Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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Justification for Use of the HELP Model to Estimate Infiltration Rates for the E-Area Low-Level Waste Facility Performance Assessment

J. A. Dyer

December 2019

SRNL-STI-2019-00362, Revision 0

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Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords: *Closure Cap, Disposal, HYDRUS, Solid Waste*

Retention: *Permanent*

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REVIEWS AND APPROVALS

AUTHORS:

____

J. A. Dyer, Environmental Modeling, SRNL Date

TECHNICAL REVIEW:

____

T. L. Danielson, Environmental Modeling, SRNL Date

____

B. T. Butcher, Environmental Modeling, SRNL Date

APPROVAL:

____

D. A. Crowley, Manager Date
Environmental Modeling, SRNL

____

A. P. Fellinger, Acting Director Date
Environmental Restoration Technologies, SRNL

EXECUTIVE SUMMARY

This report supplements the infiltration data package report prepared by Dyer (2019) for the upcoming E-Area Low-Level Waste Facility (LLWF) Performance Assessment (PA) and provides further justification for the use of the Hydrologic Evaluation of Landfill Performance (HELP) model for E-Area PA infiltration calculations. Three items are addressed:

1. A comparison of HELP model results to field- and modeling-based water balance, soil infiltration, and groundwater recharge studies that have been conducted at or near the Savannah River Site (SRS) over several decades.
2. An evaluation of the hydrologic model and design and performance recommendations for the planned Saltstone Disposal Facility closure cap at SRS.
3. A side-by-side comparison of the HYDRUS-1D and HELP models to assess their capabilities to efficiently perform the wide range of intact and subsidence infiltration model simulations across multiple disposal unit types as required for the E-Area LLWF PA.

Net infiltration/recharge rates for ten studies conducted at or near SRS over several decades range from 9.1 to 16 inches/year with a median of 14.5 inches/year, which is approximately one-third of the median annual-average precipitation rate of 47.79 inches for the ten studies. The infiltration/recharge rates compare favorably with the results of HELP model simulations for the operational soil cover scenario: 49.14 inches annual-average precipitation, 0.029 inches/year surface runoff, 33.27 inches/year evapotranspiration, and 15.78 inches/year net infiltration.[1]

For the Saltstone Disposal Facility PA, Benson (2018) coupled WinUNSAT-H to simulate percolation in earthen layers above the lateral drainage layer with the Giroud equations (Giroud and Houlihan, 1995; Giroud, 1997; Giroud et al., 2000; Giroud et al., 2004) to model lateral drainage flow and composite barrier leakage (i.e., geomembrane/geosynthetic clay liner/finely textured foundation layer). Because the composite barrier in a multilayer cap design provides the predominant resistance to flow, a comparison of percolation rates through the coupled lateral drainage and composite barrier layers only was made for the E-Area Slit-and-Engineered-Trench intact case using the Giroud equations and the HELP model. Agreement between the two models was satisfactory through the first 300 years when the number of defects (holes) in the geomembrane is small. Beyond 300 years, the difference in predicted infiltration rates by the two models increases significantly with the Giroud equations calculating a much larger percolation rate through the geomembrane defects.

With one exception (single upper HDPE layer during institutional control), side-by-side comparisons of HELP and HYDRUS-1D were limited to earthen layers only for several reasons. First, HYDRUS-1D is fundamentally an agricultural modeling tool for simulating water and solute transport in variably-saturated porous media composed of non-uniform soils. There is no mechanism, for example, to easily model a composite barrier layer with defects (holes). Second, HYDRUS-1D includes a lower boundary condition that simulates horizontal drainage for a tile drainage system with an impermeable layer at the base. The tile drainage model is not adequately representative of a multilayer cover system with a

[1] A change in soil water storage equal to +0.071 inches/year is also reported by the HELP model to satisfy the water mass balance (annual avg. precipitation = evapotranspiration + Δ water storage + surface runoff + net infiltration).

separate lateral drainage layer above and free drainage at the base below. Third, HYDRUS-1D utilizes the Richards equation to model variably-saturated flow, which makes model convergence challenging for layered systems comprised of materials with widely varying porosities and saturated hydraulic conductivities (e.g., a low-permeability composite barrier sandwiched between permeable earthen layers). Conversely, convergence is rarely an issue for HELP, which is a mass balance model.

In summary, the HELP model was designed specifically for simulating infiltration through multilayer closure-cap systems, and it remains the best option for modeling such systems in wet climates where a unit hydraulic gradient is a reasonable assumption. As a mass-balance model, HELP is well suited for PA evaluations where flexibility in the model framework and ease of model convergence are important. Existing hydrologic models that use the Richards equation for variably-saturated flow, on the other hand, are not designed specifically for multilayer landfill cover systems, are more difficult to converge, and often must be coupled with a second model for drainage and composite barrier layers. Although computational codes that solve the Richards equation are more sophisticated than HELP, they can be challenging to use with a high level of accuracy when percolation rates are very low and extend over long periods (Whiteside et al., 2009). In fact, mass-balance errors associated with the numerical model simulations are of the same order of magnitude as the percolation rates themselves. The WinUNSAT-H and HYDRUS programs are better suited instead for simulating evapotranspiration cover systems typically found in arid and semi-arid climates. Evapotranspiration cover systems rely on the ability of a soil layer to store precipitation until it is naturally evaporated or transpired by a vegetative cover (U.S. EPA, 2011). This contrasts with more conventional cover systems that are engineered with a composite barrier layer of low hydraulic conductivity.

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LIST OF ABBREVIATIONS

GCL	Geosynthetic clay liner
GUI	Graphical User Interface
HDPE	High-density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
K_{sat}	Saturated hydraulic conductivity
LFRG	Low-Level Waste Disposal Facility Federal Review Group
LLWF	Low-Level Waste Facility
ORWBG	Old Radioactive Waste Burial Ground
PA	Performance Assessment
SDF	Saltstone Disposal Facility
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
USGS	United States Geological Survey

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1.0 Introduction

Whiteside et al. (2009) conducted an in-depth literature review and performed basic infiltration model simulations to evaluate the Hydrologic Evaluation of Landfill Performance (HELP) model against five alternative computational codes utilizing the Richards equation for variably-saturated flow. Of the five alternatives considered (LEACHM, UNSAT-H, SVFlux, HYDRUS-2D3D, and VADOSE/W), only HYDRUS-2D3D and VADOSE/W were selected for further evaluation, which consisted of a side-by-side comparison versus HELP of calculated infiltration rates through a one-layer soil column with two percent slope. At the time, Whiteside et al. (2009) recommended HYDRUS-2D3D over VADOSE/W for the following reasons:

- The HYDRUS software suite was more widely known and used than VADOSE/W. In addition, the one-dimensional version of HYDRUS, HYDRUS-1D, was (and still is) available for download in the public domain. Both may be important considerations for reviewers and other stakeholders.
- The licensing cost was much lower for HYDRUS-2D3D than VADOSE/W.
- While a two-dimensional code is adequate for most cover systems, the three-dimensional modeling capability of HYDRUS-2D3D would potentially allow for analysis of discrete holes in high-density polyethylene (HDPE) and GCL liners, if needed.
- HYDRUS-2D3D simulates multiphase flow and transport, while VADOSE/W models the liquid-phase only.
- The graphical user interface (GUI) for HYDRUS-2D3D was more robust during the limited testing. The VADOSE/W GUI regularly experienced a fatal error that prevented completion of numerical simulations.

On the other hand, the authors were inconclusive about using HYDRUS-2D3D in place of the HELP model pending more rigorous simulations of a multilayer closure cap design.

This report does not repeat the earlier study by Whiteside et al. (2009), but instead focuses on the following secondary issue raised in the Department of Energy's Low-Level Waste Disposal Facility Federal Review Group (LFRG) review team report (LFRG, 2008) for the 2008 E-Area Low-Level Waste Facility (LLWF) Performance Assessment (PA) as summarized by McDowell-Boyer et al. (2011):

> *"7.2.3.1: The HELP code that provided the basis of the cap infiltration analyses is well tested, generally accepted, and has been benchmarked against a broad range of codes that perform similar calculations. However, there is no discussion of the HELP modeling results with respect to the results of other analyses. Input parameters for HELP were difficult to find and were found in multiple documents cited in Phifer (2006).*
>
> *Proposed Resolution: A discussion of the HELP modeling results with respect to other modeling results for other analyses using available site data and information should be added. These data should be compiled into a single data package in the PA."*

The infiltration data package prepared by Dyer (2019) for the upcoming E-Area LLWF PA satisfies, to a large extent, the LFRG's proposed resolution to the secondary issue above. This report supplements the infiltration data package, providing more "discussion of the HELP modeling results with respect to the results of other analyses."

2.0 Net Soil Infiltration Rates at the Savannah River Site

Numerous field- and modeling-based water balance, soil infiltration, and groundwater recharge studies have been conducted at or near the Savannah River Site (SRS) over several decades by organizations including the Savannah River National Laboratory (SRNL), United States Geological Survey (USGS), State University of New York at Brockport, Pennsylvania State University, University of Arizona, and Desert Research Institute (WSRC, 2008). The studies have ranged in scale from 55-gallon drum lysimeters to entire watersheds.

The USGS performed two studies at the Barnwell Low-Level Radioactive Waste Disposal Facility, which is located immediately east of SRS. Cahill (1982) investigated geologic and hydrologic conditions near the Barnwell site and measured migration of leachates from the buried waste into surrounding unconsolidated sediments. Seven years later, Dennehy and McMahon (1989) assessed the principal factors affecting the movement of water within and adjacent to trenches excavated in the unsaturated zone.

Mean-annual groundwater discharge to streams (i.e., baseflow) is thought to approximate the long-term average recharge to local, intermediate, and regional components of the groundwater-flow system (Clarke and West, 1998). Stricker (1983) analyzed baseflow stream data from USGS gaging stations located within the Cretaceous and Tertiary clastic outcrop area of South Carolina, Georgia, Alabama, and Mississippi to estimate groundwater recharge to the southeastern sand aquifer, which includes Upper Three Runs near New Ellenton, SC. Meanwhile, Clarke and West (1998) used MODFLOW to simulate groundwater flow and stream–aquifer relations for seven aquifers in Coastal Plain sediments near SRS, including three gaging stations in the Upper Three Runs basin (water years 1967-1993 and 1975-1993).

Hubbard and Emslie (1984) from the State University of New York at Brockport collaborated with the Savannah River Laboratory (which was designated a national laboratory in 2004) to develop a water budget for the Savannah River Plant Old Radioactive Waste Burial Ground (ORWBG). The ORWBG water balance was updated in 1986 using information from the Defense Waste Lysimeter study (Hubbard, 1986). Finally, the State University of New York at Brockport, in collaboration with the University of Arizona, used the CREAMS model and site-specific weather data for 1961 through 1986 to generate annual water balances for the ORWBG (Hubbard and Englehardt, 1987).

Parizek and Root (1986) from the Pennsylvania State University completed a hydrologic water budget for the McQueen Branch watershed in the central portion of SRS as part of the development of a groundwater model.

Young and Pohlmann (2001) at the Desert Research Institute conducted both deterministic and probabilistic (100 Monte Carlo realizations) simulations utilizing the HYDRUS 2-D finite-difference model to estimate infiltration rates within E-Area at SRS. The model was refined in 2003 to incorporate additional site-specific data (Young and Pohlmann, 2003).

Table 2-1 summarizes relevant annual-average water balance, infiltration, and groundwater recharge estimates from the ten studies introduced above. Net infiltration/recharge rates range from 9.1 to 16 inches/year with a median of 14.5 inches/year, which is approximately one-third of the median annual-average precipitation rate of 47.79 inches for the ten studies. The rates in Table 2-1 compare favorably with the results of HELP model simulations for the operational soil cover scenario: 49.14 inches annual-average precipitation, 0.029 inches/year surface runoff, 33.27 inches/year evapotranspiration, and 15.78 inches/year net infiltration.[2]

Table 2-1. Summary of Historical Water Balance, Infiltration, and Groundwater Recharge Field and Modeling Studies Relevant to SRS.

Source	Annual-Average Rate (inches/year) [a]			
	Precipitation	**Runoff**	**Evapotranspiration**	**Net Infiltration/Recharge**
Cahill (1982)	46.62	0	31.62	15
Stricker (1983)	-	-	-	14
Hubbard and Emslie (1984)	47	2	30	15
Hubbard (1986)	48	2	30	16
Parizek and Root (1986)	47.78	2	30.78	15
Hubbard and Englehardt (1987)	48.51	1.21	32.6	14.7
Dennehy and McMahon (1989)	47.8	0	33.5	14.3
Clarke and West (1998)	-	-	-	15.6 (New Ellenton) 14.3 (above Road C) [c] 10.6 (at Road A)
Young and Pohlmann (2001)	10 years Augusta, GA data from 1977 to 1987	-	Determined but not reported in the document [b]	9.1
Young and Pohlmann (2003)	10 years Augusta, GA data from 1977 to 1987	-	Determined but not reported in the document [2]	11.7
Median of the ten studies [d]	**47.79**	**1.6**	**31.2**	**14.5**

[a] All studies assumed that the change in water storage was a negligible component in the overall water budget.

[b] Based on the magnitude of the infiltration rate, the associated evapotranspiration rate would be relatively high (i.e., > 30 inches/year).

[c] Station closest to E-Area.

[d] The median of the ten studies does not include precipitation, runoff, and evapotranspiration rates from Young and Pohlmann (2001, 2003), Stricker (1983), and Clarke and West (1998).

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[2] A change in soil water storage equal to +0.071 inches/year is also reported by the HELP model to satisfy the water mass balance (annual avg. precipitation = evapotranspiration + Δ water storage + surface runoff + net infiltration).

3.0 Consideration of Alternatives to the HELP Model

3.1 Hydrologic Model of the SRS Saltstone Disposal Facility Closure Cap

At a September 2018 Performance Assessment Community of Practice webinar, Benson (2018) shared a hydrologic model of the planned Saltstone Disposal Facility (SDF) closure cap at SRS. The SDF model, developed by Benson and Benavides (2018), is based on current best practices for predicting long-term percolation rates through closure caps, including the recommendation by Benson et al. (2011) to employ long-term engineering properties in performance assessment hydrologic models. Relevant conclusions reached by Benson et al. (2011) were:

- "Increases in the saturated hydraulic conductivity, saturated volumetric water content, and the air entry suction (as characterized by van Genuchten's α parameter) occurred due to formation of soil structure, regardless of climate, cover design, or service life."
- "Substantial changes in hydraulic conductivity were observed in some geosynthetic clay liners (GCLs) that did not hydrate completely and underwent cation exchange."
- "Changes in geomembranes and geosynthetic drainage layers over time were modest or small, and computations based on antioxidant depletion rates suggest that the minimum service life of geomembranes is on the order of 50-125 years (the actual service life will be longer)."

Ongoing studies by Benson's research team since 2011 have led to a more optimistic outlook on long-term closure cap performance:

- An erosion layer creates a hydraulic choke that maintains nearly saturated conditions in the earthen layers below. Therefore, an assumption of unit gradient vertical flow below the erosion layer is reasonable. *(Author note: This is consistent with use of a unit vertical hydraulic gradient in the HELP model and diminishes the importance of using a Richards-equation-based infiltration model in a wetter climate such as SRS.)*
- Exhumed covers show minimal fines migration into lateral drainage layers, while 2000-year-old burial tombs located in humid climates in Korea and Japan show no evidence of fine- and coarse-layer blending. Benson and Benavides (2018) conclude that there is no justification to assume a saturated hydraulic conductivity less than 5E-02 cm/s for the lateral drainage layer. *(Author note: The E-Area LLWF PA HELP model simulations assume a steady decrease in the saturated hydraulic conductivity of the lateral drainage layer from 5E-02 cm/s at installation to 1.4E-03 cm/s beyond 2600 years due to clay fines migration from the upper backfill layer above.)*
- Tian et al. (2017) investigated antioxidant depletion in HDPE geomembrane coupons immersed in synthetic low-level radioactive waste leachate; extrapolation of the experimental data suggests a total service life for HDPE geomembranes of more than 1900 years. In the SDF hydrologic model, a long geomembrane service life is accounted for by assuming a constant defect density of only five defects per hectare, which is equivalent to two approximately 1-cm^2 holes per acre (Giroud and Bonaparte, 1989). *(Author note: The E-Area PA HELP model simulations assume a sharply increasing number of 1-cm^2 defects in the HDPE geomembrane layer over time, beginning with four defects per acre at the time of installation and steadily increasing to 5,496 defects per acre at 1800 years and 34,466 defects per acre at 10,000 years.)*

- GCLs exhumed from composite barriers in covers at humid eastern sites (e.g., Barnwell, South Carolina) indicate that the long-term saturated hydraulic conductivity of a GCL (when located beneath a geomembrane) is less than 1E-09 cm/s, even under substantial distortion and complete cation exchange. *(Author note: The E-Area PA HELP model simulations assume a saturated hydraulic conductivity for the GCL equal to 5E-09 cm/s at installation, increasing to 5E-08 cm/s thereafter.)*
- Benson and Benavides (2018) also assume no loss in GCL integrity caused by root penetration. This is because "roots accumulate in regions where water is more plentiful and readily extracted, and do not grow toward regions where water is less plentiful and more difficult to extract." They report that when covers are exhumed, roots are present where water accumulates (i.e., in the soil overlying the lateral drainage layer and composite barrier). Root systems were not observed below the composite barrier in any of the cover systems evaluated by Benson et al. (2011). *(Author note: The E-Area PA HELP model simulations assume that pine tree tap roots begin to penetrate each defect in the geomembrane after 200 hundred years, taking advantage of increasing water percolation through the degraded geomembrane and thereby creating holes in the GCL as well.)*
- Finally, the thickness of the earthen layers above the composite barrier layer is not as important in a humid environment as it is in an arid environment, meaning that "the composite barrier formed by the geomembrane and GCL will provide the predominant resistance to flow at the base" of the SDF closure cap (Benson, 2018).

