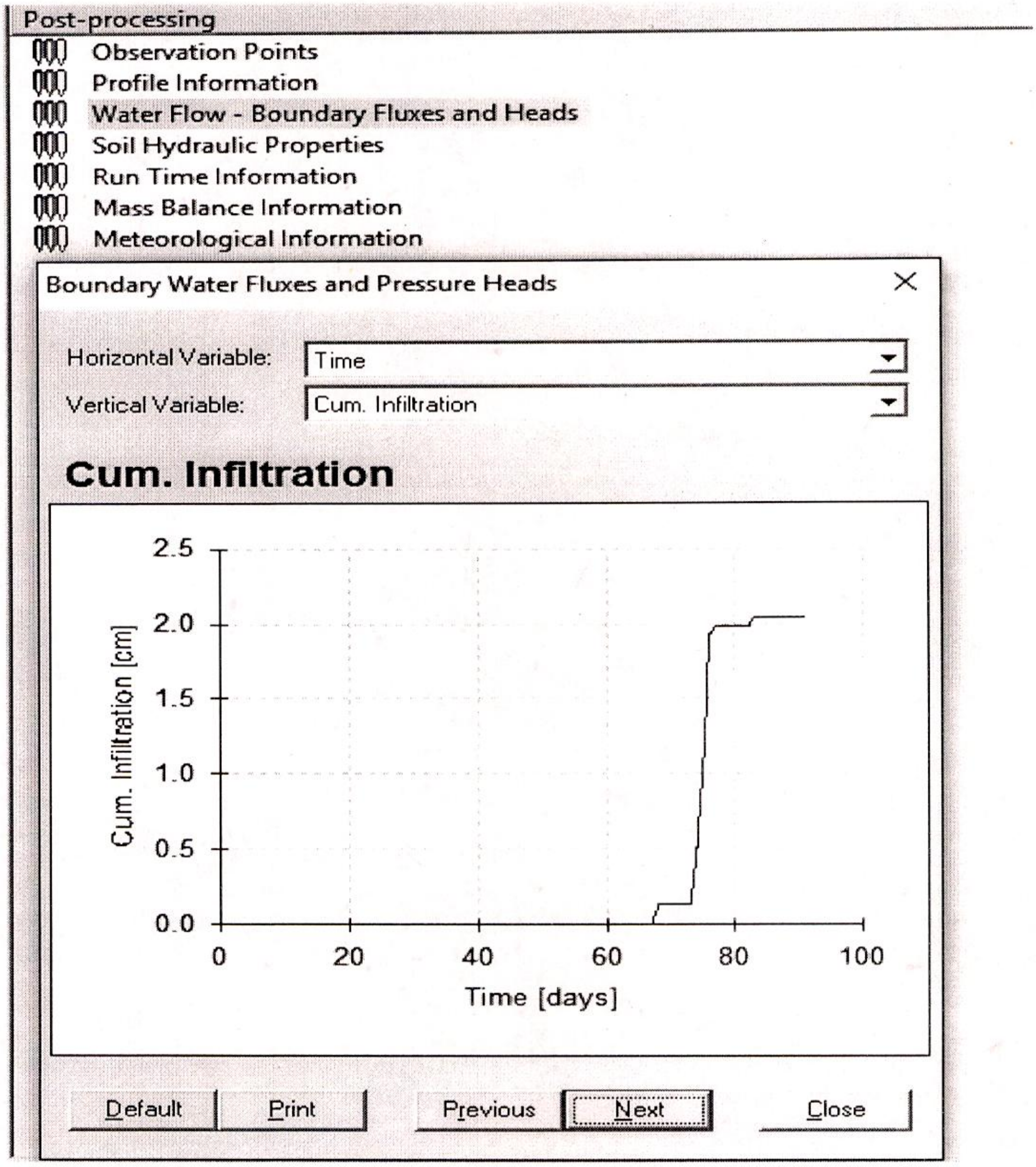
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Cum. Evaporation
Cum. Evaporation
Cum. Evaporation [cm]
Time [days]
Default
Print
Previous
Next
Close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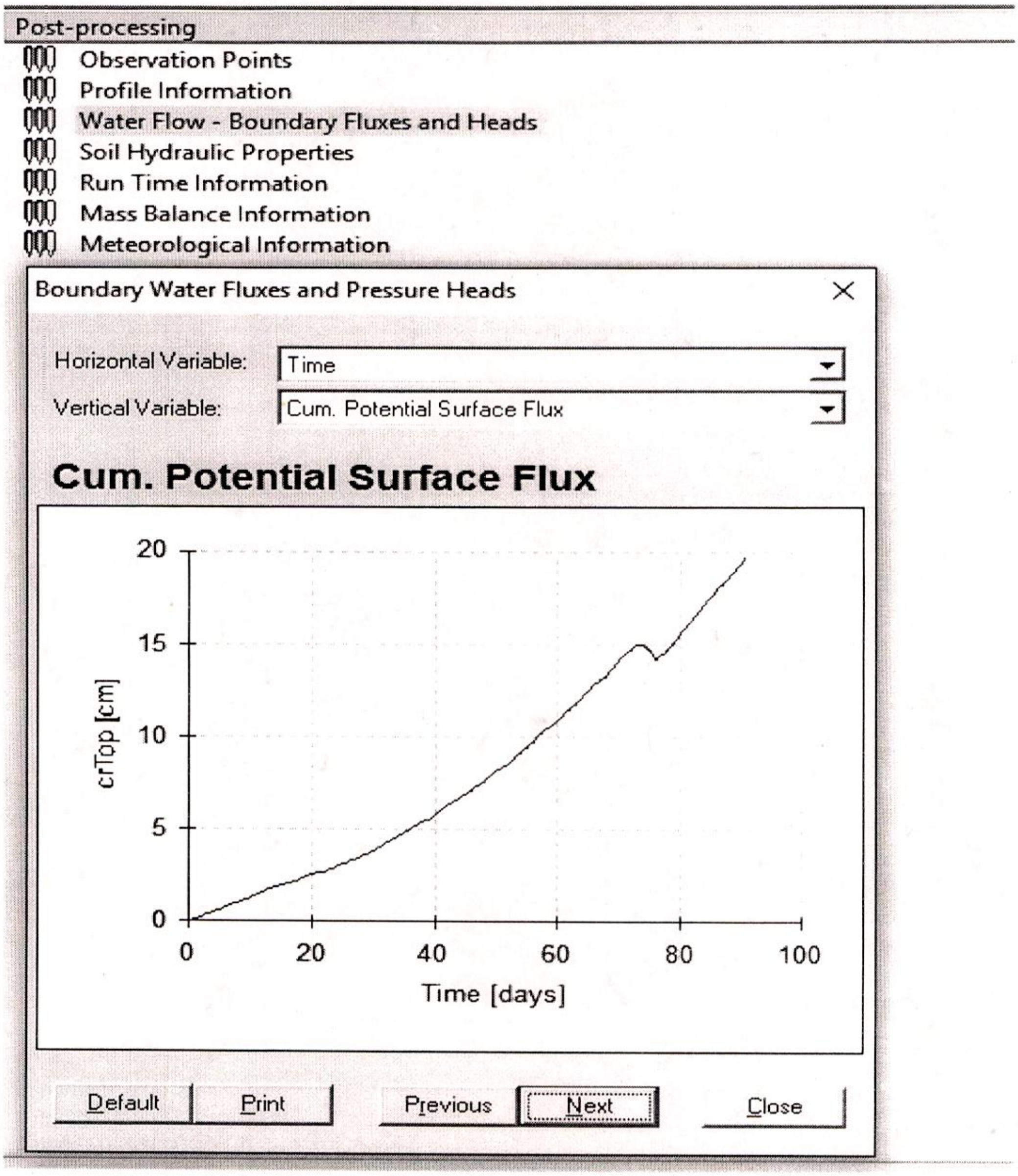
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Cum. Infiltration
Cum. Infiltration
Cum. Infiltration [cm]
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Cum. Potential Surface Flux
Cum. Potential Surface Flux
crTop [cm]
Time [days]
0
5
10
15
20
0
20
40
60
80
100
Default
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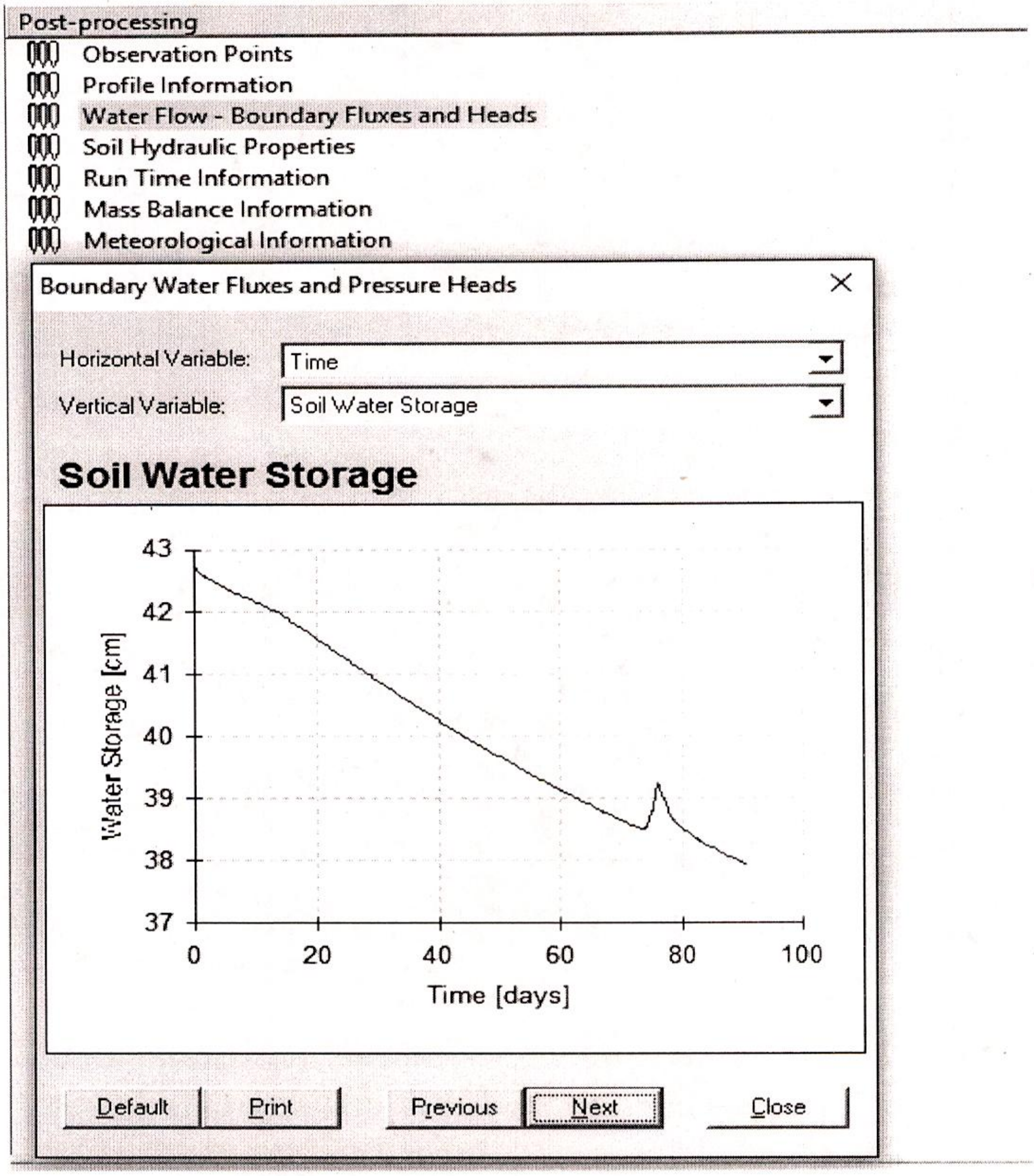
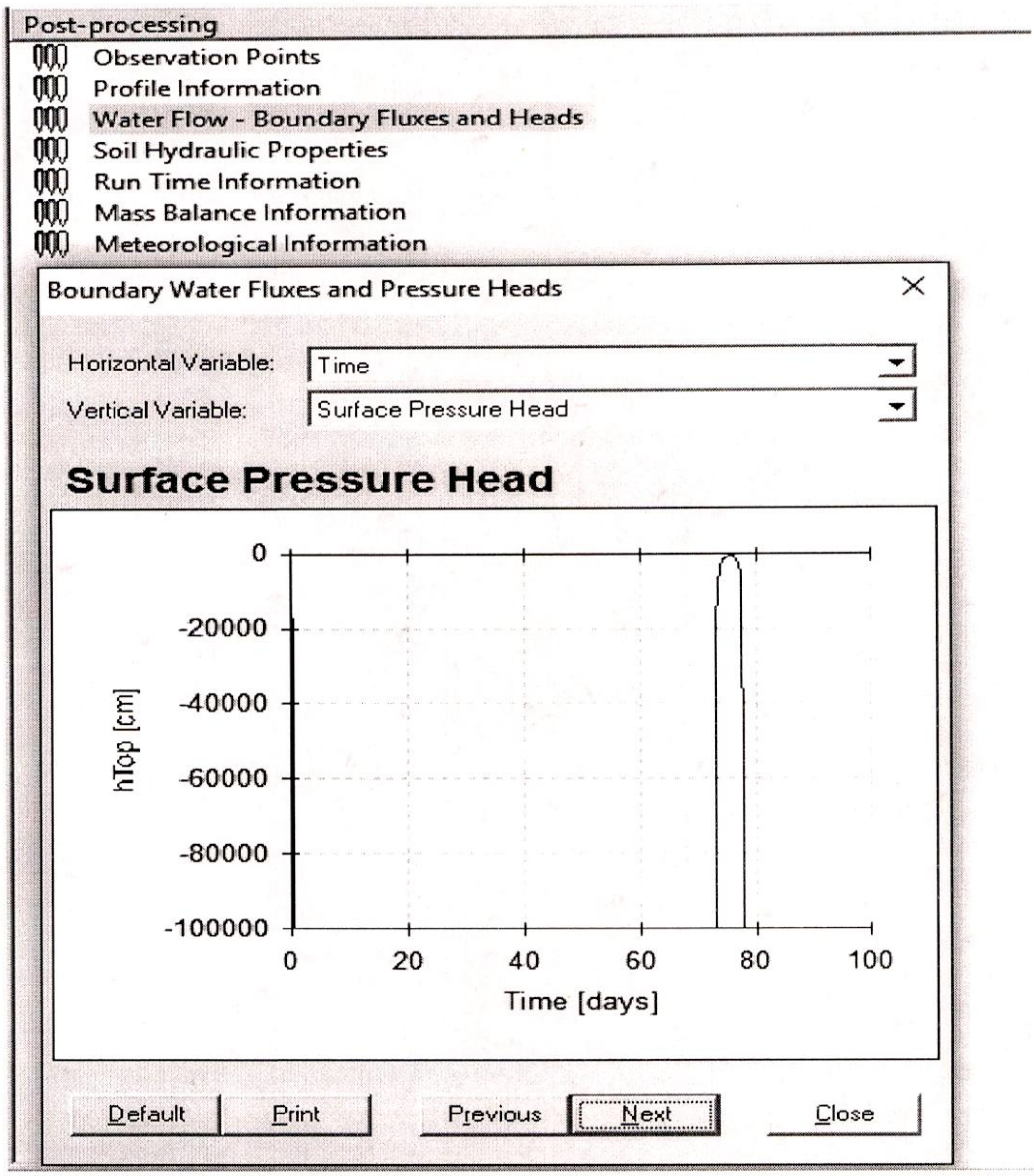
Previous
Next
Close



Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Soil Water Storage
Soil Water Storage
Water Storage [cm]
43
42
41
40
39
38
37
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close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Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Boundary Water Fluxes and Pressure Heads
Horizontal Variable:
Time
Vertical Variable:
Surface Pressure Head
Surface Pressure Head
hTop [cm]
0
-20000
-40000
-60000
-80000
-100000
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close

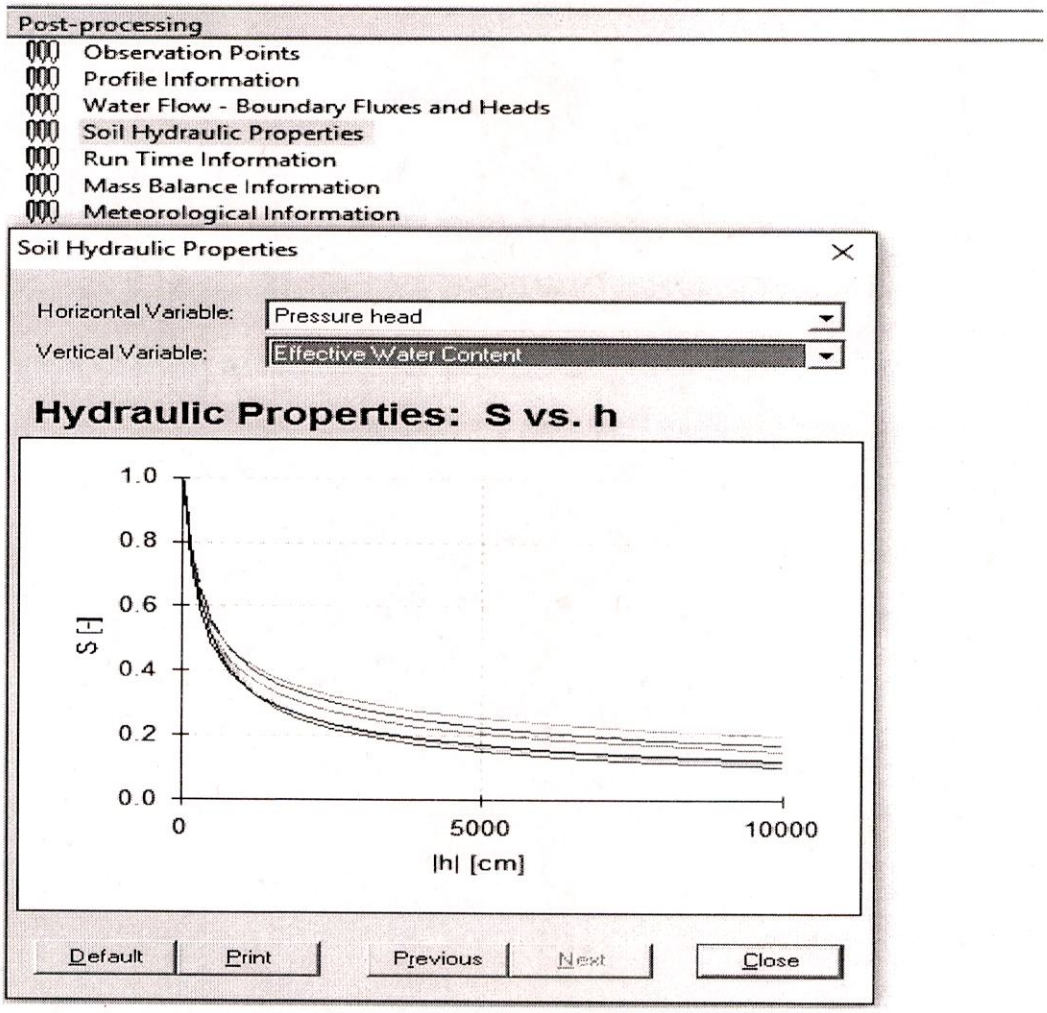
7.3 Soil Hydraulic Properties (Results Menu)