To predict long-term percolation rates for the SDF, Benson (2018) coupled WinUNSAT-H with the Giroud equations, which are analytical solutions for lateral drainage flow and composite barrier leakage. For the multilayer cover system, WinUNSAT-H models water flow in the earthen layers above the drainage layer, while the Giroud equations (Giroud and Houlihan, 1995; Giroud, 1997; Giroud et al., 2000; Giroud et al., 2004) calculate drainage layer flow and percolation through the composite barrier layer (e.g., geomembrane/GCL/finely textured foundation layer).

WinUNSAT-H (Fayer, 2000) is a FORTRAN code developed at Pacific Northwest Laboratory for simulating the one-dimensional flow of water, vapor, and heat in variably saturated soils with atmospheric interaction. Developed for the semiarid Hanford site, WinUNSAT-H simulates precipitation, evaporation, plant transpiration, storage, and deep drainage processes. The code simulates liquid water flow using the Richards equation, water vapor diffusion using Fick's law, and sensible heat flow using the Fourier equation. Unlike the HELP model, WinUNSAT-H does not include a weather generator, nor does it simulate lateral drainage and barrier layers with or without defects (holes). Any improvement in model accuracy potentially gained by switching to a Richards-equation-based model of the vadose zone, therefore, will be offset by the limitations associated with the WinUNSAT-H code as described above.

As for the SDF final closure cap, the planned E-Area LLWF final closure cap will also be located in a wetter climate and will include a composite barrier providing the predominant resistance to flow at its base. For this reason, a direct comparison was made of percolation rates through the combined lateral drainage and composite barrier layers only using the Giroud equations and the HELP model.

As derived by Giroud (1997) and presented by Benson (2018), the semi-empirical analytical solution for combined lateral drainage flow and composite liner leakage is:

$$Q = 0.976 C_{qo} \left[1 + 0.1 \left(\frac{h_{max}}{t_b}\right)^{0.95}\right] d^{0.2} (h_{max})^{0.9} K_b^{0.74} \quad \text{(Eqn. 1)}$$

$$h_{max} = \frac{qL}{K_d \tan\beta} \quad \text{(Eqn. 2)}$$

where:

Q = leakage rate per geomembrane hole (m^3/s per hole)
C_{qo} = contact factor = 0.21 (good placement quality)
h_{max} = maximum liquid head in drainage layer above geomembrane (m)
q = percolation rate through backfill layer above drainage layer (m/s)
L = horizontal slope length (m)
β = slope angle (degrees or radians)
K_d = saturated hydraulic conductivity of drainage layer (m/s)
K_b = saturated hydraulic conductivity of soil component of the composite liner (i.e., GCL only) (m/s)
d = geomembrane defect diameter (m)
t_b = GCL thickness (m)

Eqn. 1 assumes that leakage through the composite barrier occurs only through defects (holes) in the geomembrane and that there is “good” contact between the geomembrane liner and the permeability-controlling soil layer below (Giroud and Bonaparte, 1989). This contrasts with the HELP model which calculates leakage through the intact portion of the geomembrane via vapor diffusion in addition to leakage through the defects. Interestingly, the HELP model also bases its predictions of leakage rate through holes in the geomembrane on the work of Giroud and Bonaparte (1989), but selects from a more complex set of empirical leakage rate equations that are chosen based on two input parameters specified by the user:

- Placement quality[3] (i.e., perfect, excellent, good, poor, or worst case) of the geomembrane liner on top of the low-permeability earthen layer (e.g., GCL) below. Placement quality is reflected in the value for C_{qo} used in Eqn. 1.[4]

[3] According to Schroeder (1994a), placement quality refers to the degree of contact between the geomembrane layer and the flow-limiting layer (e.g., GCL) below. Liquid passing through an assumed circular hole in the geomembrane will flow laterally between the geomembrane and the GCL unless there is either “perfect” contact between the two layers or “free flow” from the hole. The size of the space between the geomembrane and GCL depends on the roughness of the soil surface, soil particle size, rugosity and stiffness of the geomembrane, and overburden pressure. The HELP model ranks the contact between a geomembrane and GCL as perfect, excellent, good, poor, and worst case (free flow). Interfacial flow is assumed to be radial, covering a circular area called the wetted area, and is controlled by the hydraulic transmissivity of the gap between the geomembrane and the GCL. Giroud and Bonaparte (1989) examined steady-state leakage through a geomembrane liner for all these qualitative levels of contact and provided either theoretical or empirical solutions for the leakage rate and the radius of interfacial flow.

[4] Giroud et al. (1989) established the following values for C_{qo}: 0.21 for good placement quality and 1.15 for poor placement quality. C_{qo} for excellent placement quality was not given but would be less than 0.21.

- Saturated hydraulic conductivity of the flow-controlling earthen layer (e.g., GCL).[5]

Because the comparison with the HELP model is focused solely on flow through the combined lateral drainage and composite barrier layers, the percolation rate from the upper backfill layer, q, in Eqn. 2 was calculated from the results of the HELP model simulations for the intact case, rather than running WinUNSAT-H. The flow from the upper backfill layer in the HELP model was determined by mass balance (units of length per time):

q (m/s) = annual avg. precipitation – evapotranspiration – Δ water storage – surface runoff (Eqn. 3)

Table 3-1 lists the input parameter assumptions for Eqn. 1 and Eqn. 2 in metric units for the Slit and Engineered Trench intact infiltration cases. For this comparison alone, the HELP model simulations assumed a "good" placement quality[6] for the geomembrane layer to be consistent with the value for C_{qo} used in Eqn. 1 by Benson (2018) for the SDF closure cap design. Appendix A provides the HELP model input parameter data sheets for each time step listed in Table 3-1.

Table 3-1. Input Parameter Assumptions for the Giroud Equations – Slit and Engineered Trench Intact Infiltration Cases (2% slope, 585-foot slope length).

HELP Model Intact Case	Description [a]	q (m/s) [b]	L (m) [c]	tan β [d]	K_d (m/s) [e]	K_b (m/s) [f]	d (m) [g]	t_b (m) [h]	# holes per hectare
ST00	t = 100 yr	1.289E-08	178.308	0.02	5.00E-04	5.00E-11	0.0113	0.00508	12.4
ST01	t = 180 yr	1.282E-08	178.308	0.02	4.48E-04	5.00E-11	0.0113	0.00508	101.3
ST02	t = 290 yr	1.279E-08	178.308	0.02	3.86E-04	5.00E-10	0.0113	0.00508	239.7
ST03	t = 300 yr	1.278E-08	178.308	0.02	3.81E-04	5.00E-10	0.0113	0.00508	252.0
ST05	t = 380 yr	1.268E-08	178.308	0.02	3.41E-04	5.00E-10	0.0113	0.00508	350.9
ST06	t = 480 yr	1.269E-08	178.308	0.02	2.98E-04	5.00E-10	0.0113	0.00508	1186.1
ST07	t = 660 yr	1.258E-08	178.308	0.02	2.33E-04	5.00E-10	0.0113	0.00508	2757.7
ST08	t = 1,100 yr	1.211E-08	178.308	0.02	1.28E-04	5.00E-10	0.0113	0.00508	6597.7

[a] Relative time (t): 100 yr is the end of institutional control when the final closure cap is installed.
[b] Calculated from HELP model results for intact cases using Eqn. 3.
[c] Slope length for bounding intact case is 178.308 m (585 feet).
[d] Slope angle, β, is 1.1458 degrees or 0.02 radians.
[e] K_d of drainage layer (5E-04 m/s) decreases over time due to silting in from the backfill layer above.
[f] K_b of GCL layer equals 5E-11 m/s at t = 100 yr and 180 yr and decreases to 5E-10 m/s at t > 180 yr.
[g] Diameter of 1E-04 m^2 (1 cm^2) hole.
[h] Thickness of GCL is 0.00508 m (0.20 inches).

Table 3-2 displays a side-by-side comparison of total leakage rates (Q_{tot}) through the composite barrier as predicted by the HELP model and the Giroud equations for the E-Area Slit-and-Engineered-Trench intact case. Agreement between the two models is good through relative Year 380 (Case ST05) when the

[5] The HELP model designates the controlling soil layer (GCL) as either high, medium, or low permeability, where high is a saturated hydraulic conductivity greater than or equal to 1E-03 m/s, medium is greater than or equal to 1E-06 m/s and less than 1E-03 m/s, and low is less than 1E-06 m/s. The low permeability layers are assumed to remain saturated in the wetted area throughout the HELP model simulation.

[6] Intact infiltration rate calculations for the E-Area LLWF PA closure cap assume an "excellent" placement quality for the geomembrane layer. Predicted infiltration rates are quite sensitive to the placement quality assumption. For example, infiltration rates predicted by the HELP model are 1.1X to 6.5X lower when an excellent versus a good placement quality is assumed.

number of defects (holes) in the geomembrane is small. Beyond relative Year 380, the difference in predicted infiltration rates by the two models increases significantly with the Giroud equations calculating a much larger percolation rate through the geomembrane defects. This difference is likely due to several factors:

- When used outside a mass-balance model such as HELP, the Giroud equations are not constrained by the conservation of mass. For example, at relative Year 660 and later, the percolation rates predicted by the Giroud equations exceed the liquid supply rates from the backfill layers above. Conversely, the HELP code ensures that total leakage through the geomembrane and controlling layers is not greater than the total volume of drainable water. The HELP code also checks to make certain that the leakage rate is not greater than the product of the hydraulic gradient and the saturated hydraulic conductivity of the controlling GCL layer (Schroeder et al. 1994a).
- The Giroud equations as implemented by Benson (2018) in Eqn. 1 for the SDF closure cap design utilize the maximum hydraulic head acting on the geomembrane layer to calculate the leakage rate through each hole. On the other hand, the HELP code uses the slope-length-averaged hydraulic head at each time step (1 day) for 100 years of simulated daily precipitation data.
- Giroud and Bonaparte (1989) and Giroud et al. (1992) developed their leakage rate equations for intact geomembranes, geomembranes surrounded by high-permeability materials, and composite liners (i.e., drainage layer/geomembrane/low-permeability soil liner) assuming relatively low defect densities (i.e., less than 10 to 20 defects per acre) characteristic of modern equipment, materials, and installation and QA/QC practices (Schroeder et al., 1994a; Schroeder et al., 1994b). Conversely, the closure cap degradation model for the E-Area LLWF assumes a much greater defect density that increases linearly with time (i.e., 141, 479, and 1115 defects per acre at relative Years 380, 480, and 660, respectively).

For these collective reasons, poor agreement between the standalone Giroud equations and the HELP mass-balance model at high defect densities is not surprising.

Table 3-2. Comparison of HELP Model Results to Giroud Equation – Slit and Engineered Trench Intact Cases (2% slope, 585-foot slope length).

HELP Model Intact Case	Description[a]	Giroud Equation h_{max} (m)	Giroud Equation Q_{tot} (mm/yr)	HELP Model Q_{tot} (mm/yr)[b]	Ratio HELP:Giroud
ST00	t = 100 yr	0.23	0.098	0.102	1.04
ST01	t = 180 yr	0.26	0.95	1.11	1.17
ST02	t = 290 yr	0.30	15.86	17.37	1.10
ST03	t = 300 yr	0.30	17.04	18.59	1.09
ST05	t = 380 yr	0.33	28.22	32.68	1.16
ST06	t = 480 yr	0.38	120.34	86.65	0.72
ST07	t = 660 yr	0.48	421.25 [c]	158.82	0.38
ST08	t = 1,100 yr	0.84	2708.45 [c]	240.10	0.09

[a] Relative time (t): 100 yr is the end of institutional control when the final closure cap is installed.
[b] For this comparison, HELP model results assume a good, rather than an excellent, geomembrane placement quality.
[c] Q_{tot} exceeds the liquid supply rate, q. Liquid supply rate is 397 mm/yr at 660 yr and 382 mm/yr at 1,100 yr.

3.2 Comparison of HYDRUS-1D to the HELP Model

HYDRUS-1D (Šimůnek et al., 2013) is a public-domain, Windows-based modeling environment which utilizes a one-dimensional finite element model (HYDRUS) to simulate the movement of water, heat, and one or more solutes in variably-saturated porous media. For saturated-unsaturated water flow, HYDRUS employs the Richards equation, which is modified to include a sink term for water uptake by plant roots. According to Šimůnek et al. (2013), the flow zone may consist of heterogeneous soil types, while flow and transport can occur vertically, horizontally, or in a generally inclined direction. The user can specify constant or time-varying prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, or free-drainage boundary conditions. Soil surface boundary conditions can change during the simulation from prescribed flux to prescribed head-type conditions (and vice versa). Unsaturated soil hydraulic properties are described using van Genuchten, Brooks and Corey, and modified van Genuchten-type analytical functions, while root growth is simulated with a logistic growth function. The model does not include a synthetic weather generator.

3.2.1 *Published Case Studies*

Pontedeiro et al. (2013) selected HYDRUS-1D to model water flux through a municipal solid waste landfill in Rio de Janeiro, Brazil. Two different cover systems were considered: a capillary barrier made from municipal solid waste compost and an evapotranspiration cover using grass or native vegetation. Hydraulic parameters for the cover soil were estimated using the Rosetta pedotransfer functions[7] in HYDRUS-1D and measured soil texture data for the fines. In all simulations, the thickness of the operational and final soil cover layers was 60 centimeters, while the municipal waste layer was 500 centimeters. The cover design included no erosion, lateral drainage, or geosynthetic barrier layers. The model was calibrated by simulating each vertical landfill cell separately and then summing the individual deep drainage rates from each cell. The sum was compared to the estimated recharge rate for the aquifer based on local weather data and potential evapotranspiration rates calculated with the Hargreaves (1975) equation. The deep drainage volume predicted by HYDRUS-1D during 2010 was 27,020 m^3 compared to a measured volume of 33,100 m^3. A capillary barrier layer of 30 to 50 centimeters reduced the drainage water flux by approximately 40 percent compared to a compacted surface soil. Similarly, a vegetative cover lowered the drainage water flux by 34 percent for grass and 48 percent for the native *brachiaria*.

Worthy et al. (2011) compared the performance of the HELP, HYDRUS-1D, and WinUNSAT-H models in simulating the expected hydrologic performance of a capillary barrier cover system for the uranium mill tailings disposal facility in Monticello, Utah. The actual four-layer cover system (fine-textured soil and rock water storage layer, sand capillary barrier layer, HDPE geomembrane layer, and low-permeability compacted soil liner) was modeled for simplicity as a single 1,100-millimeter-thick soil layer with equivalent hydraulic properties matching field conditions at the repository. Worthy et al. (2011) noted that "HELP is the only landfill-specific water balance model available." Three climate scenarios were considered for each model: a typical temporal year (annual-average precipitation), a design temporal year (maximum precipitation), and a future synthetic-analogue year based on a general circulation climate model. Daily precipitation and temperature data from the Utah State University Climate Center database were used in all three models for the Scenario 1 (typical year) and Scenario 2 (design year) simulations. Conversely, the HELP model's synthetic weather generator used monthly-average precipitation and temperature data to generate (1) the daily precipitation and temperature data for

[7] Pedotransfer functions are predictive functions of certain soil properties using data from soil surveys.

the Scenario 3 (synthetic analogue year) simulations for all three models, and (2) the synthetic daily solar radiation data for all three models for the three simulation scenarios. Despite the single-layer simplification, results varied significantly among the three models. For the HELP model, predicted changes in evapotranspiration, runoff, percolation, and water storage for the three climate scenarios were modest and trended in the directions expected. The WinUNSAT-H model predicted much higher surface runoff and percolation rates than HELP and HYDRUS-1D due to a large, negative change in water storage. In addition, percolation rates predicted by WinUNSAT-H decreased from Scenario 2 to Scenario 3, while they increased for both HELP and HYDRUS-1D. With HYDRUS-1D, differences in the percolation rate and water storage among the three scenarios were larger and less predictable. Compared to HELP, HYDRUS-1D predicted much higher percolation rates, partly because HYDRUS-1D calculated zero surface runoff for all three scenarios.

Meadows and Waite (2016) used HYDRUS-1D to simulate the hydrologic performance of a proposed alternative evapotranspiration cover for the Salt Lake Valley Landfill in Utah. The cover system was designed to store water that infiltrates into the cover material and to remove it via transpiration and evaporation before percolating into the underlying waste. The cover system uses the water-storage capacity of the soil layers, rather than the lower-permeability physical characteristics of a geomembrane or GCL, to minimize infiltration. The proposed evapotranspiration cover system design included three to four feet of vegetated, fine-grained (i.e., silty to clayey loam) soil to provide moisture storage capacity above the buried waste. Meadows and Waite (2016) evaluated three sets of hydraulic properties for the final cover soil at two different cover thicknesses each. Daily climate data representing the five consecutive wettest years on record were used. Two hydraulic properties sets were based on site-specific values for on-site materials that could be used for the evapotranspiration cover, while the third set represented weathered values for fine-grained soils. HYDRUS-1D model results for all three hydraulic properties sets indicated that a four-foot cover thickness will limit water flux through the base of the evapotranspiration cover to less than three millimeters per year.

3.2.2 *E-Area LLWF Comparison Cases*

Table 3-3 lists the E-Area LLWF closure cap cases included in a side-by-side comparison of the HYDRUS-1D and HELP models. Comparison cases were limited to earthen multilayer systems only (the lone exception being the institutional control case) for several reasons:

- HYDRUS-1D is fundamentally an agricultural modeling tool designed to simulate water and solute transport in variably-saturated porous media composed of nonuniform soils. For example, there is no mechanism to include a geomembrane/GCL barrier layer with an assumed defect density.

- HYDRUS-1D includes a lower boundary condition that simulates horizontal drainage representative of a tile drainage system[8] and assumes an impermeable layer at the base. Unfortunately, the tile drainage model is not representative of a multilayer cover system with a separate lateral drainage layer above and free drainage at the base below. As a result, the tile

[8] A tile drainage system consists of a network of belowground pipes called laterals and mains that function to manage the water table. Laterals are spaced throughout the field to collect water that then drains to a main. The main allows the system to transport the water away from the field in a controlled manner. The tile drainage system is designed on a grade so water flows in the desired direction.

drainage model outputs the total drainage from a multilayer soil column (i.e., the sum of horizontal drainage and any vertical drainage from the permeable soil layers below the lateral drainage layer).

- The Richards equation, which is used in HYDRUS-1D to model variably-saturated flow, makes model convergence more challenging. This is particularly true for layered systems comprised of materials with widely varying porosities and saturated hydraulic conductivities (e.g., a low-permeability composite geomembrane/GCL sandwiched between permeable earthen layers). Conversely, model convergence is rarely an issue with a mass balance model such as HELP.

Screen captures of the input parameter templates used in the HYDRUS-1D model simulations for Cases 3-1 through 3-4 are displayed in Appendix B. Appendix C contains screen captures from HYDRUS-1D of the boundary water fluxes of interest for comparison to the HELP model results. Summaries of the HELP/HYDRUS-1D side-by-side comparisons are shown in Table 3-4, Table 3-5, Table 3-6, and Table 3-7 for Cases 3-1, 3-2, 3-3, and 3-4, respectively. All results are reported as annual-average values.

Table 3-4 presents the results for the single-layer operational soil cover case. Agreement between the HYDRUS-1D and HELP models is satisfactory when daily time steps were used in the HYDRUS-1D simulation (by default, the HELP model uses daily weather data and a daily time step). Because HYDRUS-1D does not include a weather generator, both annual-average and daily weather data were exported from HELP to be used in the HYDRUS-1D simulations. The predicted percolation rate through the operational soil cover layer is 15.78 inches/year per the HELP model and 14.8 inches/year per HYDRUS-1D, a difference of 0.98 inches/year or -6.2% relative to the HELP model result.

Results for the two-layer institutional control case (HDPE stormwater runoff cover overlying a four-foot-thick operational soil cover) are displayed in Table 3-5. Two subcases for the HDPE cover were considered in the HYDRUS-1D simulations: K_{sat} equal to 5.0E-08 cm/sec (same value as used in the HELP model simulations) and K_{sat} equal to 1.0E-09 cm/sec. In both cases, HYDRUS-1D predicts substantially more evapotranspiration (transpiration is zero because there is no vegetative cover) than the HELP model and, therefore, less surface run-off. For an assumed $K_{sat\ HDPE}$ of 5.0E-08 cm/sec, HYDRUS-1D calculates a percolation rate at the base of the soil column equal to 0.71 inches/year, which is approximately eight times higher than the HELP model prediction of 0.089 inches/year. If $K_{sat\ HDPE}$ is reduced to 1.0E-09 cm/sec in the HYDRUS-1D model only, agreement between the HELP and HYDRUS-1D models is improved.

Table 3-6 summarizes results for the top three earthen layers in the proposed E-Area LLWF closure cap design at the time of installation: six-inch topsoil layer, 30-inch upper backfill layer, and 12-inch erosion barrier. The same material properties values assumed for the three layers in the HELP model simulations were also used in the HYDRUS-1D model simulations. HYDRUS-1D predicts more surface runoff and evapotranspiration than the HELP model; therefore, the percolation rate at the base of the soil column is approximately five inches/year lower for HYDRUS-1D than HELP.

Table 3-7 displays the results for the top four layers in the proposed E-Area LLWF closure cap design at the time of installation: six-inch topsoil layer, 30-inch upper backfill layer, 12-inch erosion barrier, and 12-inch lateral drainage layer. The same material properties values assumed for the top four layers in the

Table 3-3. E-Area LLWF Infiltration Scenarios used in the HELP and HYDRUS-1D Side-by-Side Comparison.

Comparison Case	Infiltration Scenario	Description
3-1a 3-1b	Operational Soil Cover	Four-foot soil cover for Slit Trench installed at end of operations [a] (a) Annual rainfall data; (b) Daily rainfall data 100-year simulation period Grass cover with active root growth Atmospheric upper boundary condition with surface runoff Free drainage lower boundary condition
3-2a 3-2b	Institutional Control (HDPE)	HDPE geomembrane overlying four-foot soil cover for Slit Trench installed at end of operations [a] (a) $K_{sat\ HDPE}$ = 5.0E-08 cm/s; (b) $K_{sat\ HDPE}$ = 1.0E-09 cm/s Minimal (0.1 cm) soil layer on top of HDPE to enable HELP model execution Daily rainfall data 100-year simulation period No root growth Atmospheric upper boundary condition with surface runoff Free drainage lower boundary condition
3-3	Upper Three Layers of Intact Multilayer Cover (at installation)	Topsoil, Upper Backfill, and Erosion Barrier layers Daily rainfall data 100-year simulation period Grass cover with active root growth Atmospheric upper boundary condition with surface runoff Free drainage lower boundary condition
3-4	Upper Four Layers of Intact Multilayer Cover (at installation)	Topsoil, Upper Backfill, Erosion Barrier, and Lateral Drainage layers Daily rainfall data 100-year simulation period Grass cover with active root growth Atmospheric upper boundary condition with surface runoff Horizontal deep-drainage lower boundary condition

[a] A relative comparison between the two models was made assuming a minimum uniform four-foot-thick clean soil layer. In practice, the soil layer thickness will be greater than four feet and the soil will be sloped away from the centerline (crest) to obtain positive drainage toward the edges.

Table 3-4. Case 3-1 – Operational Soil Cover – Comparison of HYDRUS-1D and HELP Model Predictions.

Modeled Flux	HELP Model (Daily Rainfall)	Case 3-1a HYDRUS-1D (Annual Rainfall)	Case 3-1a Difference (Annual Rainfall)	Case 3-1b HYDRUS-1D (Daily Rainfall)	Case 3-1b Difference (Daily Rainfall)
Precipitation (inches/year)	49.14	49.08	-0.06	48.98	-0.16
Runoff (inches/year)	0.029	0.00	-0.03	0.00	-0.03
Evapotranspiration (inches/year)	33.27	29.50	-3.77	34.18	0.92
Percolation Rate (inches/year)	15.78	19.58	3.80	14.80	-0.98

Table 3-5. Case 3-2 – Institutional Control (HDPE Cover) – Comparison of HYDRUS-1D and HELP Model Predictions.

Modeled Flux	HELP Model	Case 3-2a HYDRUS-1D (K_{sat} = 5.0E-08 cm/s)	Case 3-2a Difference (K_{sat} = 5.0E-08 cm/s)	Case 3-2b HYDRUS-1D (K_{sat} = 1.0E-09 cm/s)	Case 3-2b Difference (K_{sat} = 1.0E-09 cm/s)
Precipitation (inches/year)	49.14	48.34	-0.80	49.04	-0.10
Runoff (inches/year)	48.98	36.09	-12.90	37.87	-11.11
Evapotranspiration (inches/year)	0.066	11.54	11.47	11.12	11.05
Percolation Rate (inches/year)	0.089	0.71	0.62	0.044	-0.045

Table 3-6. Case 3-3 – Upper Three Layers of Intact Multilayer Cover – Comparison of HYDRUS-1D and HELP Model Predictions.

Modeled Flux	HELP Model (at installation)	Case 3-3 HYDRUS-1D	Case 3-3 Difference
Precipitation (inches/year)	49.14	48.94	-0.20
Runoff (inches/year)	0.002	0.62	0.62
Evapotranspiration (inches/year)	32.54	36.47	3.93
Percolation Rate (inches/year)	16.57	11.85	-4.72

Table 3-7. Case 3-4 – Upper Four Layers of Intact Multilayer Cover – Comparison of HYDRUS-1D and HELP Model Predictions.

Modeled Flux	HELP Model (at installation)	Case 3-4 HYDRUS-1D	Case 3-4 Difference
Precipitation (inches/year)	49.14	49.35	0.21
Runoff (inches/year)	0.002	0.60	0.60
Evapotranspiration (inches/year)	32.54	36.93	4.39
Percolation Rate (inches/year)	16.57	11.82	-4.75

HELP model simulations were also used in the HYDRUS-1D model simulations. As noted above, HYDRUS-1D includes the choice of a lower boundary condition for horizontal drainage that simulates a tile drainage system only and assumes an impervious layer at the base. This substantially limits its applicability to the E-Area cap design because the PA infiltration conceptual model assumes degradation and, hence, increasing permeability of the geomembrane/GCL barrier layers with time. Agreement between the HELP model and HYDRUS-1D is the same as for Case 3-3.

Simulation cases that included a low-permeability geomembrane and/or GCL barrier layer below the lateral drainage layer were tested in HYDRUS-1D; however, numerical convergence was not achieved.

Conclusions

The HELP model remains the preferred choice over other commercial and public-domain hydrologic models for the E-Area LLWF PA for the following reasons:

- Benson and Benavides (2018) coupled the Richards-equation-based, one-dimensional WinUNSAT-H model with the Giroud equations to simulate the multilayer SDF cover system because WinUNSAT-H cannot simulate flow through lateral drainage and barrier layers. WinUNSAT-H was used to model water flow in the earthen layers above the lateral drainage layer, while the Giroud equations calculated drainage-layer flow and percolation through the composite barrier layer (i.e., geomembrane/GCL/finely textured foundation layer). Like the SDF, the E-Area LLWF is also located in a wetter climate and its final closure cap design will include a composite barrier providing the predominant resistance to flow at its base. As a result, any improvement in accuracy gained by switching to a Richards-equation-based model of the vadose zone is largely offset in a wet climate by the need to couple WinUNSAT-H, HYDRUS-1D, or HYDRUS-2D3D with a separate model for the drainage and barrier layers.
- The HELP model bases its predictions of leakage rate through holes in the geomembrane barrier layer on the same family of semi-empirical Giroud equations mentioned above. The HELP model selects from a set of empirical leakage rate equations developed originally by Giroud and Bonaparte (1989) that are chosen based on two user-specified input parameters: placement quality of the geomembrane and saturated hydraulic conductivity of the flow-controlling GCL below the geomembrane. If "good" placement quality and low to moderate defect density are assumed, the Giroud equations (as implemented by Benson and Benavides (2018) for the SDF cap) predict a leakage rate through the barrier layer that is in close agreement with the leakage rate predicted by the HELP model for the same cap design. The leakage rate is quite sensitive to the placement quality assumption.
- The cap degradation and subsidence scenarios for the E-Area LLWF closure cap necessitate a flexible, robust infiltration model that readily converges over a wide range of assumed cap and material design properties and conditions. The Richards equation is inherently unstable; therefore, obtaining a numerical solution can be a challenge. Whiteside et al. (2009) noted convergence challenges with sandy-clay soils under high-rainfall conditions typical of SRS. Despite its limitations, the HELP model excels in this regard over models using the Richards equation for variably-saturated flow, which includes WinUNSAT-H, HYDRUS-1D, and HYDRUS-2D3D. For example, the coupled WinUNSAT-H/Giroud equation model used by Benson and Benavides (2018) gave unrealistic predictions for leakage rate through the composite barrier as the number of assumed defects in the geomembrane layer exceeded on the order of 1,000 holes per hectare.
- Benson and Benavides (2018) showed that the erosion barrier in the SDF and E-Area LLWF closure cap designs will create a hydraulic choke that maintains nearly saturated conditions in the earthen layers below. Therefore, an assumption of unit gradient vertical flow below the erosion layer is reasonable and consistent with the use of a unit vertical hydraulic gradient in the HELP model, which diminishes the importance of using a Richards-equation-based infiltration model in a wetter climate such as SRS.

- The HELP model contains an internal weather generator that creates synthetic daily weather data for long-term simulations (e.g., 100 years) using historical monthly-average precipitation, temperature, and solar radiation data. WinUNSAT-H and the HYDRUS software do not include a synthetic weather generator, which makes data entry more cumbersome and limited to the availability of historical daily data.

- Sensitivity studies by Shipmon and Dyer (2017) using the HELP model identified the primary drivers for the predicted infiltration rate for the F-Area Tank Farm closure cap design. The primary drivers include the degradation rate of the geomembrane liner (number of holes per unit area vs. time), the silting-in rate of the lateral drainage layer, the rate of pine tree intrusion and associated root penetration through the GCL, and the size and location of subsided areas due to non-crushable containers disposed in slit and engineered trenches. The primary drivers change the infiltration rate by more than four orders of magnitude over a 10,000-year period. In contrast, this evaluation concludes that the choice of one hydrologic model over another is only a secondary driver of predicted infiltration rates (i.e., differences among WinUNSAT-H, HYDRUS-1D, and HELP model predictions for the same scenario are less than one order of magnitude).

In summary, the HELP model was designed specifically to simulate infiltration through multilayer closure-cap systems, and it remains the best option for modeling such systems in wet climates where a unit hydraulic gradient is a reasonable assumption. As a mass-balance model, HELP is well suited for PA evaluations where flexibility in the model framework and ease of model convergence are important. Existing hydrologic models that use the Richards equation for variably-saturated flow, on the other hand, are not designed specifically for multilayer landfill cover systems, are more difficult to converge, and often must be coupled with a second model for drainage and composite barrier layers. Although computational codes that solve the Richards equation are more sophisticated than HELP, they can be challenging to use with a high level of accuracy when percolation rates are very low and extend over long periods (Whiteside et al., 2009). One reason cited by Whiteside et al. (2009) is that mass-balance errors associated with the numerical model simulations are of the same order of magnitude as the percolation rates themselves.

The WinUNSAT-H and HYDRUS programs are better suited instead for simulating evapotranspiration cover systems typically found in arid and semi-arid climates. Evapotranspiration cover systems rely on the ability of a soil layer to store precipitation until it is naturally evaporated or transpired by a vegetative cover (U.S. EPA, 2011). This contrasts with more conventional cover systems that are engineered with a composite barrier layer of low hydraulic conductivity.

4.0 Quality Assurance

A technical review of this report was performed consistent with the E7 Manual, procedure 2.60 as outlined in the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

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Appendix A. HELP Model Input Parameters for Slit-and-Engineered-Trench Cases used in Comparisons with the Giroud Equations

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Table A-1. HELP Model Input Data for Year 100 (ST00.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane	5	4 (geomembrane liner)
GCL	6	3 (barrier soil liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	6		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.417	0.045	0.018	0.045
5	4	0.06					
6	3	0.2		0.75	0.747	0.4	0.75
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	5.0E-02	585	2			
5	4	2.0E-13					
6	3	5.0E-09					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	4	3	

Table A-2. HELP Model Input Data for Year 180 (ST01.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane	5	4 (geomembrane liner)
GCL	6	3 (barrier soil liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.96		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.416	0.048	0.021	0.048
5	4	0.06					
6	3	0.2		0.75	0.747	0.4	0.75
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	4.48E-02	585	2			
5	4	2.0E-13					
6	3	5.0E-09					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	40	3	

Table A-3. HELP Model Input Data for Year 290 (ST02.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane	5	4 (geomembrane liner)
GCL	6	3 (barrier soil liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.90		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.414	0.052	0.024	0.052
5	4	0.06					
6	3	0.2		0.75	0.747	0.4	0.75
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	3.86E-02	585	2			
5	4	2.0E-13					
6	3	5.0E-08					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	96	3	

Table A-4. HELP Model Input Data for Year 300 (ST03.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane	5	4 (geomembrane liner)
GCL	6	3 (barrier soil liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.90		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.414	0.053	0.024	0.053
5	4	0.06					
6	3	0.2		0.75	0.747	0.4	0.75
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	3.81E-02	585	2			
5	4	2.0E-13					
6	3	5.0E-08					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	101	3	

Table A-5. HELP Model Input Data for Year 380 (ST05.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	**CN Input Parameter Value**
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.85		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.413	0.056	0.027	0.056
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	3.41E-02	585	2			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	141	3	

Table A-6. HELP Model Input Data for Year 480 (ST06.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.84		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.412	0.06	0.03	0.06
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	2.98E-02	585	2			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	479	3	

Table A-7. HELP Model Input Data for Year 660 (ST07.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.82		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.409	0.067	0.036	0.067
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	2.33E-02	585	2			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	1115	3	

Table A-8. HELP Model Input Data for Year 1,100 (ST08.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.76		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.403	0.084	0.049	0.084
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	1.28E-02	585	2			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
5	4	1	2669	3	