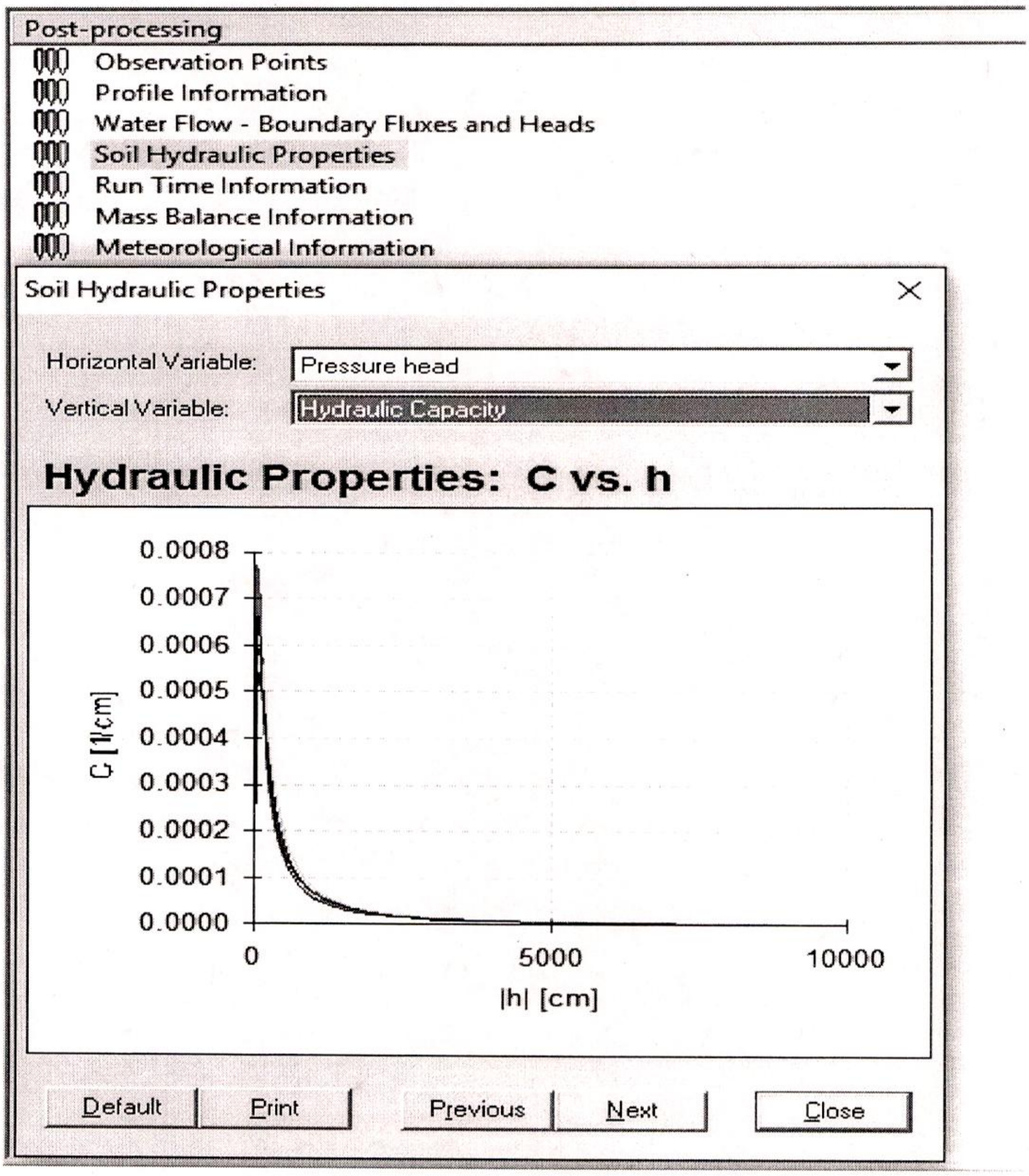
Graphical display of the unsaturated soil hydraulic properties. Several combinations of dependent and independent variables are possible.

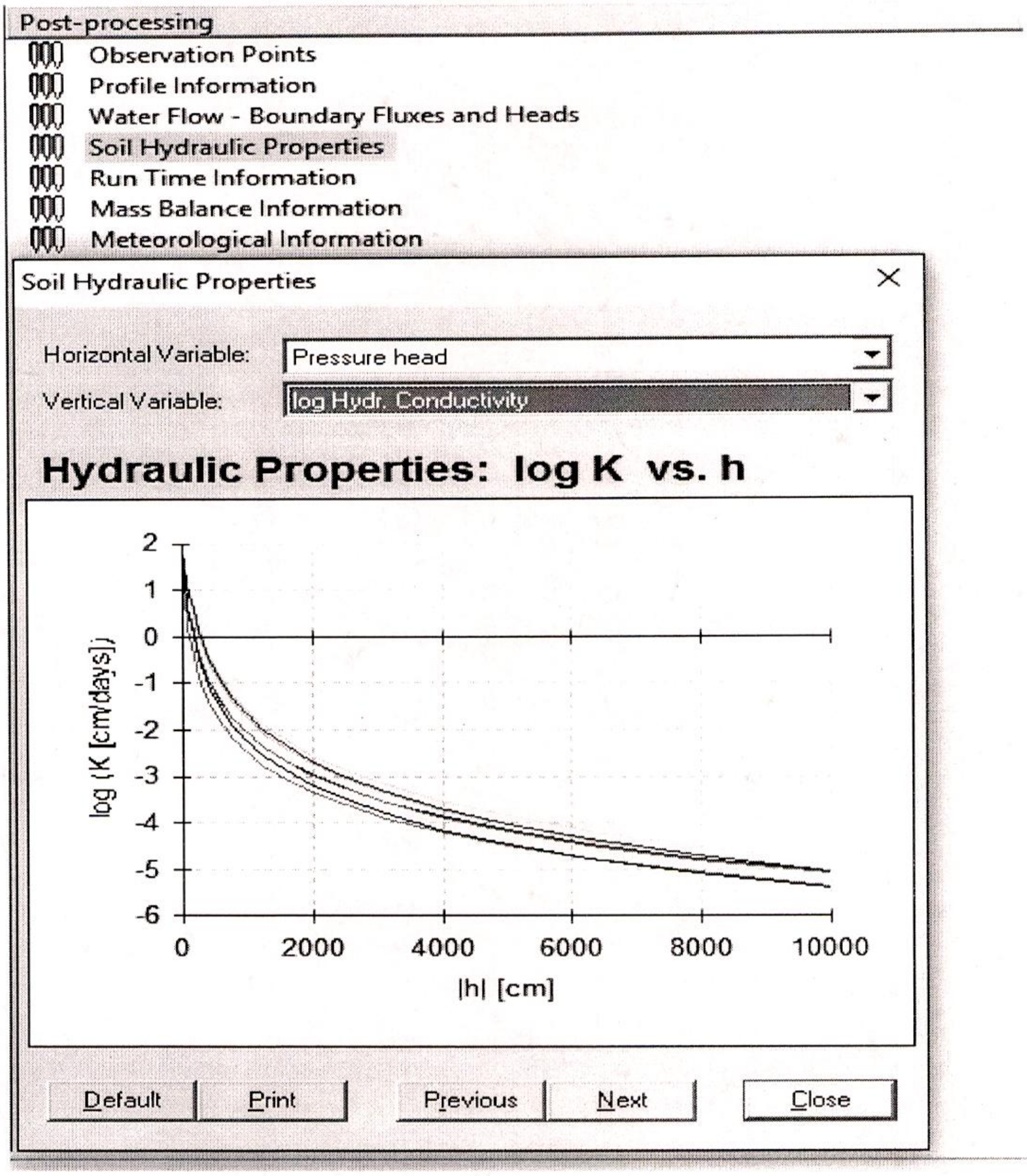
The pressure head, the logarithm of the pressure head, or the water content can be selected as the dependent variable (vertical axis).

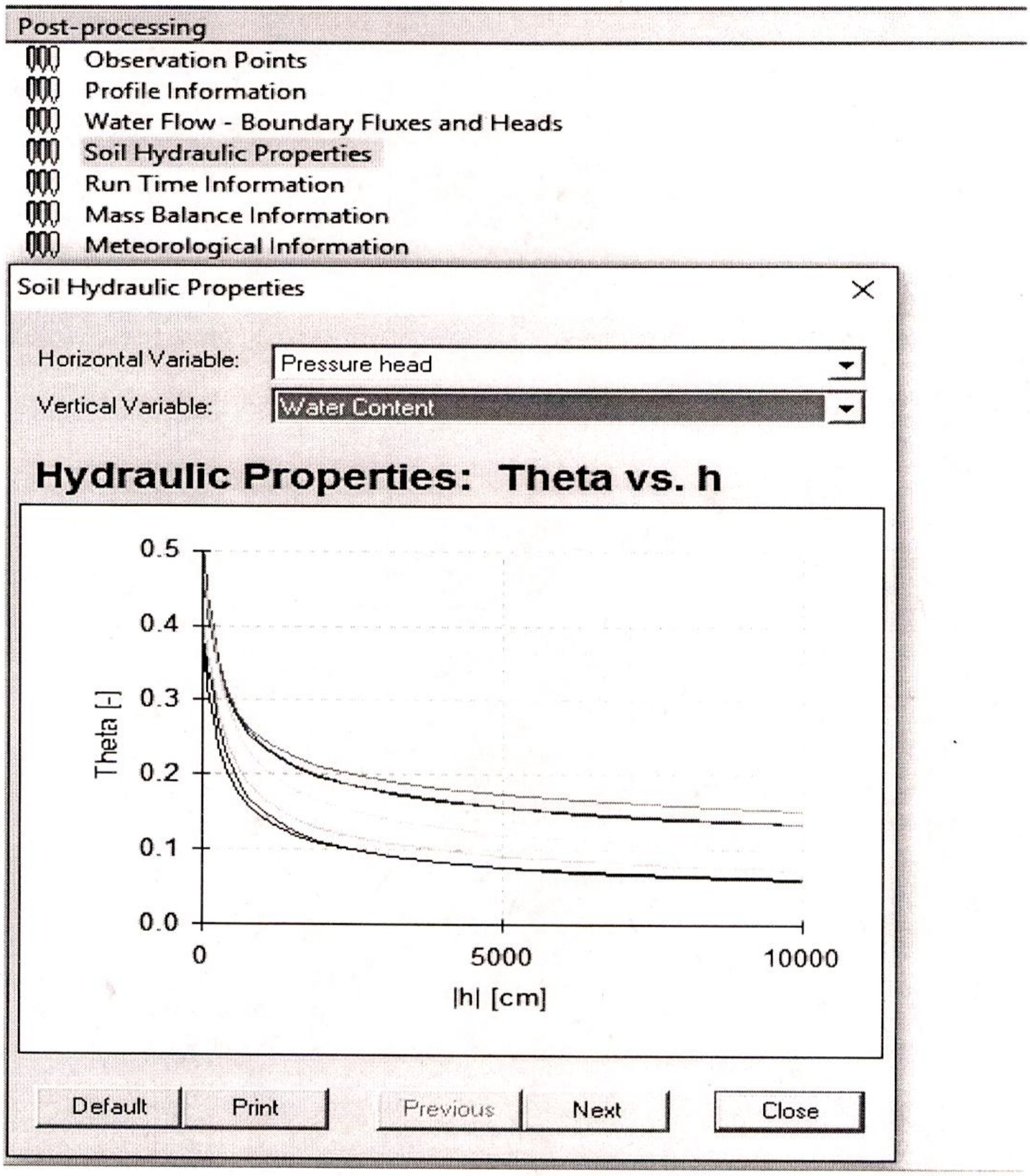
The water content, the effective water content, the hydraulic conductivity, the logarithm of the hydraulic conductivity, or the water capacity can be selected as the independent variable (horizontal axis).

Fig 7.4: Graphical representation of changes in Effective Water Content, Hydraulic Capacity, log Hydraulic Conductivity and Water Content.




Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Soil Hydraulic Properties
Horizontal Variable:
Pressure head
Vertical Variable:
Hydraulic Capacity
Hydraulic Properties: C vs. h
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
C [1/cm]
0
5000
10000
|h| [cm]
Default
Print
Previous
Next
Close

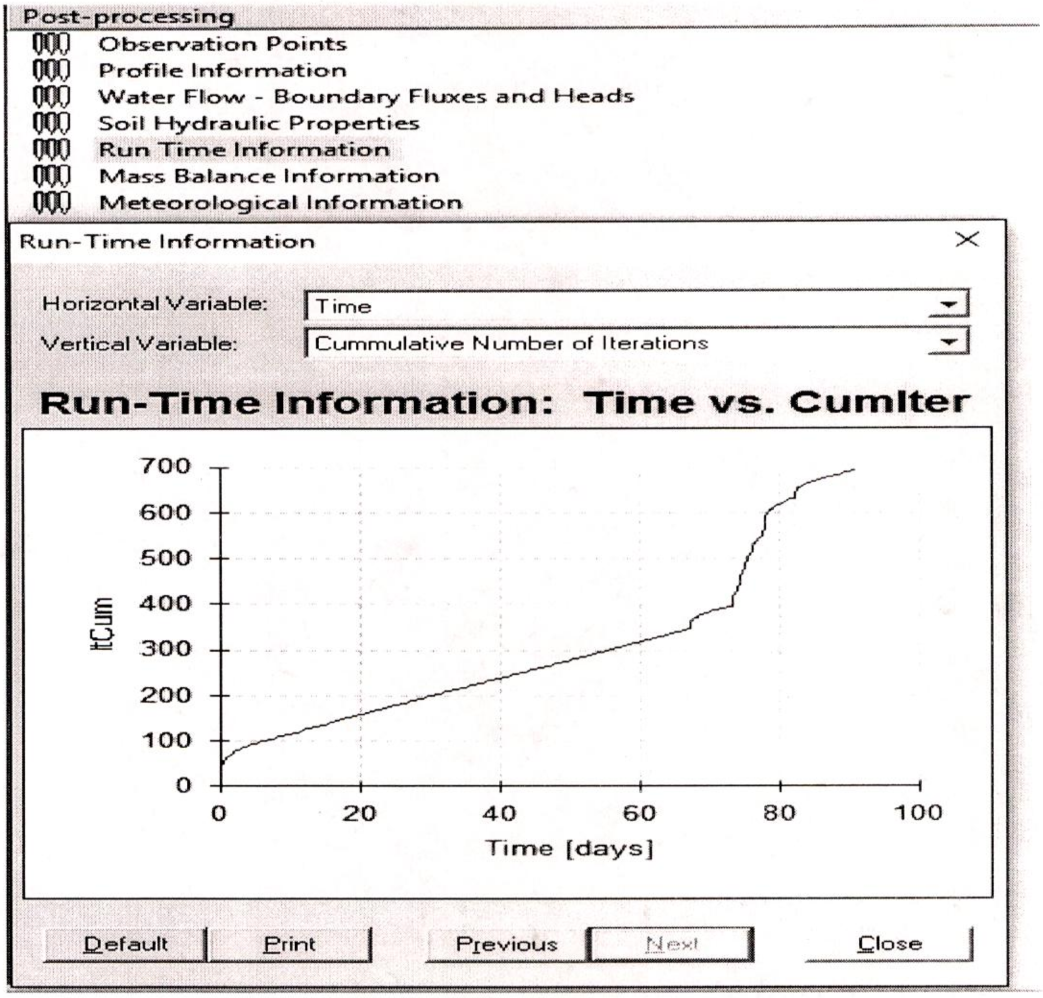

Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Soil Hydraulic Properties
Horizontal Variable:
Pressure head
Vertical Variable:
log Hydr. Conductivity
Hydraulic Properties: log K vs. h
log (K [cm/days])
|h| [cm]
2
1
0
-1
-2
-3
-4
-5
-6
0
2000
4000
6000
8000
10000
Default
Print
Previous
Next
Close

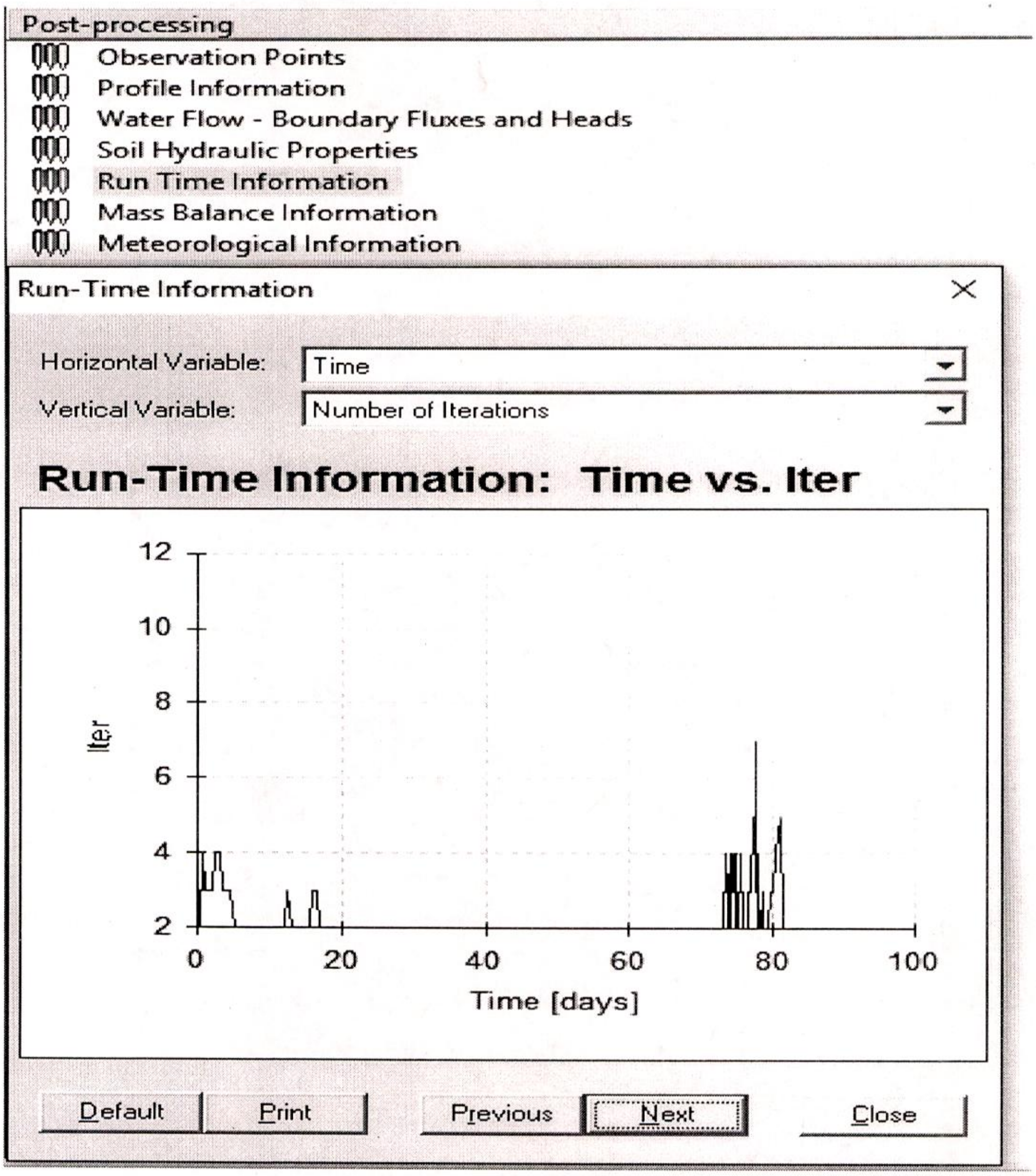

Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Soil Hydraulic Properties
Horizontal Variable:
Pressure head
Vertical Variable:
Water Content
Hydraulic Properties: Theta vs. h
Theta [-]
0.5
0.4
0.3
0.2
0.1
0.0
0
5000
10000
|h| [cm]
Default
Print
Previous
Next
Close