Appendix B. HYDRUS-1D Input Parameters

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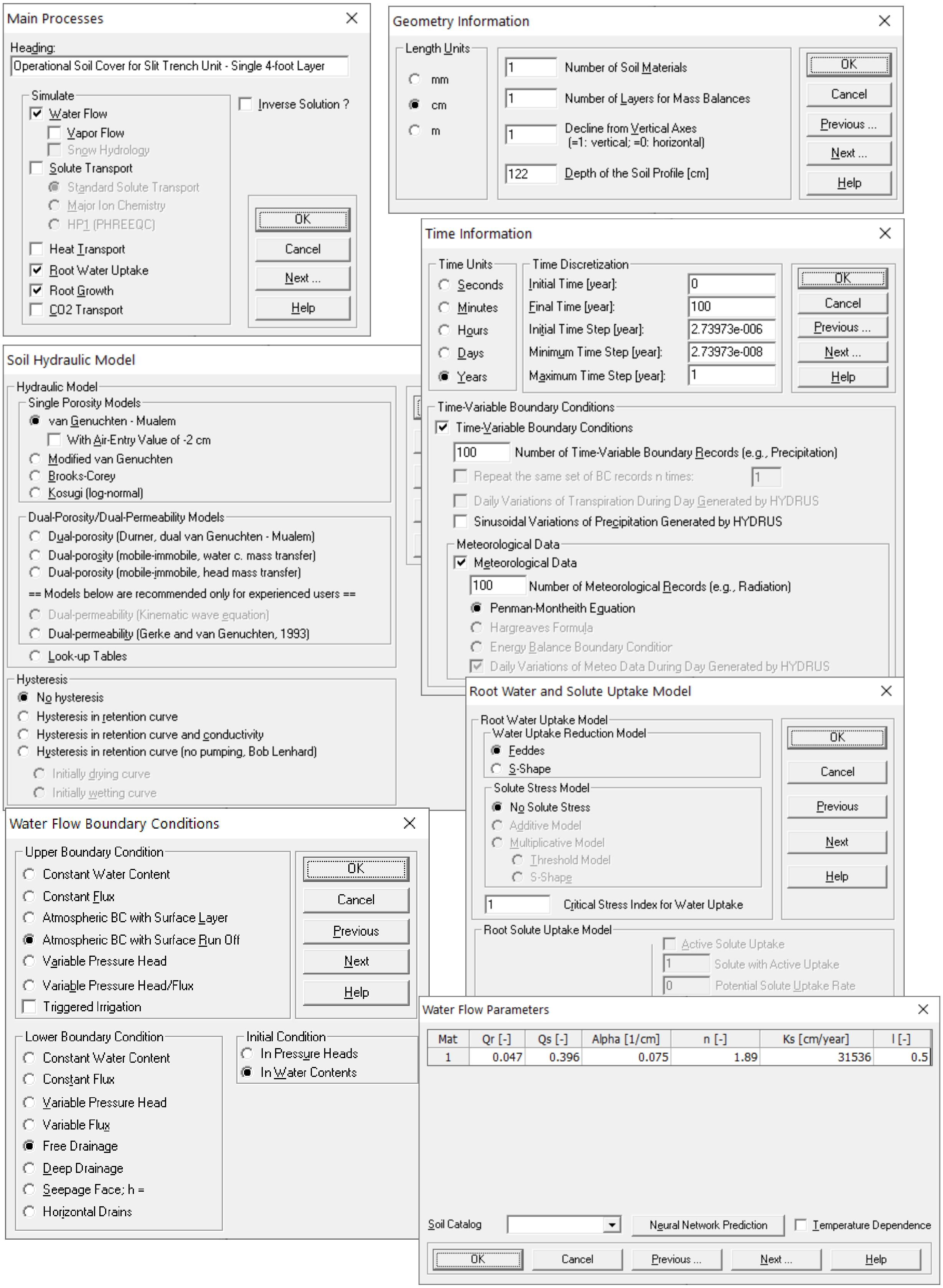
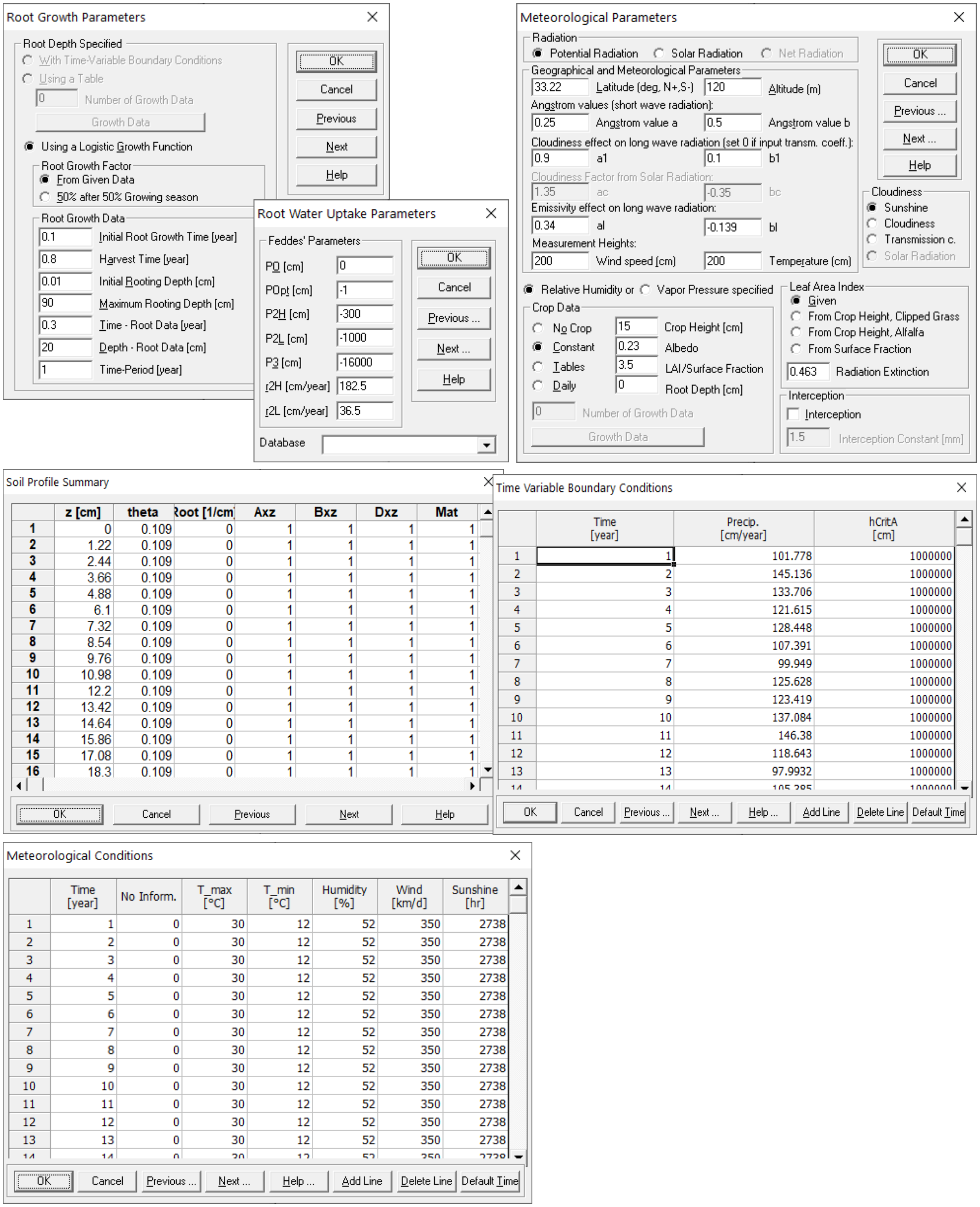
Case 3-1a – Operational Soil Cover (Annual Weather Data)

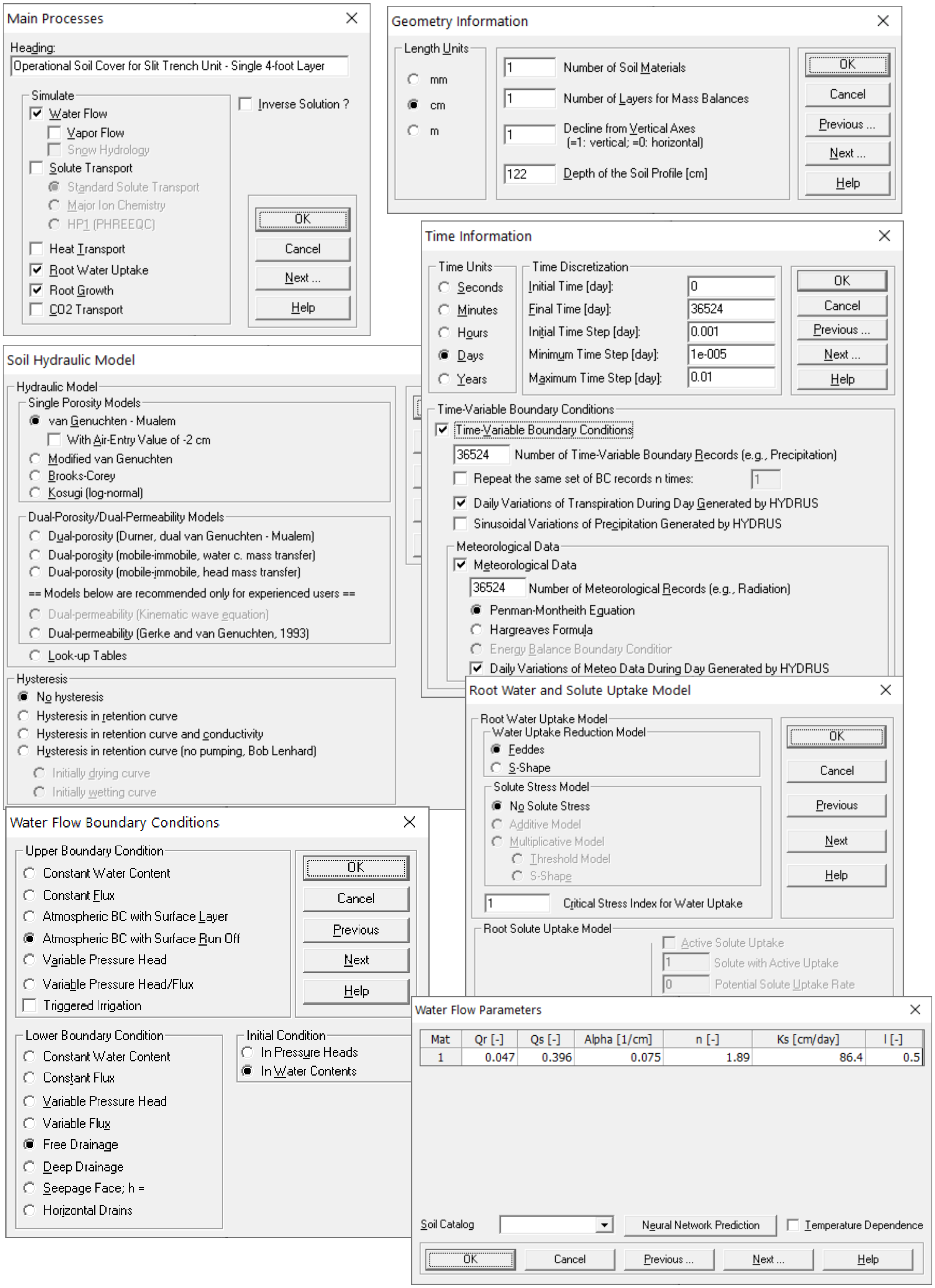


Case 3-1a – Operational Soil Cover (Annual Weather Data)

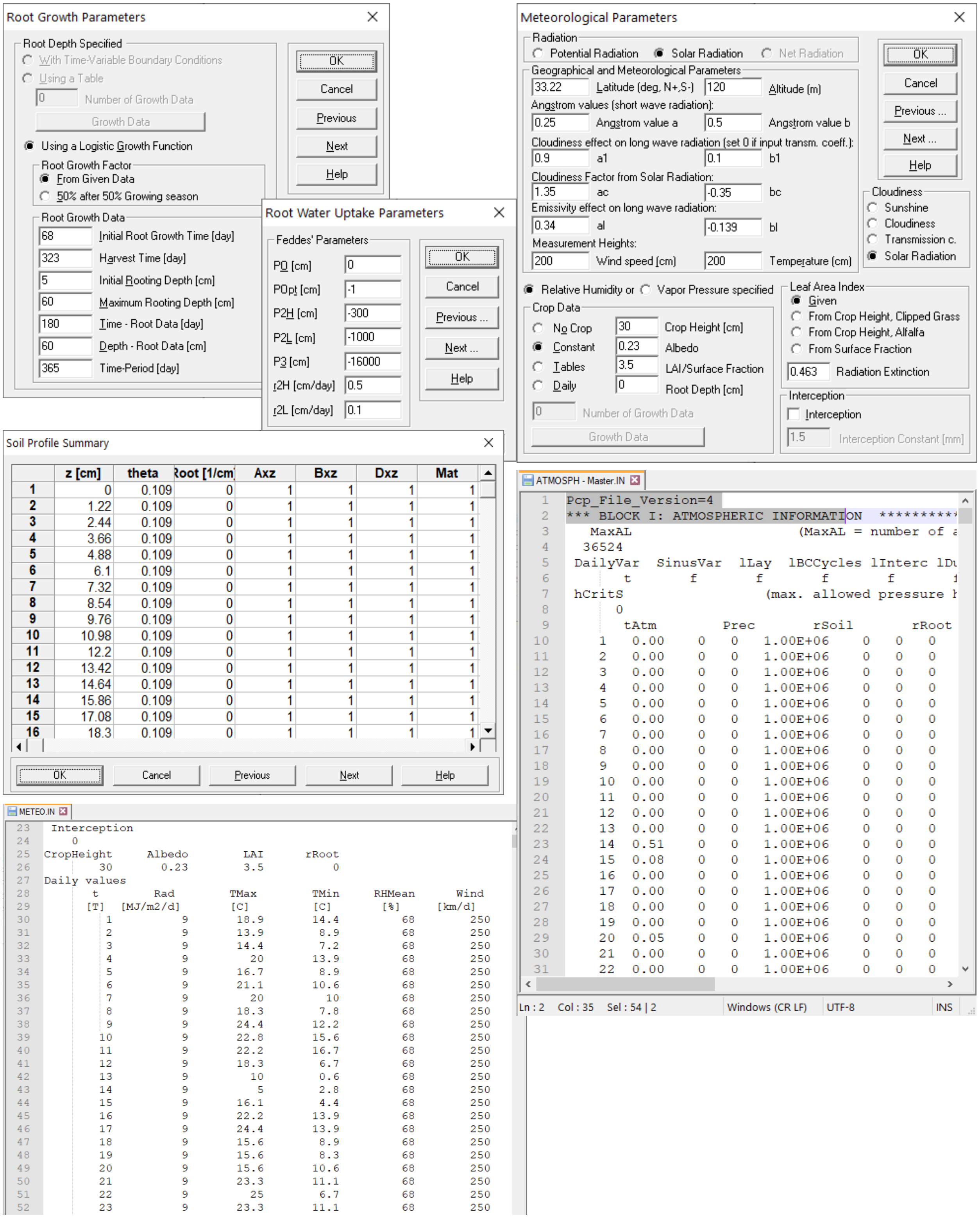


* The Soil Profile Summary, Time Variable Boundary Conditions, and Meteorological Conditions screen captures show only a small portion of the total input dataset due to their large size.

Case 3-1b – Operational Soil Cover (Daily Weather Data)



Case 3-1b – Operational Soil Cover (Daily Weather Data)



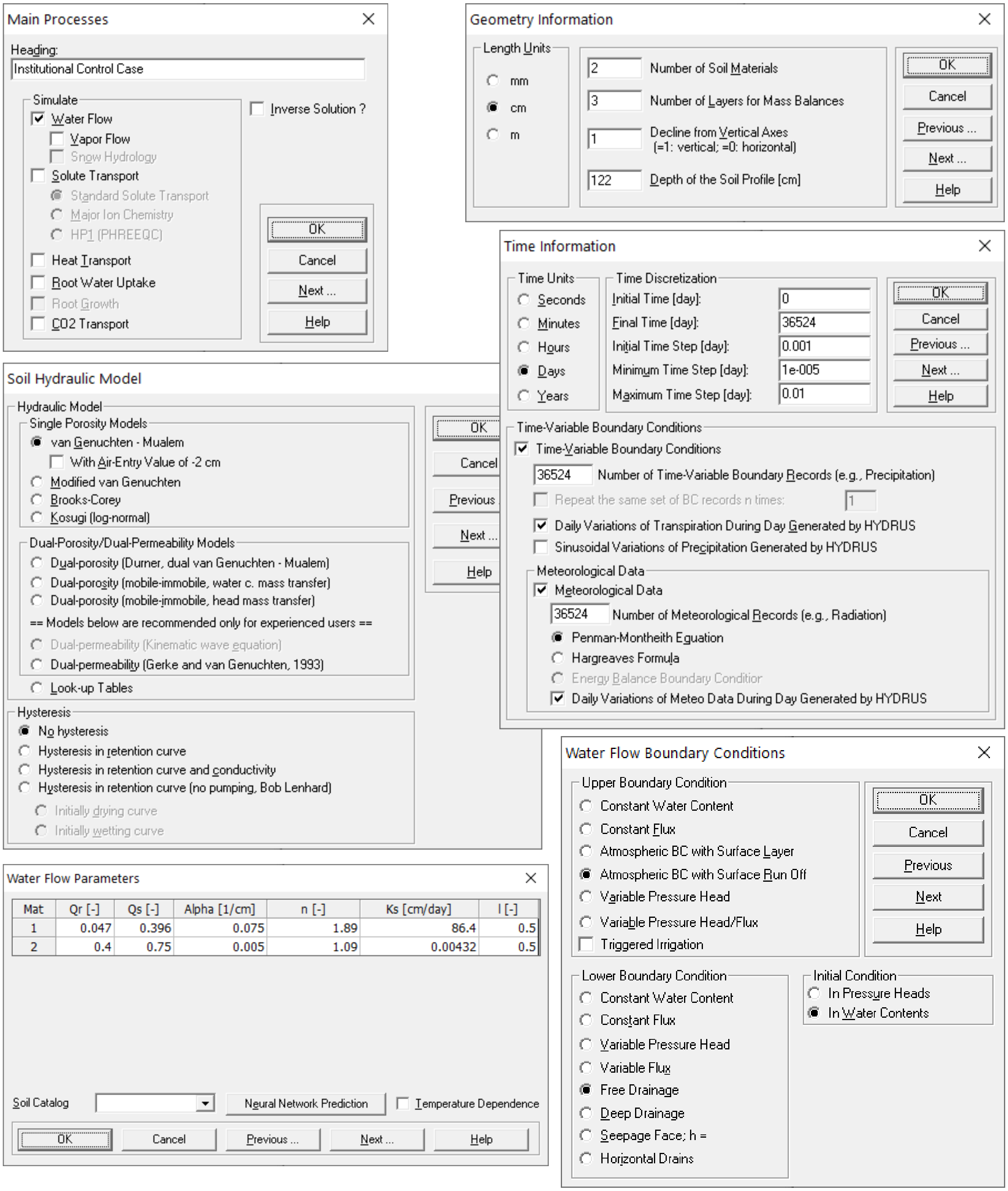
* The Soil Profile Summary, Time Variable Boundary Conditions (ATMOSPH – Master.IN), and Meteorological Conditions (METEO.IN) screen captures show only a small portion of the total input dataset due to their large size.