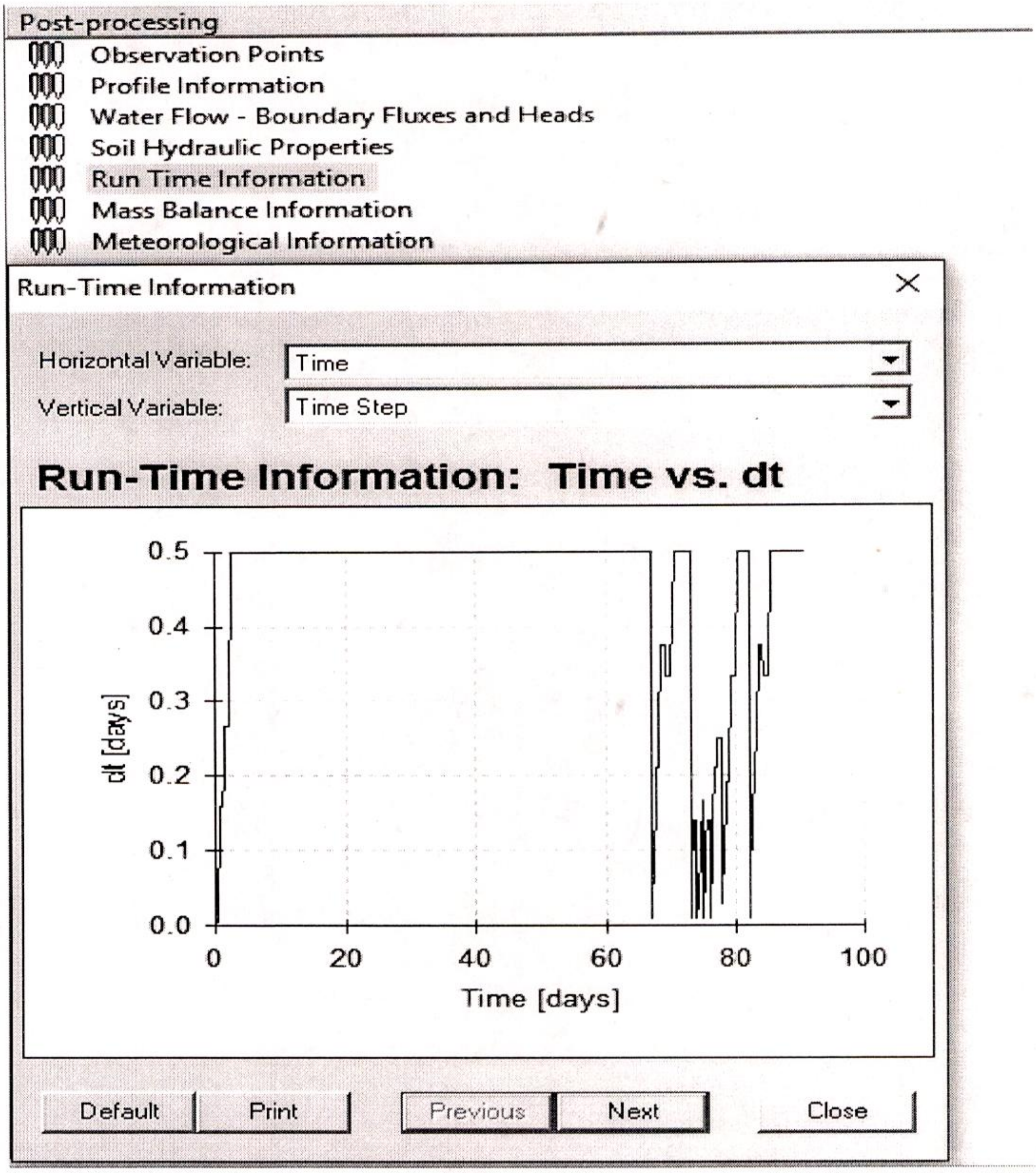
7.4 Run Time Information (Results Menu)

Generates graphs of temporal changes in the time step, number of iterations necessary to solve the Richards equation at a particular time level, cumulative number of iterations, and dimensionless Peclet and Courant numbers. These variables can be plotted against either time or time-step number.

Fig 7.5: Graphical representation of temporal changes in the time step, number of iterations necessary to solve the Richards equation at a particular time level, cumulative number of iterations.



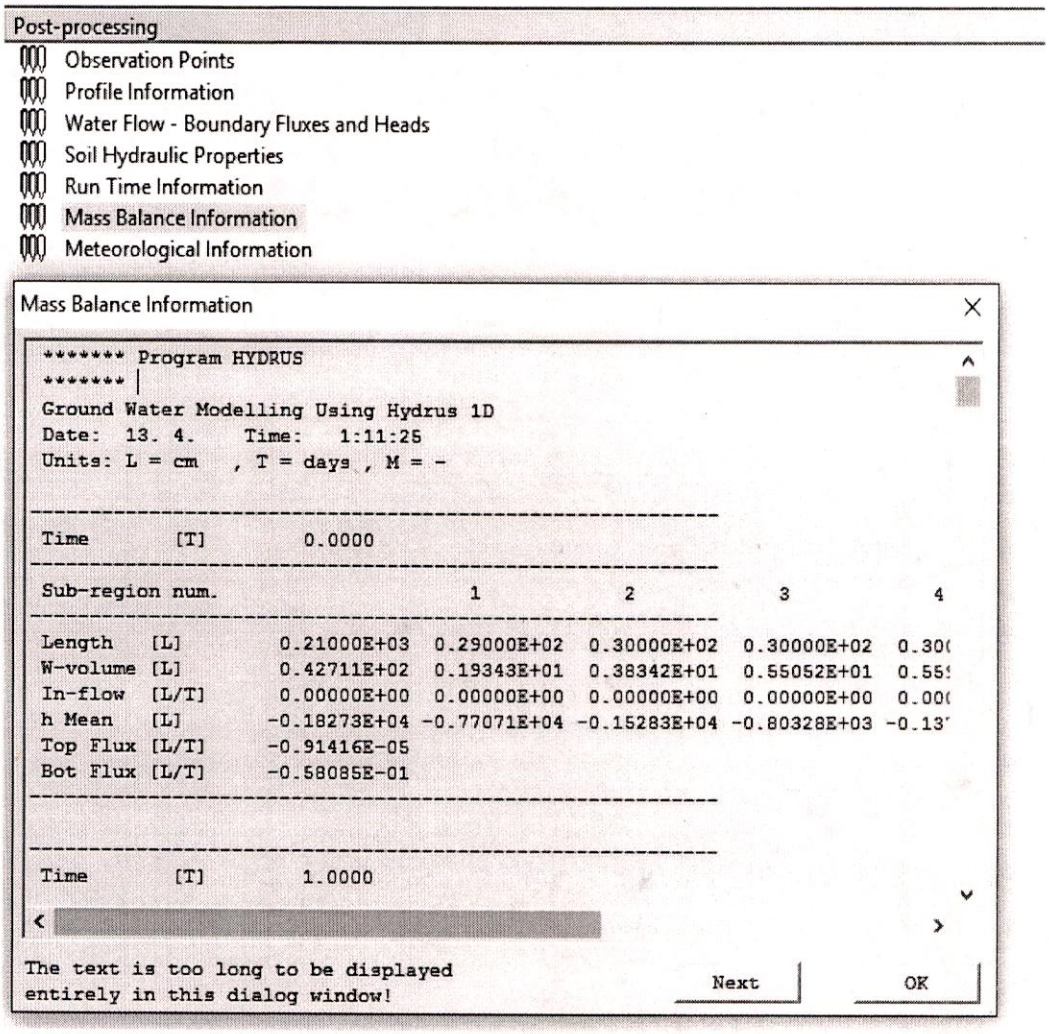

Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Run-Time Information
Horizontal Variable:
Time
Vertical Variable:
Number of Iterations
Run-Time Information: Time vs. Iter
Iter
12
10
8
6
4
2
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Run-Time Information
Horizontal Variable:
Time
Vertical Variable:
Time Step
Run-Time Information: Time vs. dt
dt [days]
Time [days]
Default
Print
Previous
Next
Close

7.5 Mass Balance Information (Results Menu)

This command shows an ASCII file containing information about the amount of water in the profile, inflow and outflow rates, mean pressure head, amount of solute in the profile, and mean concentration in the entire flow domain or a specified Subregion.