Case 3-1a/b – Soil Profile Summary

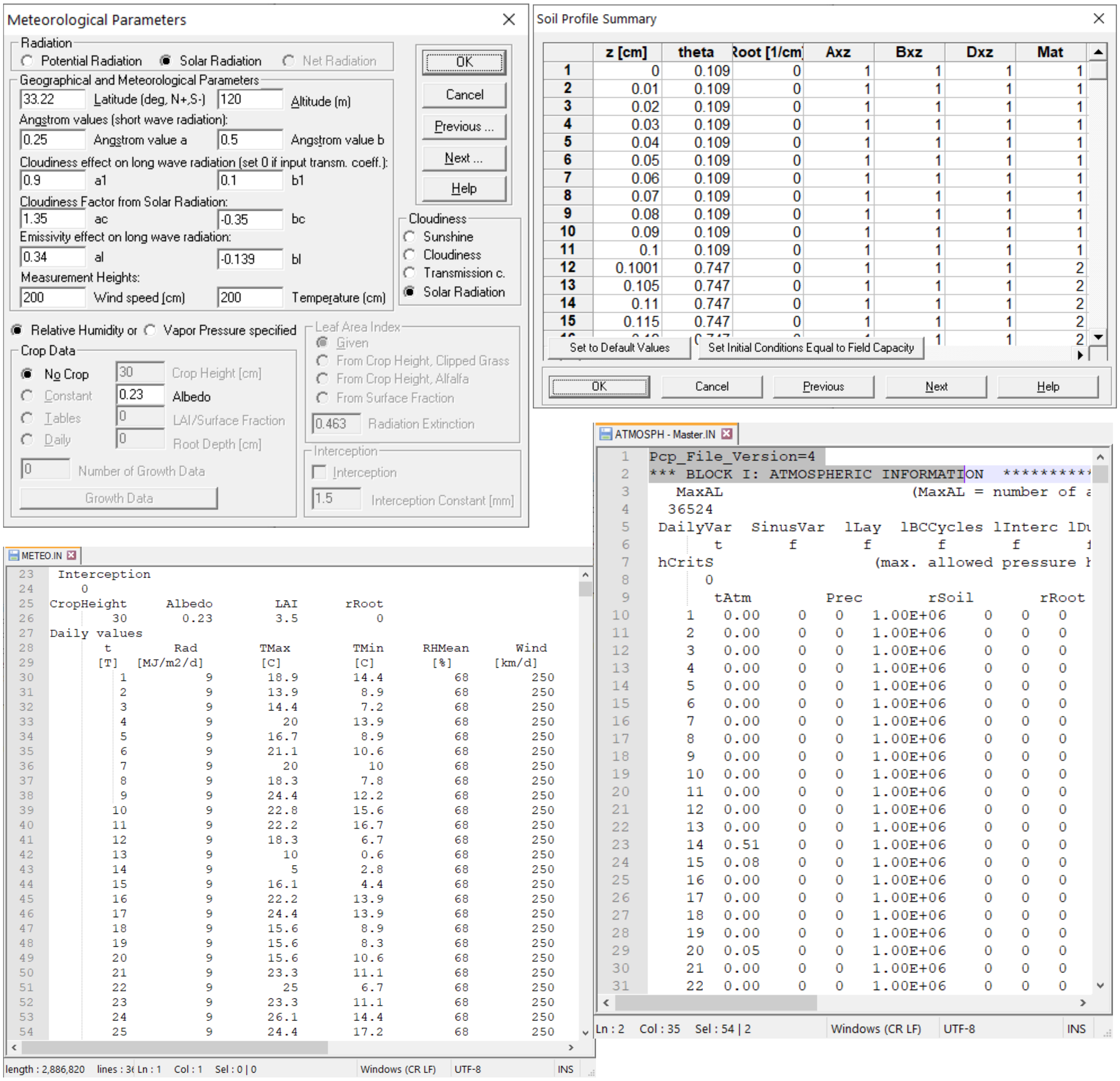
z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
0	0.109	0	1	1	1	1	1
1.22	0.109	0	1	1	1	1	1
2.44	0.109	0	1	1	1	1	1
3.66	0.109	0	1	1	1	1	1
4.88	0.109	0	1	1	1	1	1
6.1	0.109	0	1	1	1	1	1
7.32	0.109	0	1	1	1	1	1
8.54	0.109	0	1	1	1	1	1
9.76	0.109	0	1	1	1	1	1
10.98	0.109	0	1	1	1	1	1
12.2	0.109	0	1	1	1	1	1
13.42	0.109	0	1	1	1	1	1
14.64	0.109	0	1	1	1	1	1
15.86	0.109	0	1	1	1	1	1
17.08	0.109	0	1	1	1	1	1
18.3	0.109	0	1	1	1	1	1
19.52	0.109	0	1	1	1	1	1
20.74	0.109	0	1	1	1	1	1
21.96	0.109	0	1	1	1	1	1
23.18	0.109	0	1	1	1	1	1
24.4	0.109	0	1	1	1	1	1
25.62	0.109	0	1	1	1	1	1
26.84	0.109	0	1	1	1	1	1
28.06	0.109	0	1	1	1	1	1
29.28	0.109	0	1	1	1	1	1
30.5	0.109	0	1	1	1	1	1
31.72	0.109	0	1	1	1	1	1
32.94	0.109	0	1	1	1	1	1
34.16	0.109	0	1	1	1	1	1
35.38	0.109	0	1	1	1	1	1
36.6	0.109	0	1	1	1	1	1
37.82	0.109	0	1	1	1	1	1
39.04	0.109	0	1	1	1	1	1
40.26	0.109	0	1	1	1	1	1
41.48	0.109	0	1	1	1	1	1
42.7	0.109	0	1	1	1	1	1
43.92	0.109	0	1	1	1	1	1
45.14	0.109	0	1	1	1	1	1
46.36	0.109	0	1	1	1	1	1
47.58	0.109	0	1	1	1	1	1
48.8	0.109	0	1	1	1	1	1
50.02	0.109	0	1	1	1	1	1
51.24	0.109	0	1	1	1	1	1
52.46	0.109	0	1	1	1	1	1
53.68	0.109	0	1	1	1	1	1
54.9	0.109	0	1	1	1	1	1
56.12	0.109	0	1	1	1	1	1
57.34	0.109	0	1	1	1	1	1
58.56	0.109	0	1	1	1	1	1
59.78	0.109	0	1	1	1	1	1
61	0.109	0	1	1	1	1	1
62.22	0.109	0	1	1	1	1	1
63.44	0.109	0	1	1	1	1	1

z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
64.66	0.109	0	1	1	1	1	1
65.88	0.109	0	1	1	1	1	1
67.1	0.109	0	1	1	1	1	1
68.32	0.109	0	1	1	1	1	1
69.54	0.109	0	1	1	1	1	1
70.76	0.109	0	1	1	1	1	1
71.98	0.109	0	1	1	1	1	1
73.2	0.109	0	1	1	1	1	1
74.42	0.109	0	1	1	1	1	1
75.64	0.109	0	1	1	1	1	1
76.86	0.109	0	1	1	1	1	1
78.08	0.109	0	1	1	1	1	1
79.3	0.109	0	1	1	1	1	1
80.52	0.109	0	1	1	1	1	1
81.74	0.109	0	1	1	1	1	1
82.96	0.109	0	1	1	1	1	1
84.18	0.109	0	1	1	1	1	1
85.4	0.109	0	1	1	1	1	1
86.62	0.109	0	1	1	1	1	1
87.84	0.109	0	1	1	1	1	1
89.06	0.109	0	1	1	1	1	1
90.28	0.109	0	1	1	1	1	1
91.5	0.109	0	1	1	1	1	1
92.72	0.109	0	1	1	1	1	1
93.94	0.109	0	1	1	1	1	1
95.16	0.109	0	1	1	1	1	1
96.38	0.109	0	1	1	1	1	1
97.6	0.109	0	1	1	1	1	1
98.82	0.109	0	1	1	1	1	1
100.04	0.109	0	1	1	1	1	1
101.26	0.109	0	1	1	1	1	1
102.48	0.109	0	1	1	1	1	1
103.7	0.109	0	1	1	1	1	1
104.92	0.109	0	1	1	1	1	1
106.14	0.109	0	1	1	1	1	1
107.36	0.109	0	1	1	1	1	1
108.58	0.109	0	1	1	1	1	1
109.8	0.109	0	1	1	1	1	1
111.02	0.109	0	1	1	1	1	1
112.24	0.109	0	1	1	1	1	1
113.46	0.109	0	1	1	1	1	1
114.68	0.109	0	1	1	1	1	1
115.9	0.109	0	1	1	1	1	1
117.12	0.109	0	1	1	1	1	1
118.34	0.109	0	1	1	1	1	1
119.56	0.109	0	1	1	1	1	1
120.78	0.109	0	1	1	1	1	1
122	0.109	0	1	1	1	1	1

Case 3-2a – Institutional Control ($K_{sat\ HDPE}$ = 5.0E-08 cm/sec)

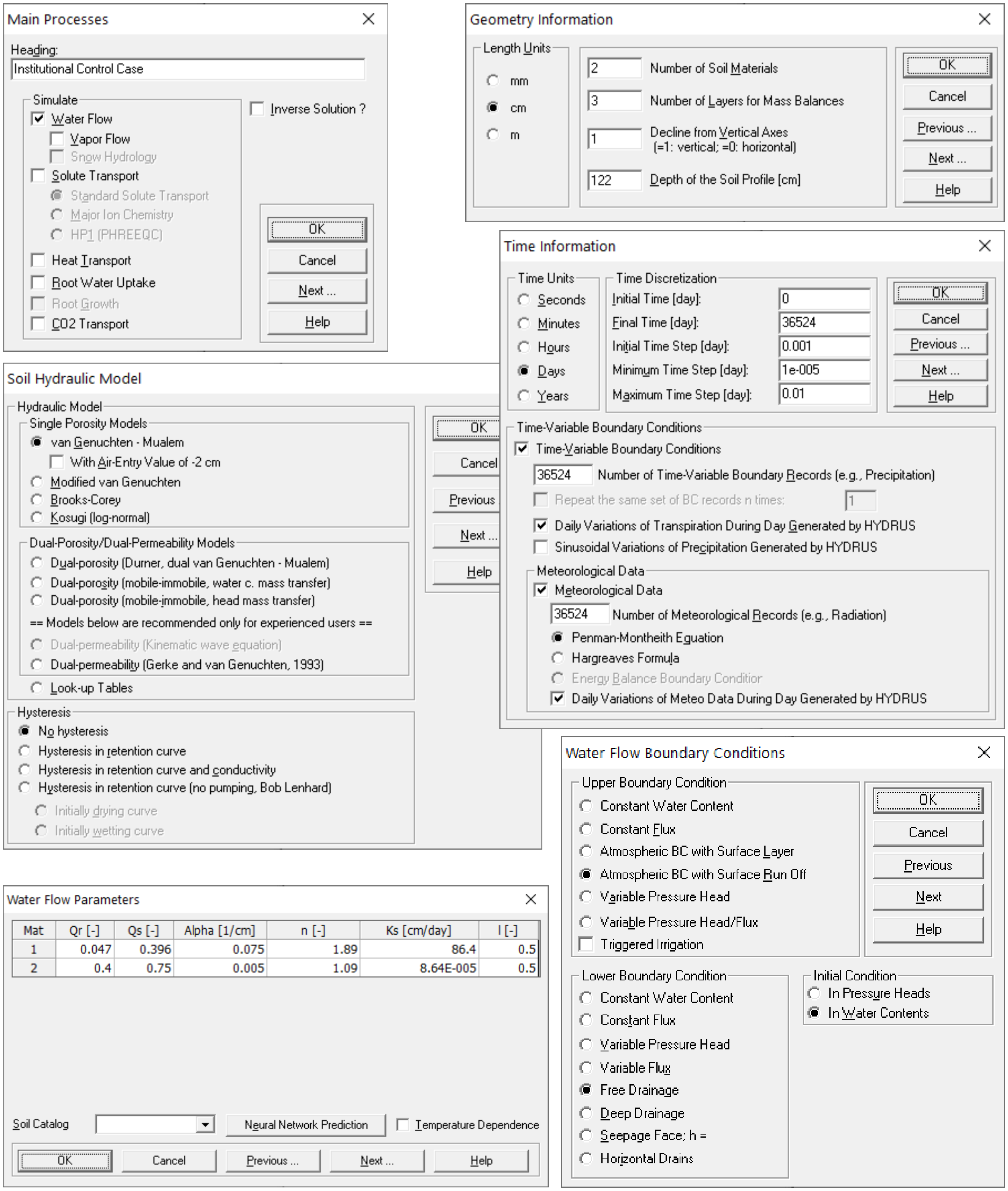


Case 3-2a – Institutional Control ($K_{sat\ HDPE}$ = 5.0E-08 cm/sec)

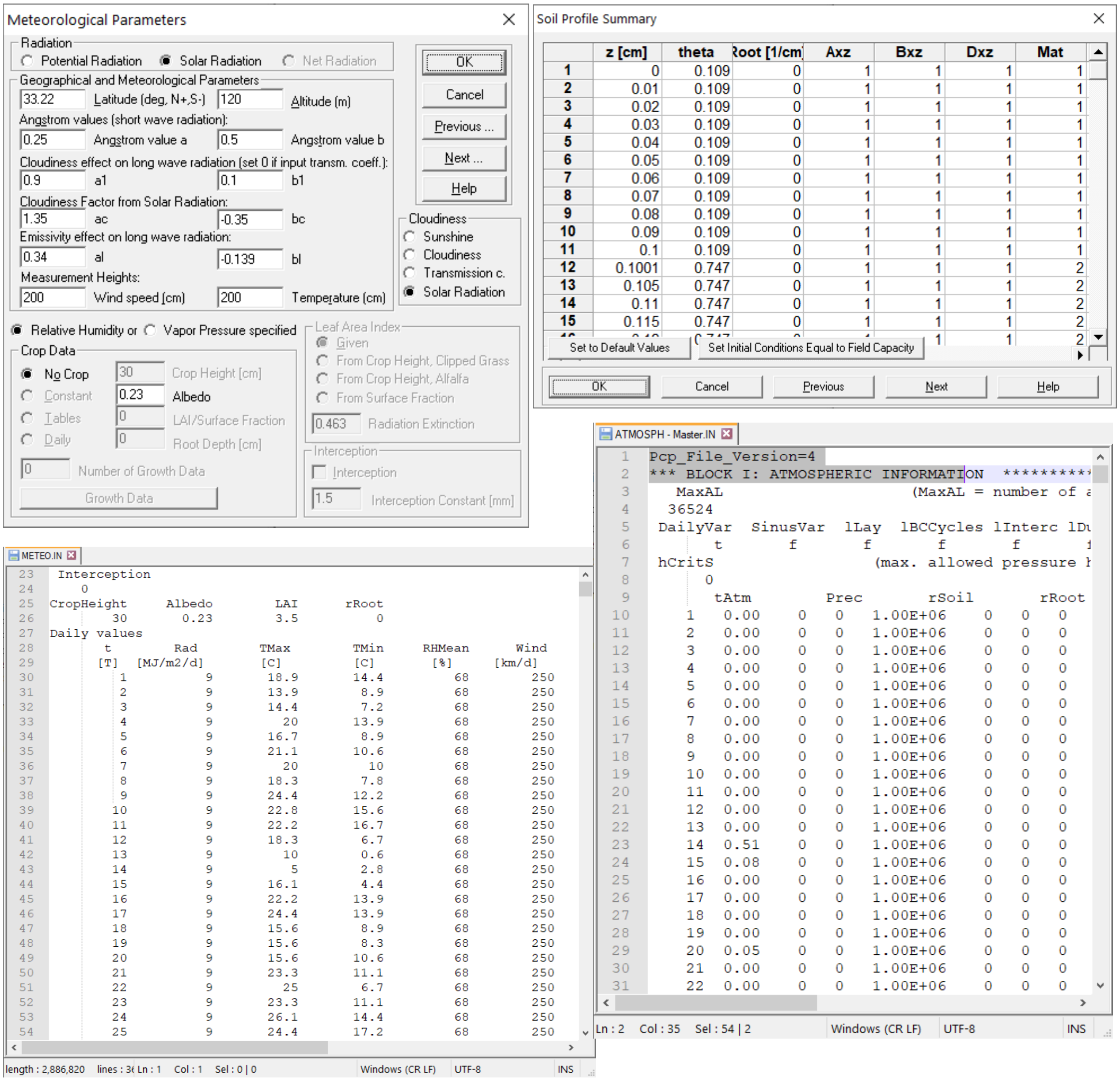


* The Soil Profile Summary, Time Variable Boundary Conditions (ATMOSPH – Master.IN), and Meteorological Conditions (METEO.IN) screen captures show only a small portion of the total input dataset due to their large size.