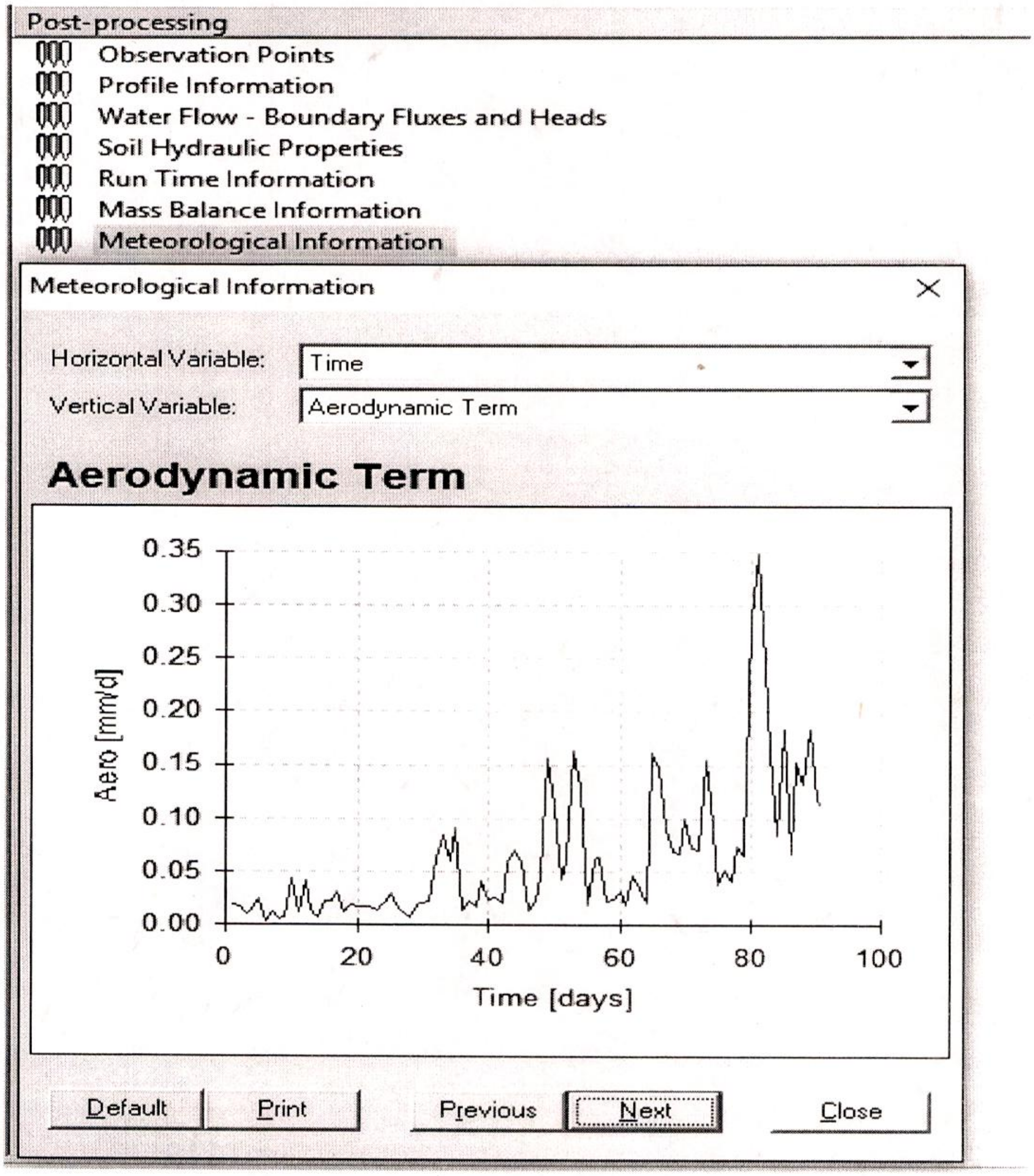
Fig 7.6: Mass Balance Information

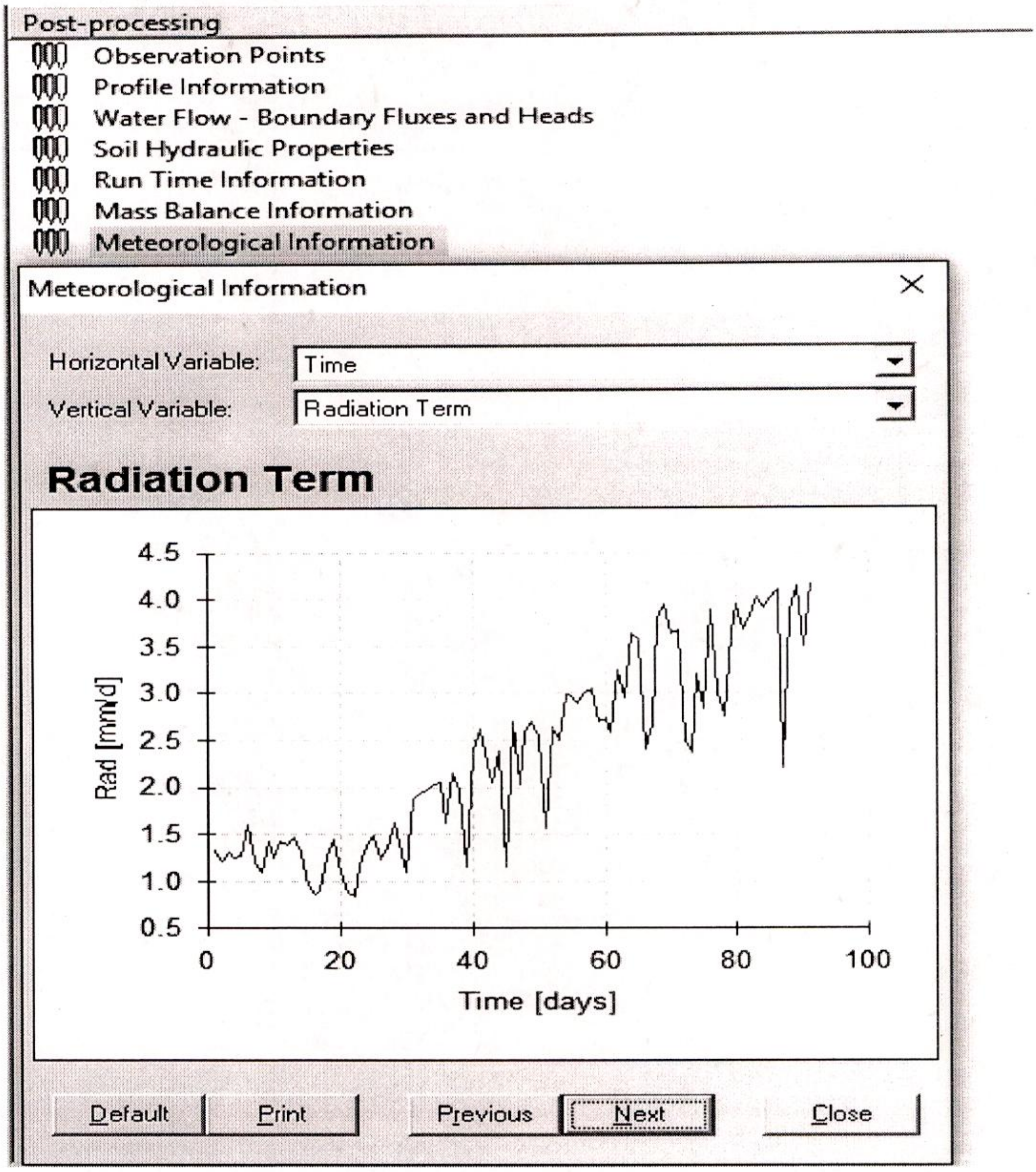


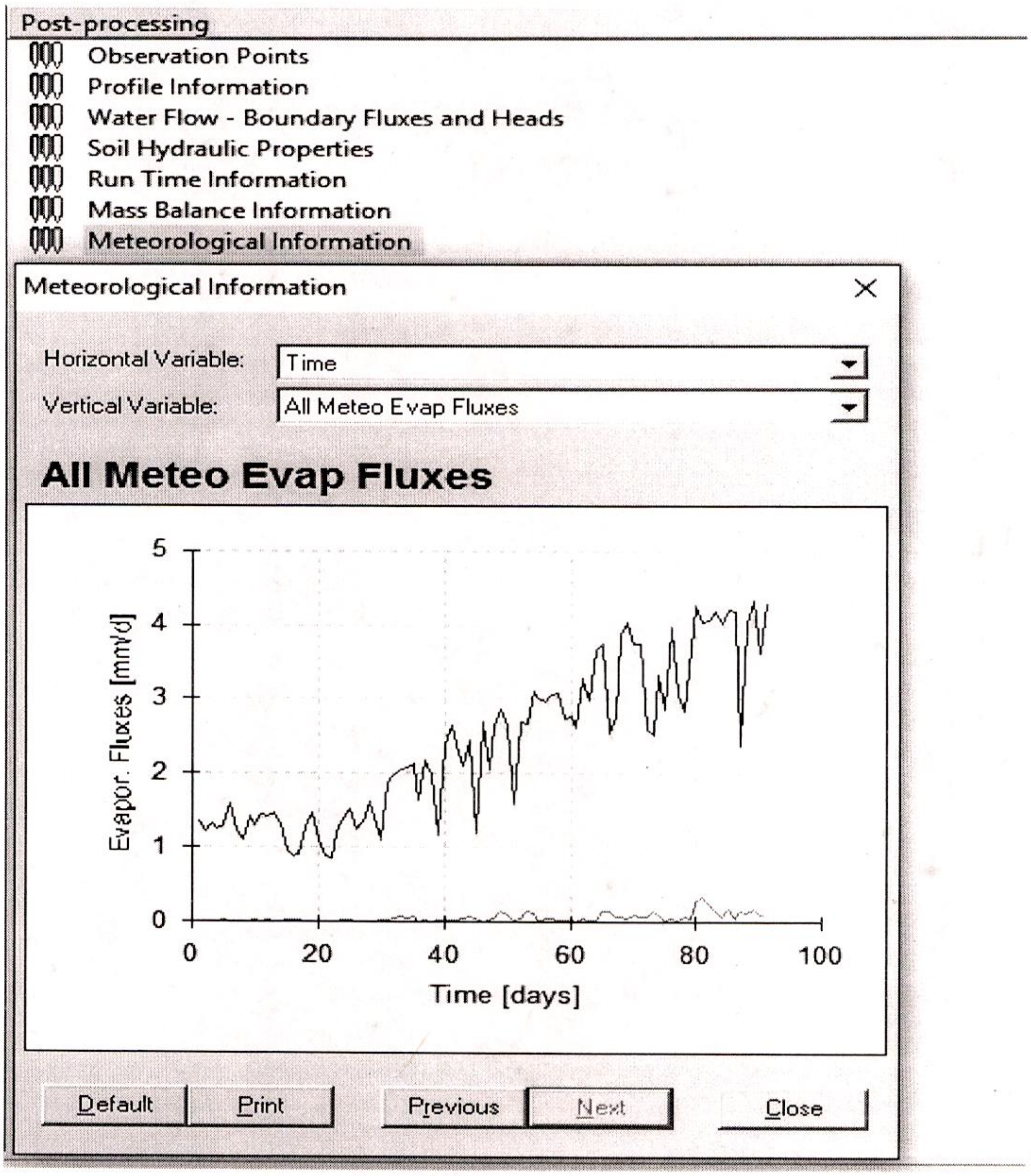
7.6 Meteorological Information (Results Menu)

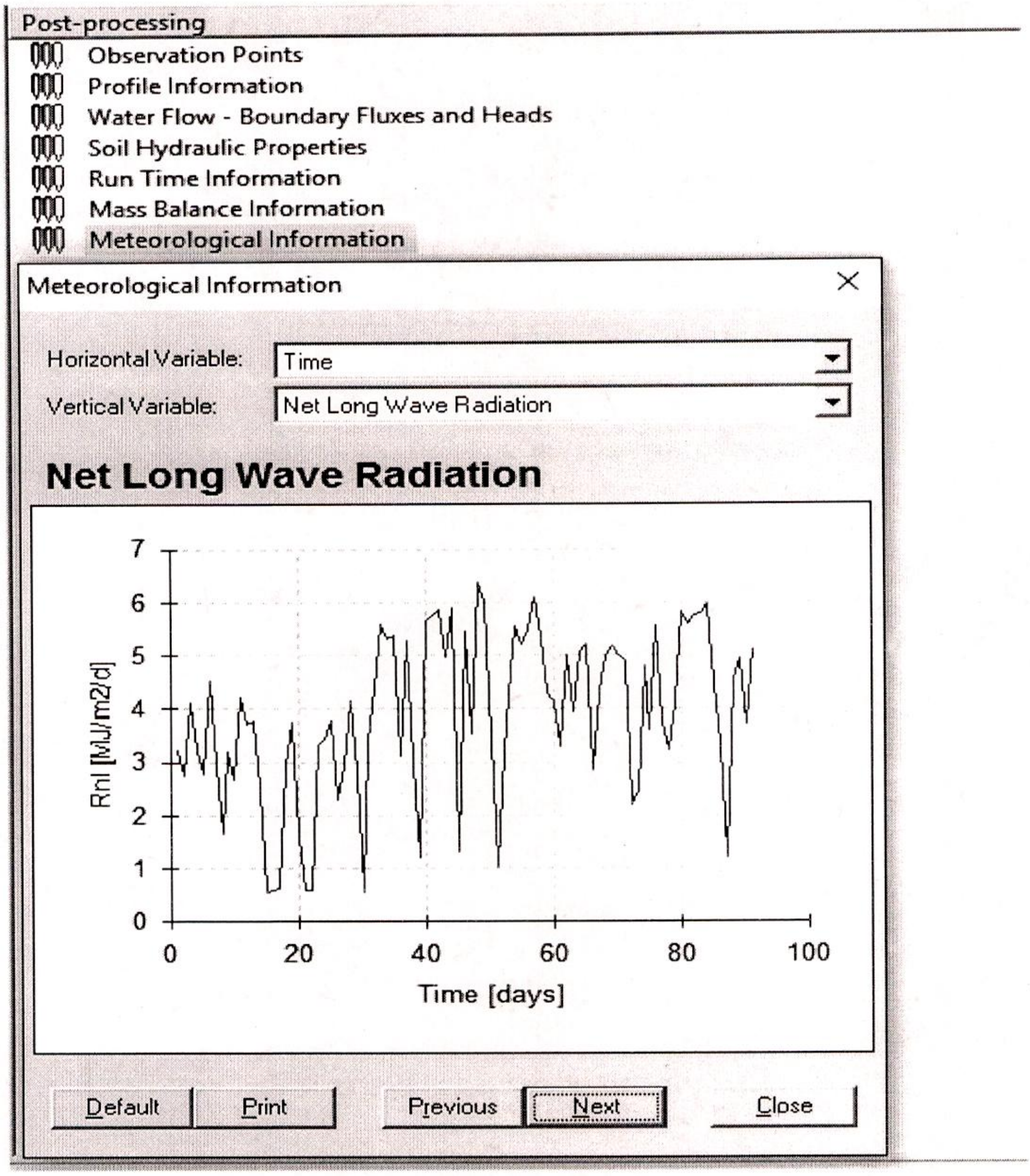
This windows displays information from the METEO.OUT file, related to meteorological information.

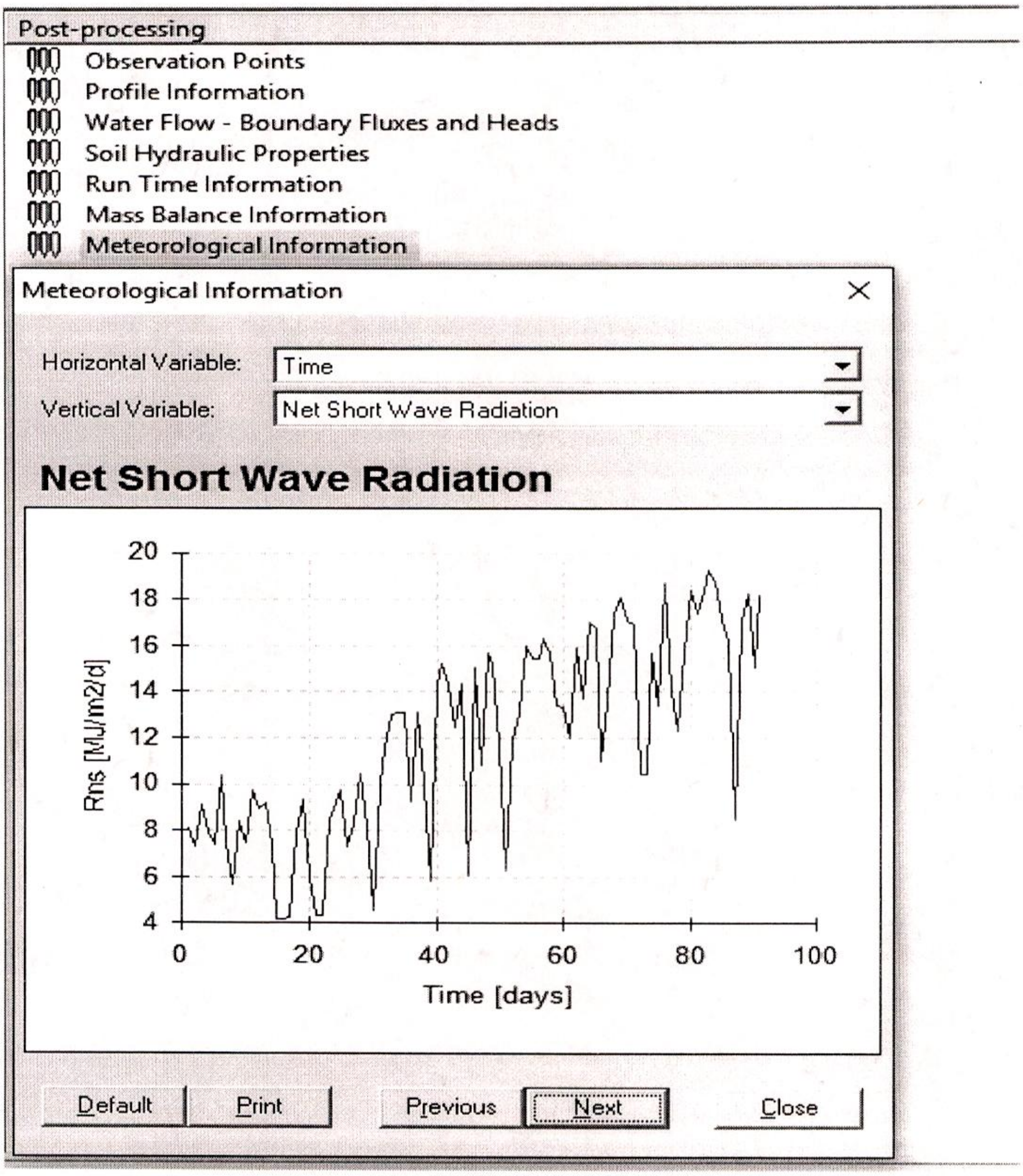
Fig 7.7: Graphical representation of information from the METEO.OUT file, related to meteorological information.