Case 3-2b – Institutional Control ($K_{sat\ HDPE}$ = 1.0E-09 cm/sec)



Case 3-2b – Institutional Control ($K_{sat\ HDPE}$ = 1.0E-09 cm/sec)



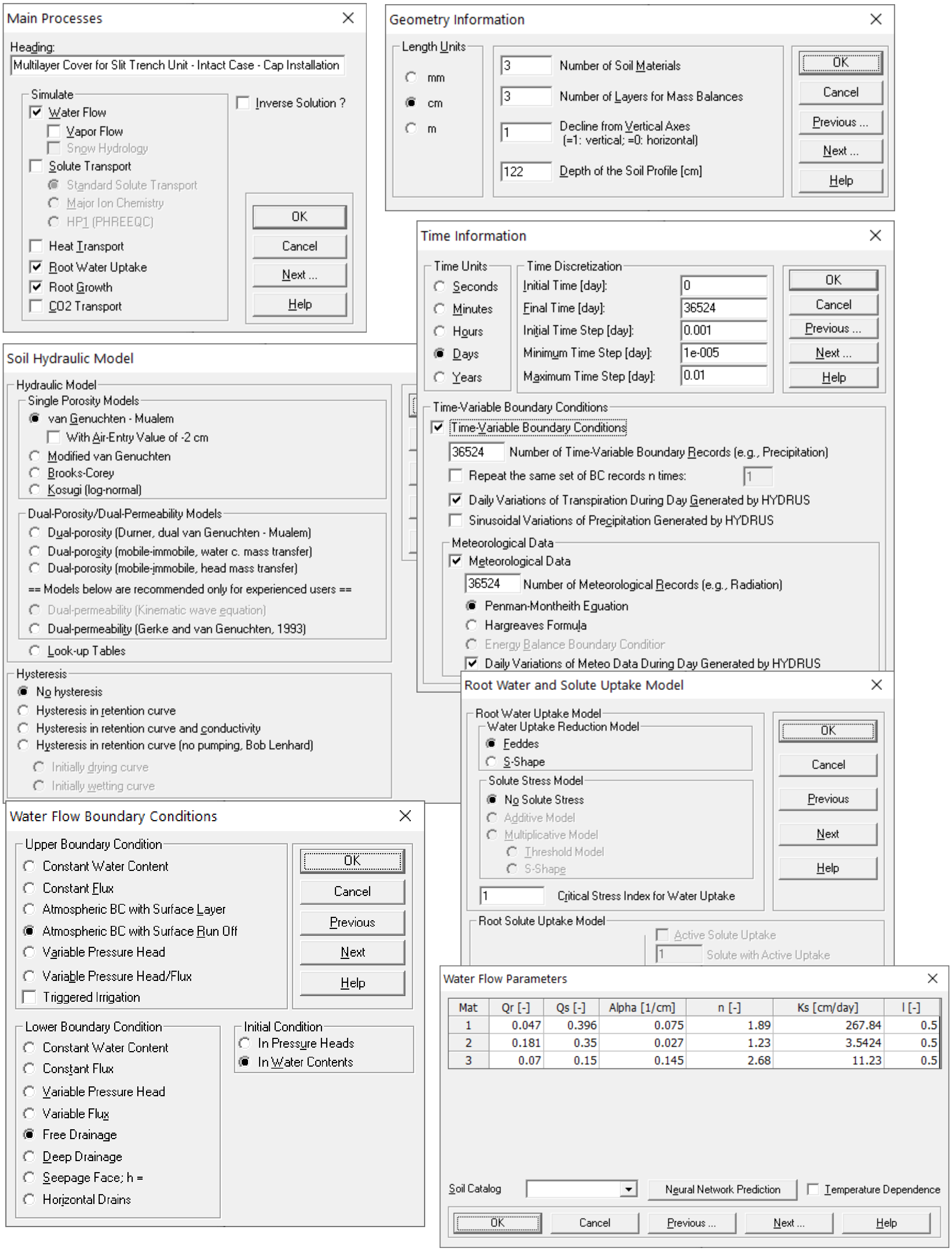
* The Soil Profile Summary, Time Variable Boundary Conditions (ATMOSPH – Master.IN), and Meteorological Conditions (METEO.IN) screen captures show only a small portion of the total input dataset due to their large size.

Case 3-2a/b – Soil Profile Summary

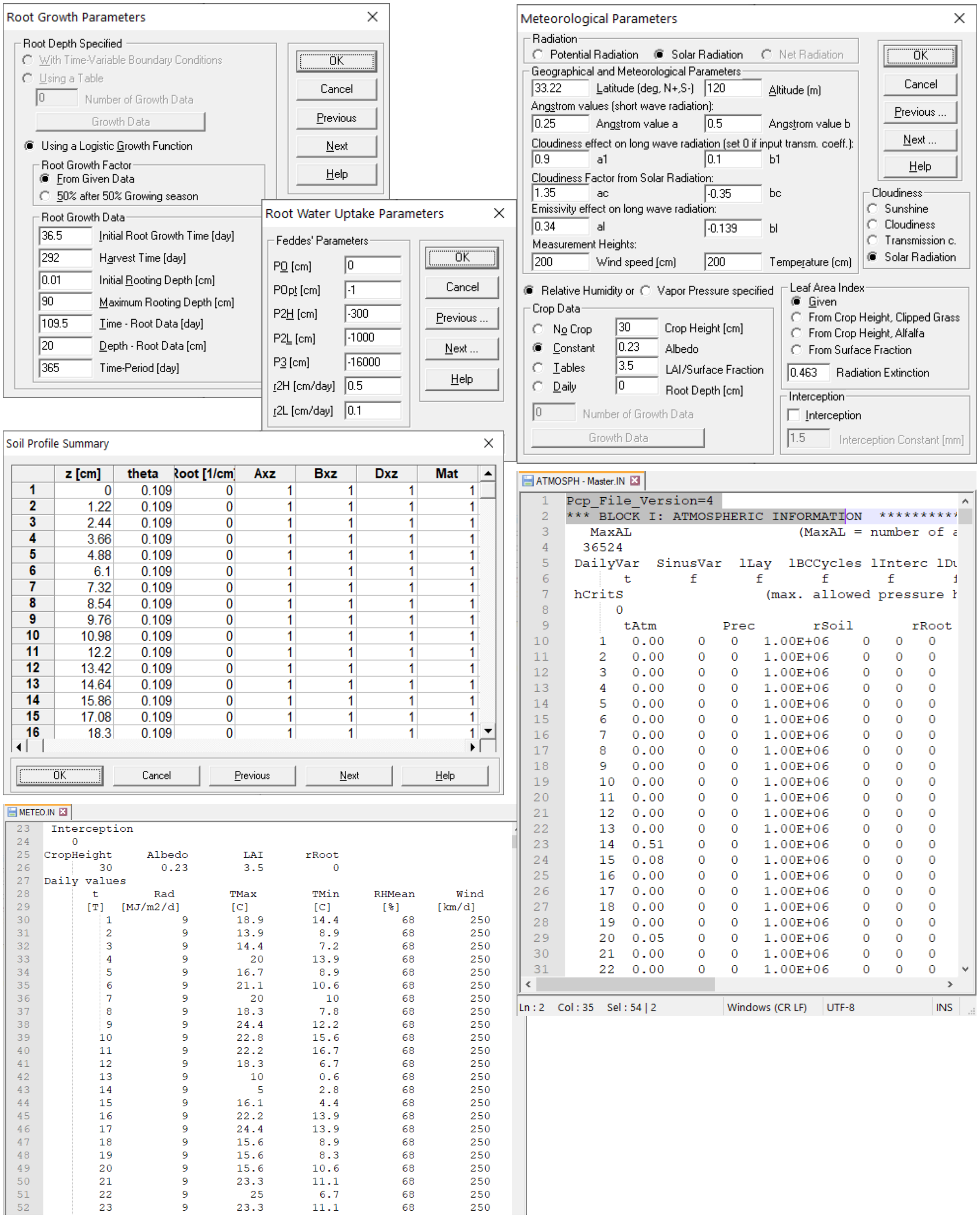
z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
0	0.109	0	1	1	1	1	1
0.01	0.109	0	1	1	1	1	1
0.02	0.109	0	1	1	1	1	1
0.03	0.109	0	1	1	1	1	1
0.04	0.109	0	1	1	1	1	1
0.05	0.109	0	1	1	1	1	1
0.06	0.109	0	1	1	1	1	1
0.07	0.109	0	1	1	1	1	1
0.08	0.109	0	1	1	1	1	1
0.09	0.109	0	1	1	1	1	1
0.1	0.109	0	1	1	1	1	1
0.1001	0.747	0	1	1	1	2	2
0.105	0.747	0	1	1	1	2	2
0.11	0.747	0	1	1	1	2	2
0.115	0.747	0	1	1	1	2	2
0.12	0.747	0	1	1	1	2	2
0.125	0.747	0	1	1	1	2	2
0.13	0.747	0	1	1	1	2	2
0.135	0.747	0	1	1	1	2	2
0.14	0.747	0	1	1	1	2	2
0.145	0.747	0	1	1	1	2	2
0.15	0.747	0	1	1	1	2	2
0.155	0.747	0	1	1	1	2	2
0.16	0.747	0	1	1	1	2	2
0.165	0.747	0	1	1	1	2	2
0.17	0.747	0	1	1	1	2	2
0.175	0.747	0	1	1	1	2	2
0.18	0.747	0	1	1	1	2	2
0.185	0.747	0	1	1	1	2	2
0.19	0.747	0	1	1	1	2	2
0.195	0.747	0	1	1	1	2	2
0.2	0.747	0	1	1	1	2	2
0.205	0.747	0	1	1	1	2	2
0.21	0.747	0	1	1	1	2	2
0.215	0.747	0	1	1	1	2	2
0.22	0.747	0	1	1	1	2	2
0.225	0.747	0	1	1	1	2	2
0.23	0.747	0	1	1	1	2	2
0.235	0.747	0	1	1	1	2	2
0.24	0.747	0	1	1	1	2	2
0.245	0.747	0	1	1	1	2	2
0.2524	0.747	0	1	1	1	2	2
0.2525	0.109	0	1	1	1	1	3
0.3	0.109	0	1	1	1	1	3
0.35	0.109	0	1	1	1	1	3
0.4	0.109	0	1	1	1	1	3
0.5	0.109	0	1	1	1	1	3
1	0.109	0	1	1	1	1	3
3	0.109	0	1	1	1	1	3
5	0.109	0	1	1	1	1	3
7	0.109	0	1	1	1	1	3
9	0.109	0	1	1	1	1	3
11	0.109	0	1	1	1	1	3

z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
13	0.109	0	1	1	1	1	3
15	0.109	0	1	1	1	1	3
17	0.109	0	1	1	1	1	3
19	0.109	0	1	1	1	1	3
21	0.109	0	1	1	1	1	3
23	0.109	0	1	1	1	1	3
25	0.109	0	1	1	1	1	3
27	0.109	0	1	1	1	1	3
29	0.109	0	1	1	1	1	3
31	0.109	0	1	1	1	1	3
33	0.109	0	1	1	1	1	3
35	0.109	0	1	1	1	1	3
37	0.109	0	1	1	1	1	3
39	0.109	0	1	1	1	1	3
41	0.109	0	1	1	1	1	3
43	0.109	0	1	1	1	1	3
45	0.109	0	1	1	1	1	3
47	0.109	0	1	1	1	1	3
49	0.109	0	1	1	1	1	3
51	0.109	0	1	1	1	1	3
53	0.109	0	1	1	1	1	3
55	0.109	0	1	1	1	1	3
57	0.109	0	1	1	1	1	3
59	0.109	0	1	1	1	1	3
61	0.109	0	1	1	1	1	3
63	0.109	0	1	1	1	1	3
65	0.109	0	1	1	1	1	3
67	0.109	0	1	1	1	1	3
69	0.109	0	1	1	1	1	3
71	0.109	0	1	1	1	1	3
73	0.109	0	1	1	1	1	3
75	0.109	0	1	1	1	1	3
77	0.109	0	1	1	1	1	3
79	0.109	0	1	1	1	1	3
81	0.109	0	1	1	1	1	3
83	0.109	0	1	1	1	1	3
85	0.109	0	1	1	1	1	3
87	0.109	0	1	1	1	1	3
89	0.109	0	1	1	1	1	3
91	0.109	0	1	1	1	1	3
93	0.109	0	1	1	1	1	3
95	0.109	0	1	1	1	1	3
97	0.109	0	1	1	1	1	3
99	0.109	0	1	1	1	1	3
101	0.109	0	1	1	1	1	3
103	0.109	0	1	1	1	1	3
105	0.109	0	1	1	1	1	3
107	0.109	0	1	1	1	1	3
109	0.109	0	1	1	1	1	3
111	0.109	0	1	1	1	1	3
113	0.109	0	1	1	1	1	3
115	0.109	0	1	1	1	1	3
117	0.109	0	1	1	1	1	3
119	0.109	0	1	1	1	1	3
122	0.109	0	1	1	1	1	3

Case 3-3 – Upper Three Layers of Intact Multilayer Cover



Case 3-3 – Upper Three Layers of Intact Multilayer Cover



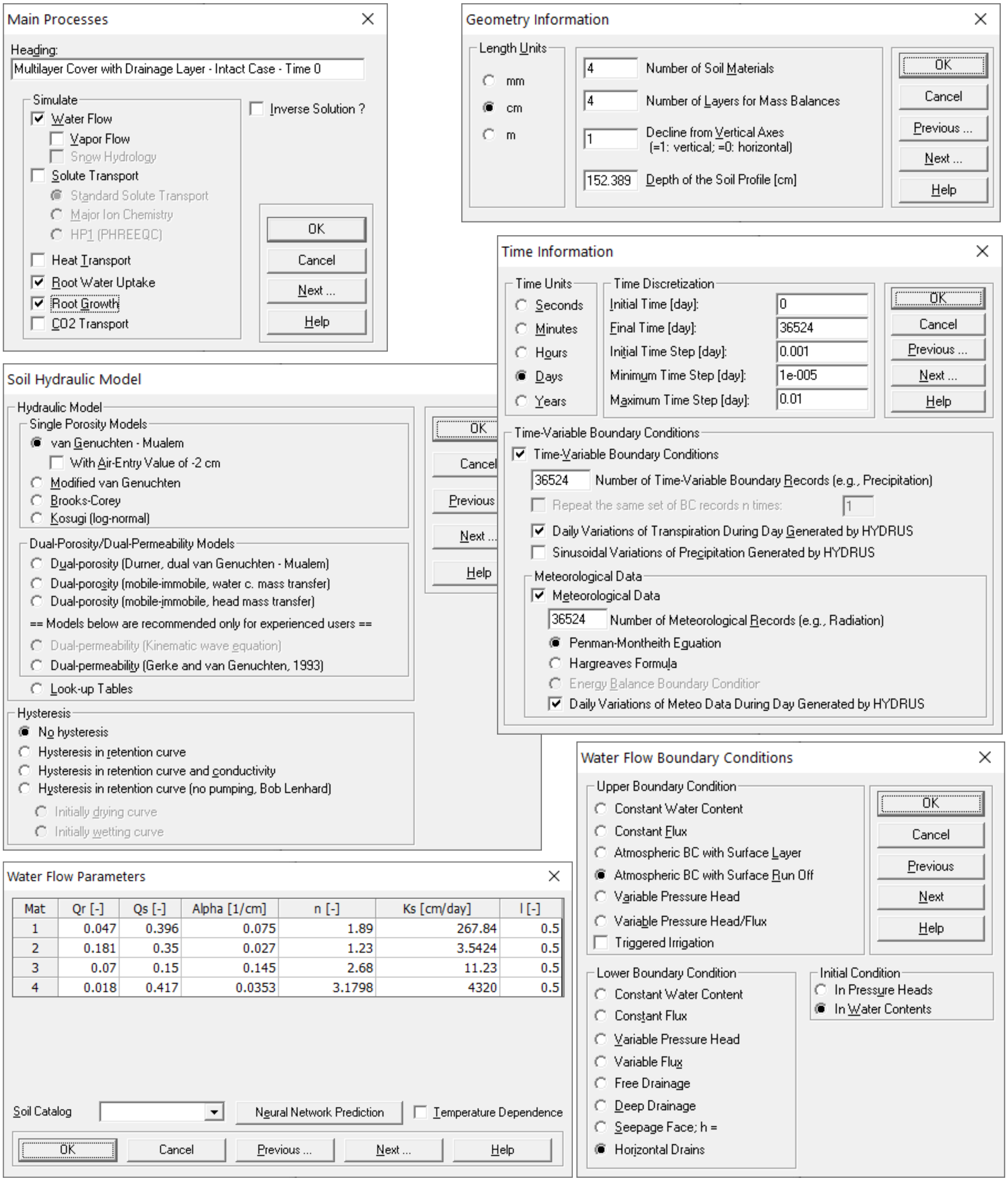
* The Soil Profile Summary, Time Variable Boundary Conditions (ATMOSPH – Master.IN), and Meteorological Conditions (METEO.IN) screen captures show only a small portion of the total input dataset due to their large size.

Case 3-3 – Soil Profile Summary

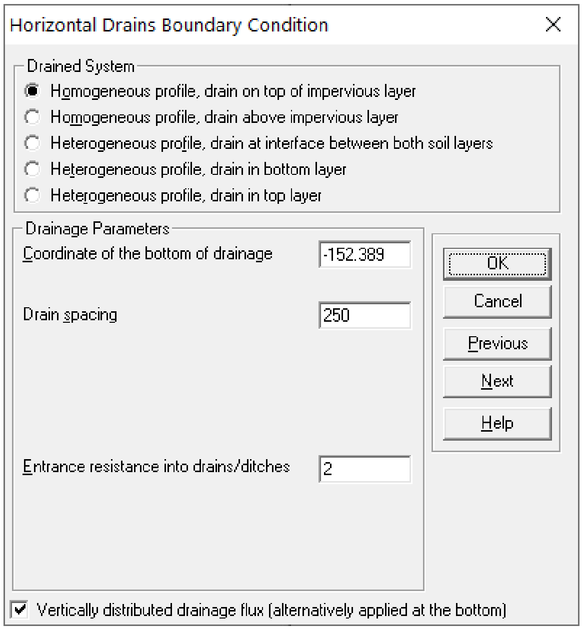
z[cm]	**theta**	**Root[1/cm]**	**Axz**	**Bxz**	**Dxz**	**Mat**	**Layer**
0	0.109	0	1	1	1	1	1
1.22	0.109	0	1	1	1	1	1
2.44	0.109	0	1	1	1	1	1
3.66	0.109	0	1	1	1	1	1
4.88	0.109	0	1	1	1	1	1
6.1	0.109	0	1	1	1	1	1
7.32	0.109	0	1	1	1	1	1
8.54	0.109	0	1	1	1	1	1
9.76	0.109	0	1	1	1	1	1
10.98	0.109	0	1	1	1	1	1
12.2	0.109	0	1	1	1	1	1
13.42	0.109	0	1	1	1	1	1
14.64	0.109	0	1	1	1	1	1
15.24	0.109	0	1	1	1	1	1
17.08	0.252	0	1	1	1	2	2
18.3	0.252	0	1	1	1	2	2
19.52	0.252	0	1	1	1	2	2
20.74	0.252	0	1	1	1	2	2
21.96	0.252	0	1	1	1	2	2
23.18	0.252	0	1	1	1	2	2
24.4	0.252	0	1	1	1	2	2
25.62	0.252	0	1	1	1	2	2
26.84	0.252	0	1	1	1	2	2
28.06	0.252	0	1	1	1	2	2
29.28	0.252	0	1	1	1	2	2
30.5	0.252	0	1	1	1	2	2
31.72	0.252	0	1	1	1	2	2
32.94	0.252	0	1	1	1	2	2
34.16	0.252	0	1	1	1	2	2
35.38	0.252	0	1	1	1	2	2
36.6	0.252	0	1	1	1	2	2
37.82	0.252	0	1	1	1	2	2
39.04	0.252	0	1	1	1	2	2
40.26	0.252	0	1	1	1	2	2
41.48	0.252	0	1	1	1	2	2
42.7	0.252	0	1	1	1	2	2
43.92	0.252	0	1	1	1	2	2
45.14	0.252	0	1	1	1	2	2
46.36	0.252	0	1	1	1	2	2
47.58	0.252	0	1	1	1	2	2
48.8	0.252	0	1	1	1	2	2
50.02	0.252	0	1	1	1	2	2
51.24	0.252	0	1	1	1	2	2
52.46	0.252	0	1	1	1	2	2
53.68	0.252	0	1	1	1	2	2
54.9	0.252	0	1	1	1	2	2
56.12	0.252	0	1	1	1	2	2
57.34	0.252	0	1	1	1	2	2
58.56	0.252	0	1	1	1	2	2
59.78	0.252	0	1	1	1	2	2
61	0.252	0	1	1	1	2	2
62.22	0.252	0	1	1	1	2	2
63.44	0.252	0	1	1	1	2	2