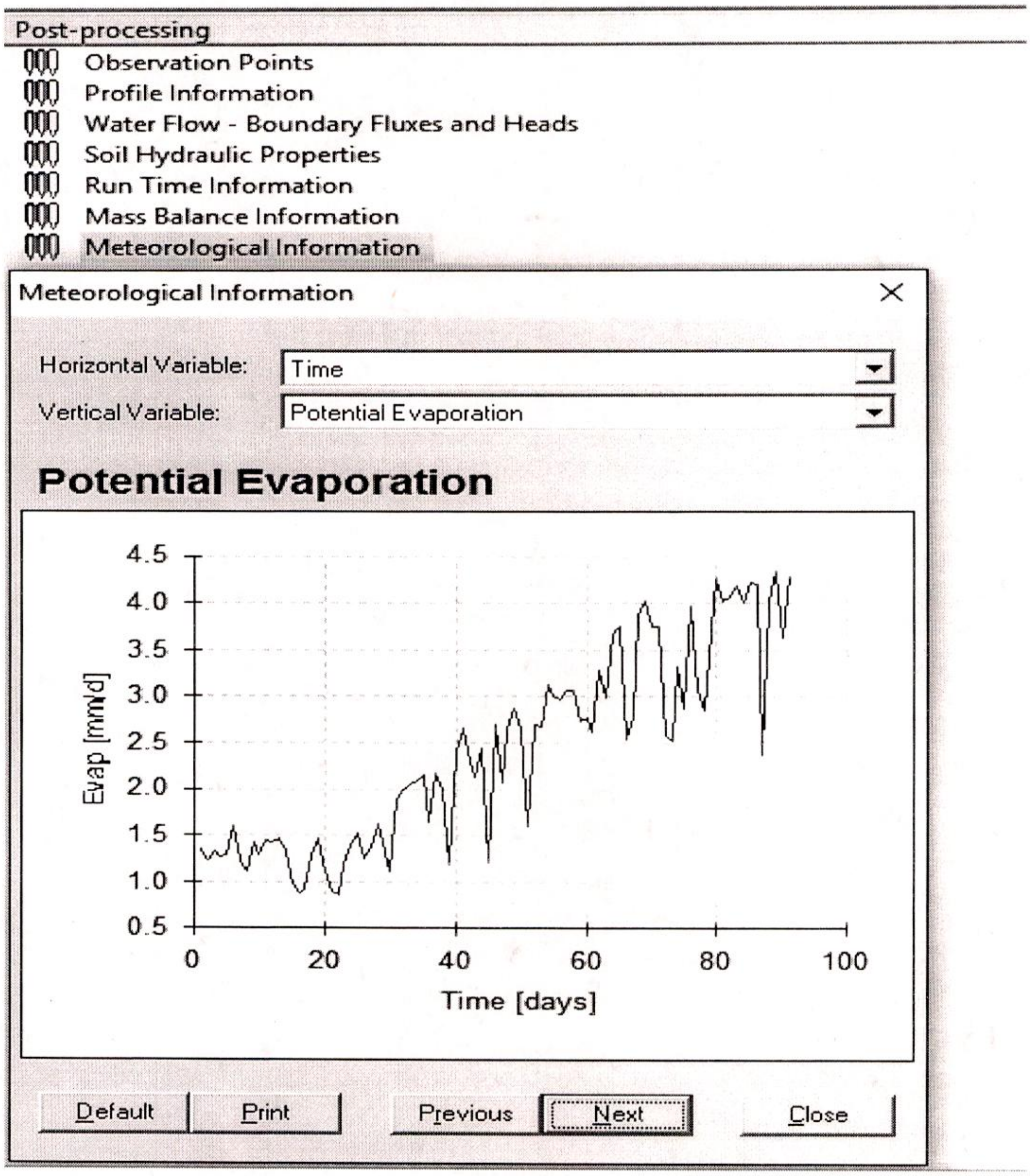


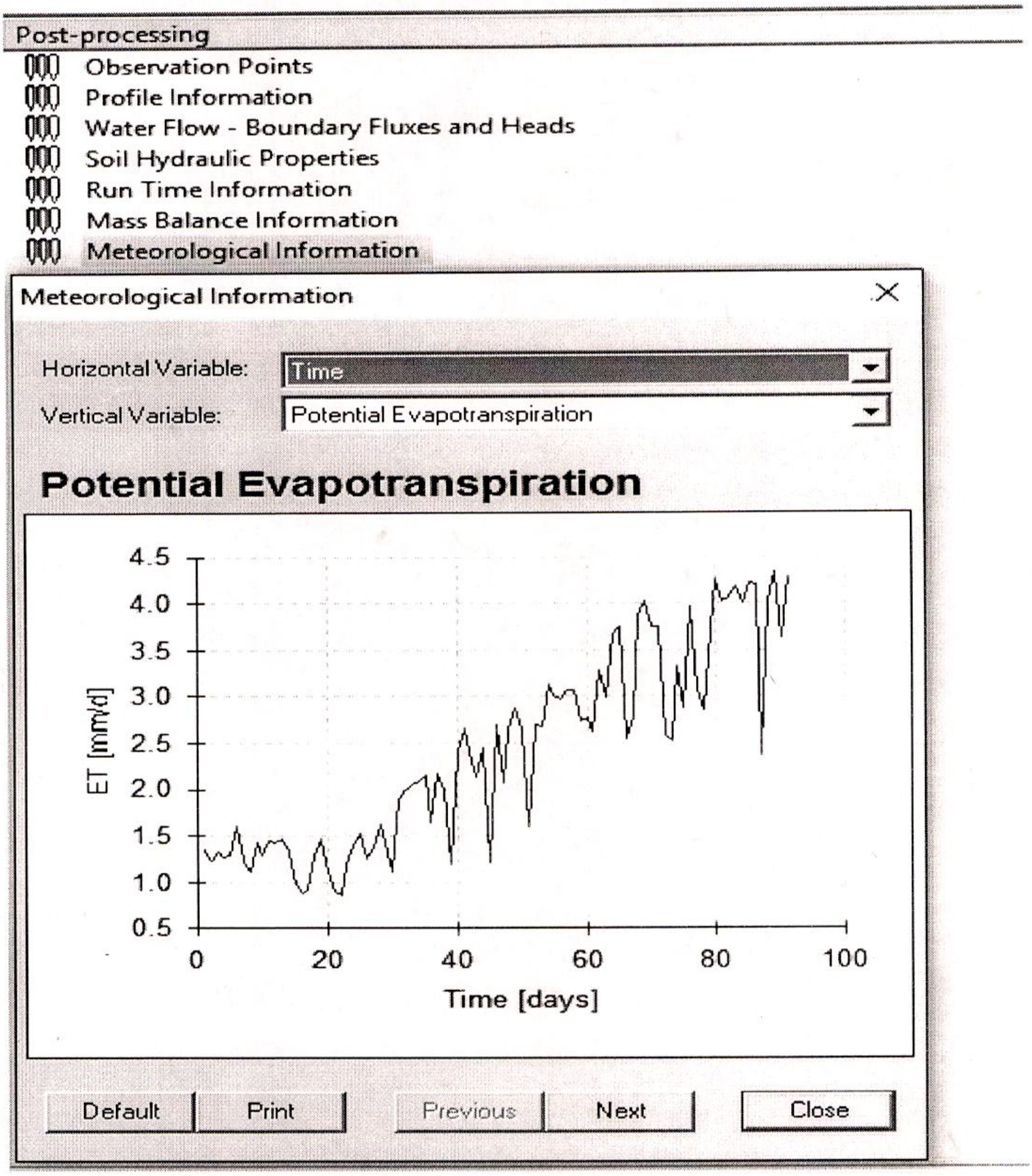

Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Radiation Term
Radiation Term
Rad [mm/d]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
All Meteo Evap Fluxes
All Meteo Evap Fluxes
Evapor. Fluxes [mm/d]
0
1
2
3
4
5
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close

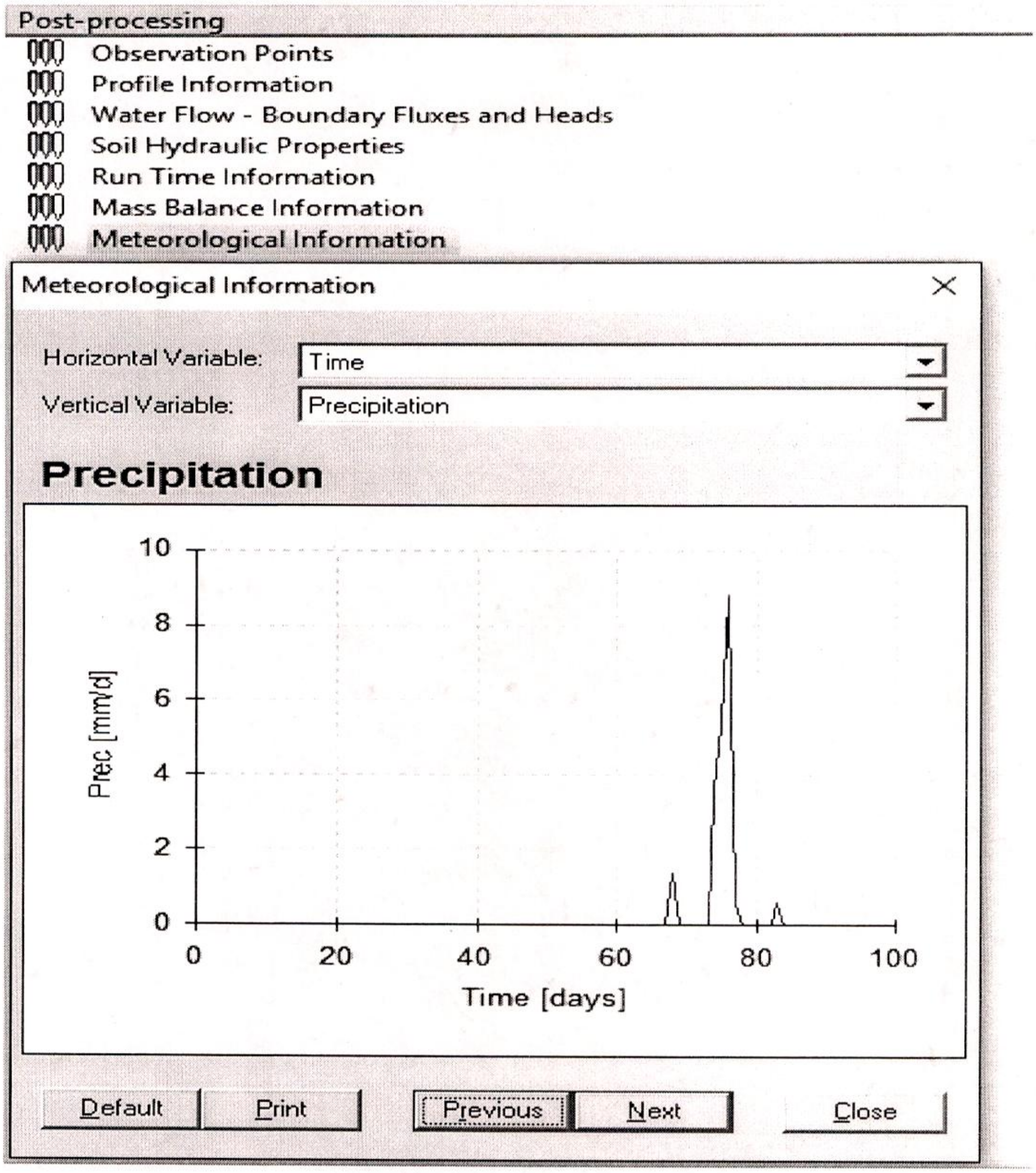

Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Net Long Wave Radiation
Net Long Wave Radiation
Rnl [MJ/m2/d]
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Net Short Wave Radiation
Net Short Wave Radiation
Rns [MJ/m2/d]
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Potential Evaporation
Potential Evaporation
Evap [mm/d]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close



Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Potential Evapotranspiration
Potential Evapotranspiration
ET [mm/d]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close


Post-processing
Observation Points
Profile Information
Water Flow - Boundary Fluxes and Heads
Soil Hydraulic Properties
Run Time Information
Mass Balance Information
Meteorological Information
Meteorological Information
Horizontal Variable:
Time
Vertical Variable:
Precipitation
Precipitation
10
8
6
4
2
0
Prec [mm/d]
0
20
40
60
80
100
Time [days]
Default
Print
Previous
Next
Close

8.0 CONCLUSIONS:

Soil Water movement in the unsaturated zone is incredibly complex process due to the heterogeneous nature of soil and variable atmospheric boundary conditions at both the soil surface over short time periods. Despite all the simplifications which were made, HYDRUS-1D is a powerful tool to simulate the movement of water in partially saturated porous media, since it can deal with different water flow boundary conditions. However, to be able to validate the model performance, more data collection and measurements are needed which in turn means more cost-effective sampling and analysis methodologies must be developed.

Results of the study show the following;

- The temporal variability in precipitation patterns has direct impact on the Soil Water Storage and the downward movement of water in different types of soils. As the precipitation occurs the soil water storage increases.
- Various Hydrological Soil Properties was determined by using Hydrus 1D.
- The Soil Water Movement in the unsaturated zone was simulated by using Hydrus 1D for the period 1st January, 2015 to 31st March, 2016.

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