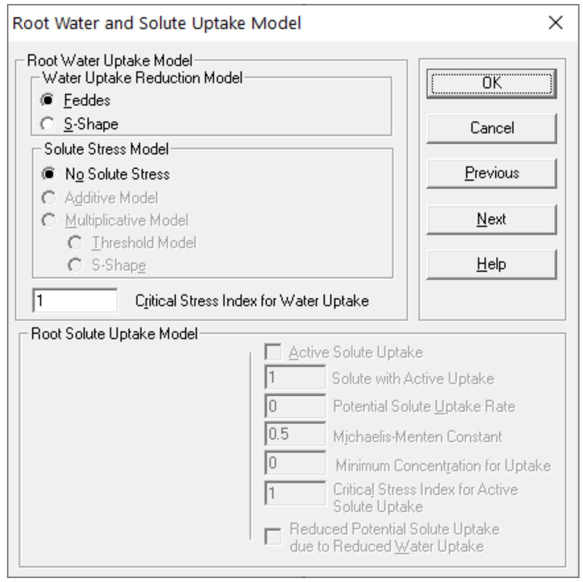
z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
64.66	0.252	0	1	1	1	2	2
65.88	0.252	0	1	1	1	2	2
67.1	0.252	0	1	1	1	2	2
68.32	0.252	0	1	1	1	2	2
69.54	0.252	0	1	1	1	2	2
70.76	0.252	0	1	1	1	2	2
71.98	0.252	0	1	1	1	2	2
73.2	0.252	0	1	1	1	2	2
74.42	0.252	0	1	1	1	2	2
75.64	0.252	0	1	1	1	2	2
76.86	0.252	0	1	1	1	2	2
78.08	0.252	0	1	1	1	2	2
79.3	0.252	0	1	1	1	2	2
80.52	0.252	0	1	1	1	2	2
81.74	0.252	0	1	1	1	2	2
82.96	0.252	0	1	1	1	2	2
84.18	0.252	0	1	1	1	2	2
85.4	0.252	0	1	1	1	2	2
86.62	0.252	0	1	1	1	2	2
87.84	0.252	0	1	1	1	2	2
89.06	0.252	0	1	1	1	2	2
90.28	0.252	0	1	1	1	2	2
91.44	0.252	0	1	1	1	2	2
92.72	0.100	0	1	1	1	3	3
93.94	0.100	0	1	1	1	3	3
95.16	0.100	0	1	1	1	3	3
96.38	0.100	0	1	1	1	3	3
97.6	0.100	0	1	1	1	3	3
98.82	0.100	0	1	1	1	3	3
100.04	0.100	0	1	1	1	3	3
101.26	0.100	0	1	1	1	3	3
102.48	0.100	0	1	1	1	3	3
103.7	0.100	0	1	1	1	3	3
104.92	0.100	0	1	1	1	3	3
106.14	0.100	0	1	1	1	3	3
107.36	0.100	0	1	1	1	3	3
108.58	0.100	0	1	1	1	3	3
109.8	0.100	0	1	1	1	3	3
111.02	0.100	0	1	1	1	3	3
112.24	0.100	0	1	1	1	3	3
113.46	0.100	0	1	1	1	3	3
114.68	0.100	0	1	1	1	3	3
115.9	0.100	0	1	1	1	3	3
117.12	0.100	0	1	1	1	3	3
118.34	0.100	0	1	1	1	3	3
119.56	0.100	0	1	1	1	3	3
120.78	0.100	0	1	1	1	3	3
122	0.100	0	1	1	1	3	3

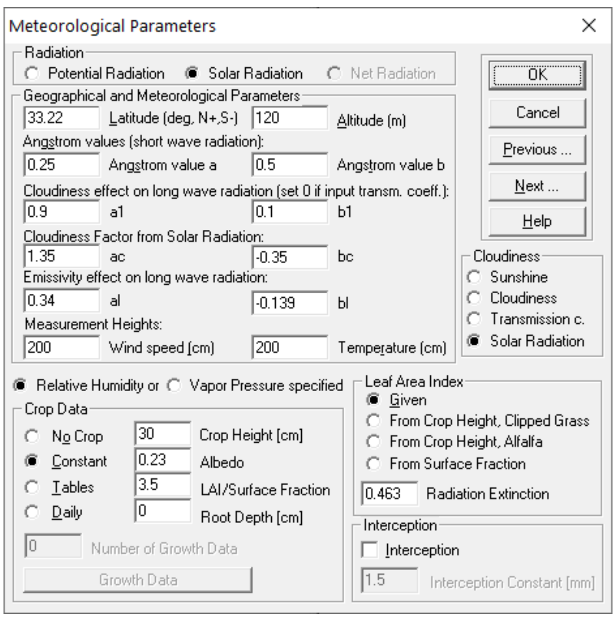
Case 3-4 – Upper Four Layers of Intact Multilayer Cover

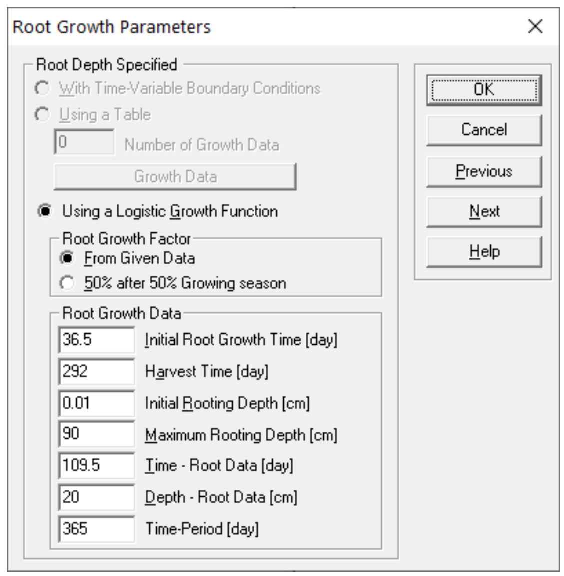


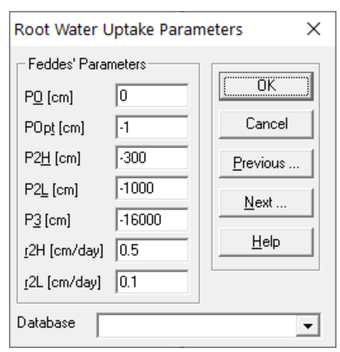
Case 3-4 – Upper Four Layers of Intact Multilayer Cover











Case 3-4 – Upper Four Layers of Intact Multilayer Cover

METEO.IN

```
 Interception
     0
CropHeight      Albedo          LAI       rRoot
        30        0.23          3.5           0
Daily values
         t         Rad         TMax         TMin      RHMean        Wind
       [T]   [MJ/m2/d]         [C]          [C]         [%]      [km/d]
         1           9         18.9         14.4          68         250
         2           9         13.9          8.9          68         250
         3           9         14.4          7.2          68         250
         4           9           20         13.9          68         250
         5           9         16.7          8.9          68         250
         6           9         21.1         10.6          68         250
         7           9           20           10          68         250
         8           9         18.3          7.8          68         250
         9           9         24.4         12.2          68         250
        10           9         22.8         15.6          68         250
        11           9         22.2         16.7          68         250
        12           9         18.3          6.7          68         250
        13           9           10          0.6          68         250
        14           9            5          2.8          68         250
        15           9         16.1          4.4          68         250
        16           9         22.2         13.9          68         250
        17           9         24.4         13.9          68         250
        18           9         15.6          8.9          68         250
        19           9         15.6          8.3          68         250
        20           9         15.6         10.6          68         250
        21           9         23.3         11.1          68         250
        22           9           25          6.7          68         250
        23           9         23.3         11.1          68         250
        24           9         26.1         14.4          68         250
        25           9         24.4         17.2          68         250
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length : 2,886,820 lines : 3(Ln : 1 Col : 1 Sel : 0 | 0 Windows (CR LF) UTF-8 INS

ATMOSPH - Master.IN

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  36524
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 hCritS                 (max. allowed pressure h
      0
       tAtm        Prec         rSoil        rRoot
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    2  0.00     0   0   1.00E+06    0   0   0
    3  0.00     0   0   1.00E+06    0   0   0
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    5  0.00     0   0   1.00E+06    0   0   0
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    8  0.00     0   0   1.00E+06    0   0   0
    9  0.00     0   0   1.00E+06    0   0   0
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   18  0.00     0   0   1.00E+06    0   0   0
   19  0.00     0   0   1.00E+06    0   0   0
   20  0.05     0   0   1.00E+06    0   0   0
   21  0.00     0   0   1.00E+06    0   0   0
   22  0.00     0   0   1.00E+06    0   0   0
```

Ln : 2 Col : 35 Sel : 54 | 2 Windows (CR LF) UTF-8 INS

Soil Profile Summary

	z [cm]	theta	Root [1/cm]	Axz	Bxz	Dxz	Mat
1	0	0.109	0	1	1	1	1
2	2.58896	0.109	0	1	1	1	1
3	4.69746	0.109	0	1	1	1	1
4	6.80597	0.109	0	1	1	1	1
5	8.91448	0.109	0	1	1	1	1
6	11.023	0.109	0	1	1	1	1
7	13.1315	0.109	0	1	1	1	1
8	15.24	0.109	0	1	1	1	1
9	17.3485	0.252	0	1	1	1	2
10	18.995	0.252	0	1	1	1	2
11	20.6415	0.252	0	1	1	1	2
12	22.2879	0.252	0	1	1	1	2
13	23.9344	0.252	0	1	1	1	2
14	25.5809	0.252	0	1	1	1	2
15	27.2274	0.252	0	1	1	1	2
16	28.8738	0.252	0	1	1	1	2

OK Cancel Previous Next Help

* The Soil Profile Summary, Time Variable Boundary Conditions (ATMOSPH – Master.IN), and Meteorological Conditions (METEO.IN) screen captures show only a small portion of the total input dataset due to their large size.

Case 3-4 – Soil Profile Summary

z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
0.0	0.109	0	1	1	1	1	1
2.58896	0.109	0	1	1	1	1	1
4.69746	0.109	0	1	1	1	1	1
6.80597	0.109	0	1	1	1	1	1
8.91448	0.109	0	1	1	1	1	1
11.023	0.109	0	1	1	1	1	1
13.1315	0.109	0	1	1	1	1	1
15.24	0.109	0	1	1	1	1	1
17.3485	0.252	0	1	1	1	2	2
18.995	0.252	0	1	1	1	2	2
20.6415	0.252	0	1	1	1	2	2
22.2879	0.252	0	1	1	1	2	2
23.9344	0.252	0	1	1	1	2	2
25.5809	0.252	0	1	1	1	2	2
27.2274	0.252	0	1	1	1	2	2
28.8738	0.252	0	1	1	1	2	2
30.5203	0.252	0	1	1	1	2	2
32.1668	0.252	0	1	1	1	2	2
33.8133	0.252	0	1	1	1	2	2
35.4598	0.252	0	1	1	1	2	2
37.1062	0.252	0	1	1	1	2	2
38.7527	0.252	0	1	1	1	2	2
40.3992	0.252	0	1	1	1	2	2
42.0457	0.252	0	1	1	1	2	2
43.6922	0.252	0	1	1	1	2	2
45.3386	0.252	0	1	1	1	2	2
46.9851	0.252	0	1	1	1	2	2
48.6316	0.252	0	1	1	1	2	2
50.2781	0.252	0	1	1	1	2	2
51.9245	0.252	0	1	1	1	2	2
53.571	0.252	0	1	1	1	2	2
55.2175	0.252	0	1	1	1	2	2
56.864	0.252	0	1	1	1	2	2
58.5104	0.252	0	1	1	1	2	2
60.1569	0.252	0	1	1	1	2	2
61.8034	0.252	0	1	1	1	2	2
63.4499	0.252	0	1	1	1	2	2
65.0964	0.252	0	1	1	1	2	2
66.7428	0.252	0	1	1	1	2	2
68.3893	0.252	0	1	1	1	2	2
70.0358	0.252	0	1	1	1	2	2
71.6823	0.252	0	1	1	1	2	2
73.3287	0.252	0	1	1	1	2	2
74.9752	0.252	0	1	1	1	2	2
76.6217	0.252	0	1	1	1	2	2
78.2682	0.252	0	1	1	1	2	2
79.9147	0.252	0	1	1	1	2	2
81.5611	0.252	0	1	1	1	2	2
83.2076	0.252	0	1	1	1	2	2
84.8541	0.252	0	1	1	1	2	2
86.5006	0.252	0	1	1	1	2	2
88.147	0.252	0	1	1	1	2	2
89.7935	0.252	0	1	1	1	2	2

z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
91.44	0.252	0	1	1	1	2	2
93.0865	0.100	0	1	1	1	3	3
94.7826	0.100	0	1	1	1	3	3
96.4787	0.100	0	1	1	1	3	3
98.1747	0.100	0	1	1	1	3	3
99.8708	0.100	0	1	1	1	3	3
101.567	0.100	0	1	1	1	3	3
103.263	0.100	0	1	1	1	3	3
104.959	0.100	0	1	1	1	3	3
106.655	0.100	0	1	1	1	3	3
108.351	0.100	0	1	1	1	3	3
110.047	0.100	0	1	1	1	3	3
111.743	0.100	0	1	1	1	3	3
113.44	0.100	0	1	1	1	3	3
115.136	0.100	0	1	1	1	3	3
116.832	0.100	0	1	1	1	3	3
118.528	0.100	0	1	1	1	3	3
120.224	0.100	0	1	1	1	3	3
121.92	0.100	0	1	1	1	3	3
123.616	0.045	0	1	1	1	4	4
126.019	0.045	0	1	1	1	4	4
128.224	0.045	0	1	1	1	4	4
130.246	0.045	0	1	1	1	4	4
132.102	0.045	0	1	1	1	4	4
133.804	0.045	0	1	1	1	4	4
135.366	0.045	0	1	1	1	4	4
136.798	0.045	0	1	1	1	4	4
138.113	0.045	0	1	1	1	4	4
139.319	0.045	0	1	1	1	4	4
140.425	0.045	0	1	1	1	4	4
141.44	0.045	0	1	1	1	4	4
142.372	0.045	0	1	1	1	4	4
143.226	0.045	0	1	1	1	4	4
144.01	0.045	0	1	1	1	4	4
144.729	0.045	0	1	1	1	4	4
145.389	0.045	0	1	1	1	4	4
145.994	0.045	0	1	1	1	4	4
146.549	0.045	0	1	1	1	4	4
147.059	0.045	0	1	1	1	4	4
147.526	0.045	0	1	1	1	4	4
147.955	0.045	0	1	1	1	4	4
148.348	0.045	0	1	1	1	4	4
148.709	0.045	0	1	1	1	4	4
149.04	0.045	0	1	1	1	4	4
149.344	0.045	0	1	1	1	4	4
149.622	0.045	0	1	1	1	4	4
149.878	0.045	0	1	1	1	4	4
150.113	0.045	0	1	1	1	4	4
150.328	0.045	0	1	1	1	4	4
150.525	0.045	0	1	1	1	4	4
150.706	0.045	0	1	1	1	4	4
150.872	0.045	0	1	1	1	4	4
151.025	0.045	0	1	1	1	4	4
151.165	0.045	0	1	1	1	4	4
151.293	0.045	0	1	1	1	4	4

z[cm]	theta	Root[1/cm]	Axz	Bxz	Dxz	Mat	Layer
151.411	0.045	0	1	1	1	4	4
151.519	0.045	0	1	1	1	4	4
151.618	0.045	0	1	1	1	4	4
151.709	0.045	0	1	1	1	4	4
151.792	0.045	0	1	1	1	4	4
151.869	0.045	0	1	1	1	4	4
151.939	0.045	0	1	1	1	4	4
152.003	0.045	0	1	1	1	4	4
152.062	0.045	0	1	1	1	4	4
152.116	0.045	0	1	1	1	4	4
152.166	0.045	0	1	1	1	4	4
152.212	0.045	0	1	1	1	4	4
152.254	0.045	0	1	1	1	4	4
152.292	0.045	0	1	1	1	4	4
152.327	0.045	0	1	1	1	4	4
152.36	0.045	0	1	1	1	4	4
152.389	0.045	0	1	1	1	4	4

Appendix C. HYDRUS-1D Output

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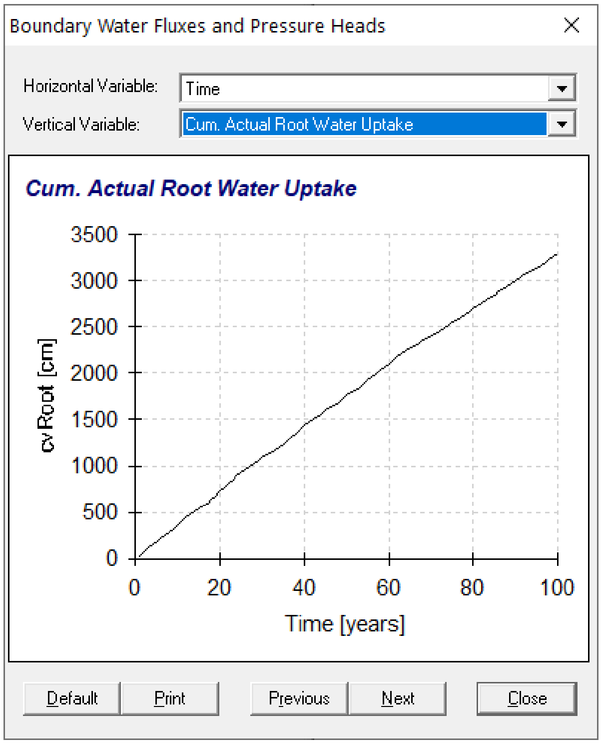
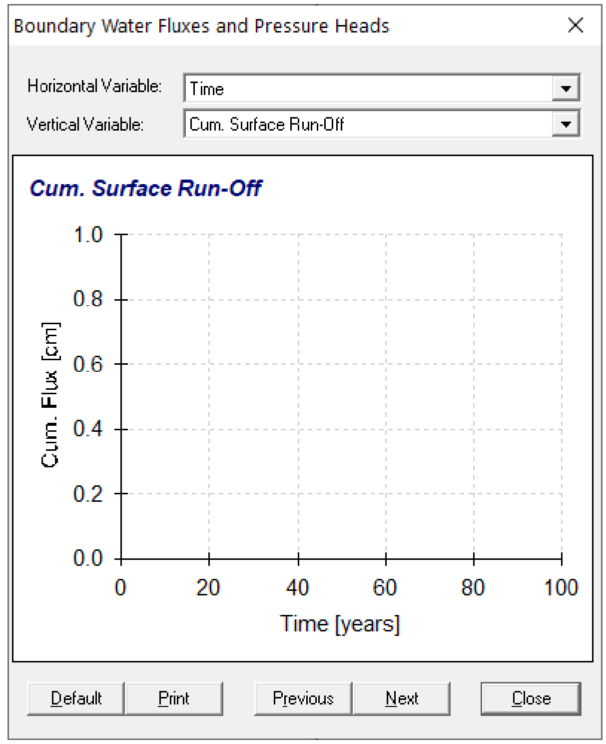
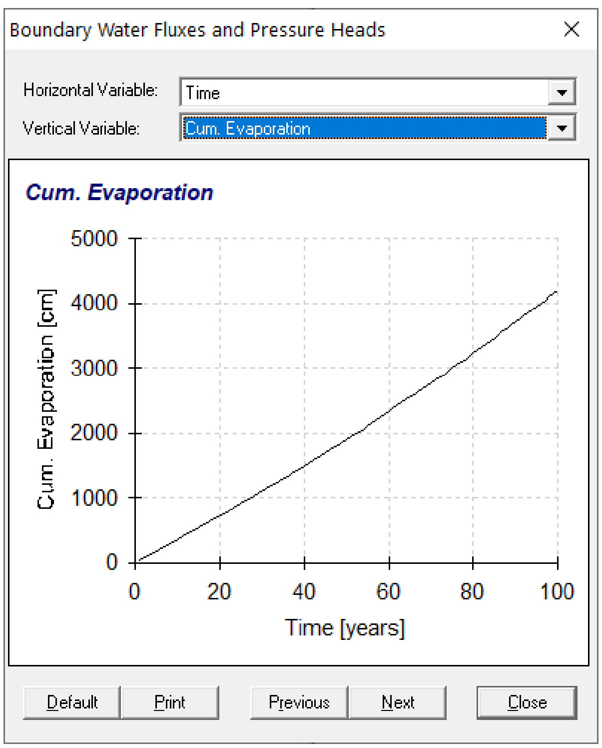
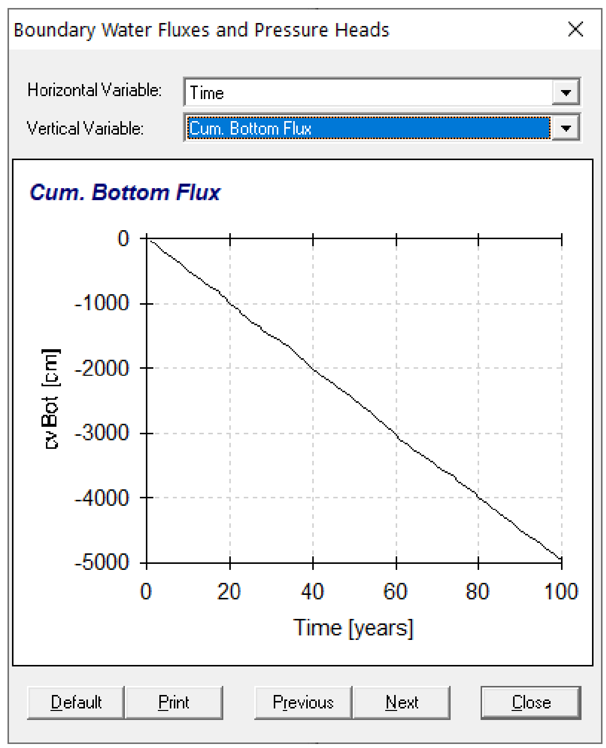
Case 3-1a – Operational Soil Cover (Annual Weather Data)



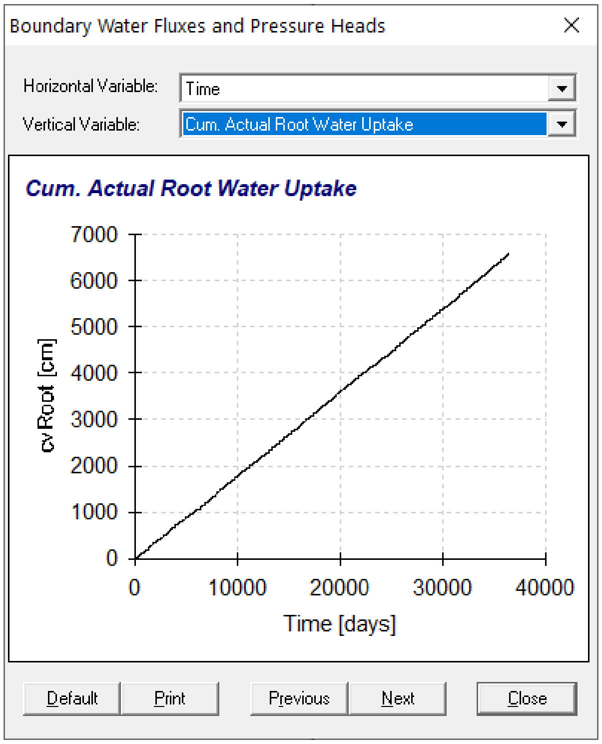


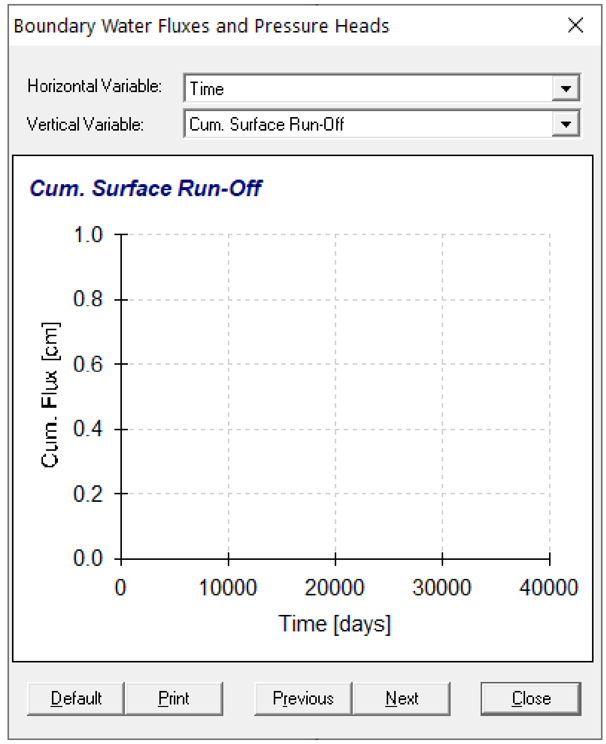


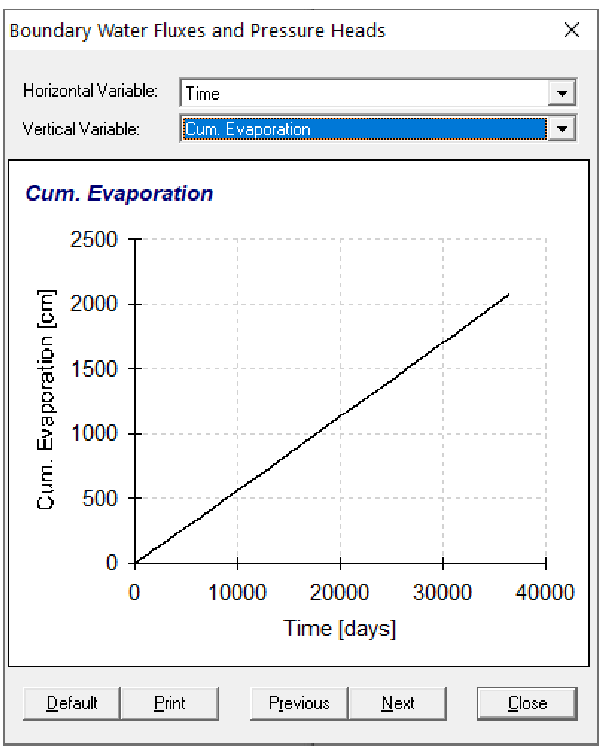


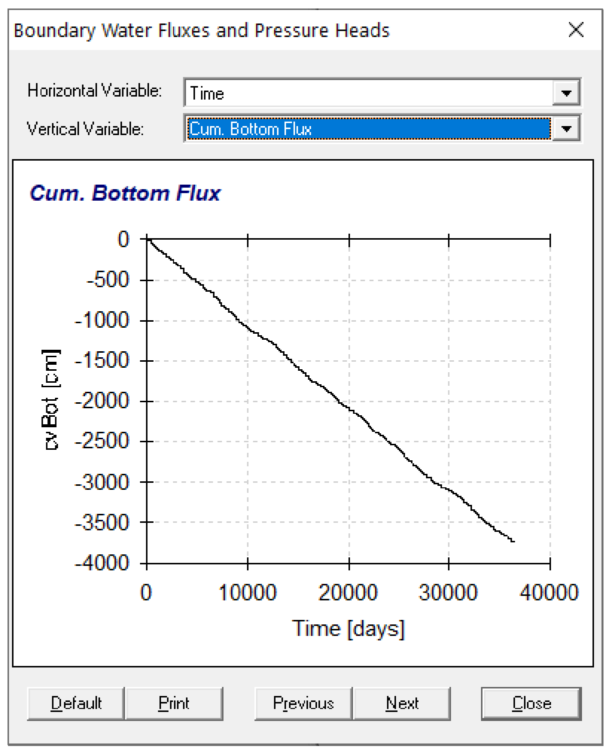
[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Case 3-1b – Operational Soil Cover (Daily Weather Data)



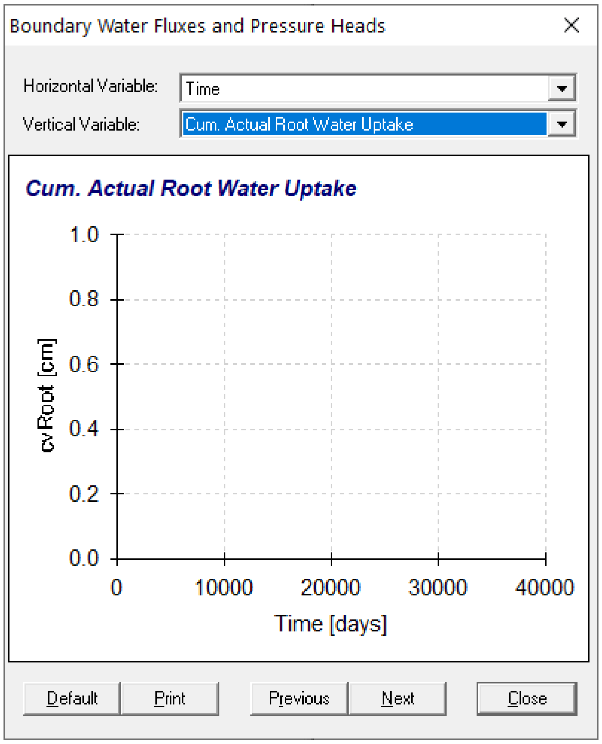


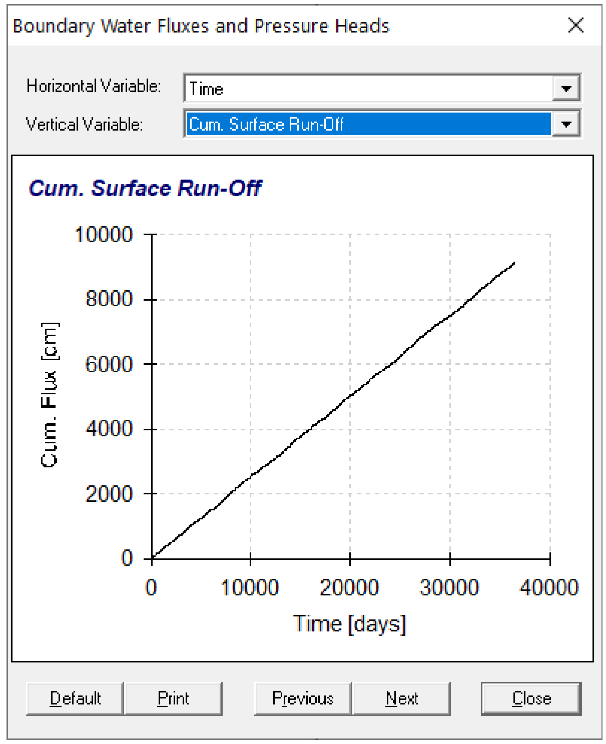


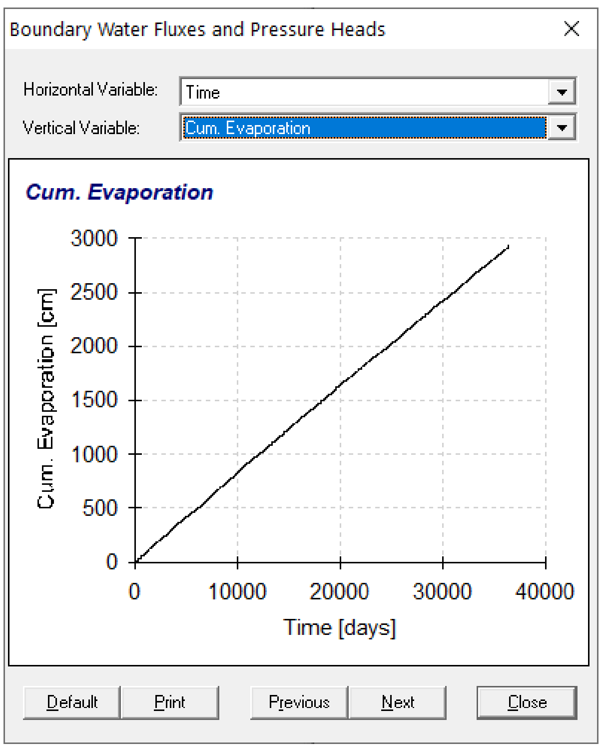


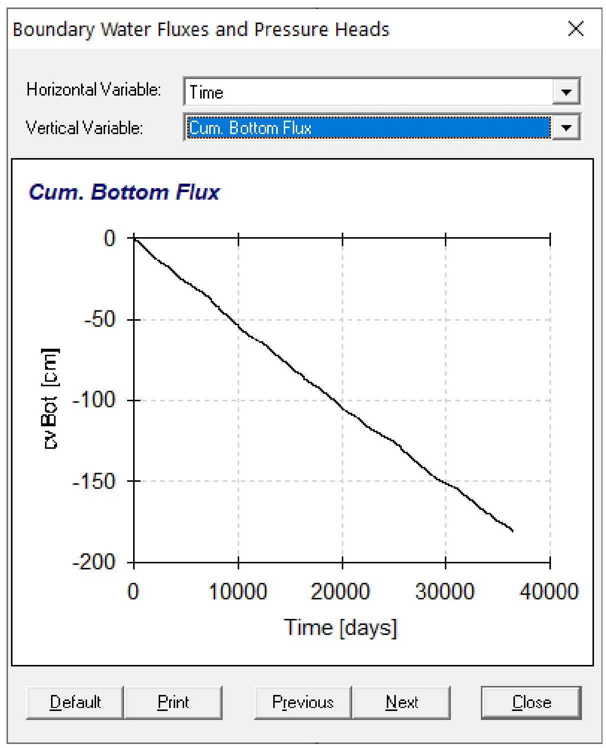
[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Case 3-2a – Institutional Control ($K_{sat\ HDPE}$ = 5.0E-08 cm/sec)



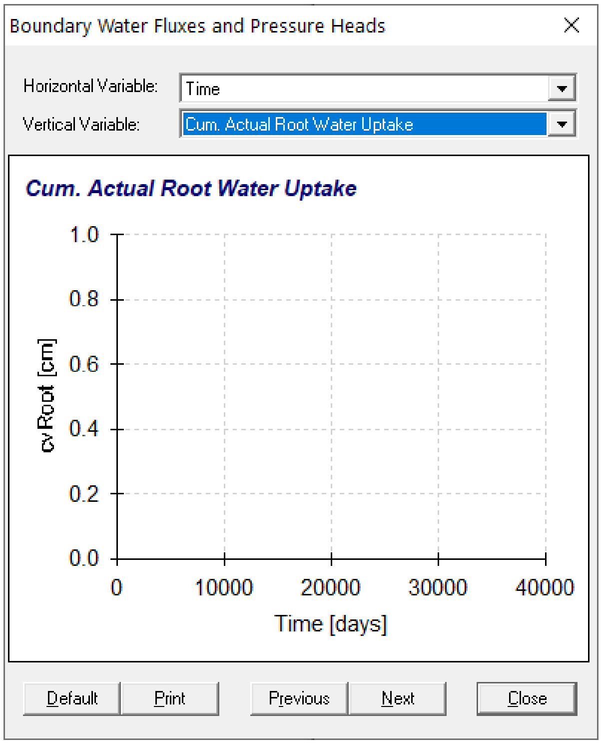


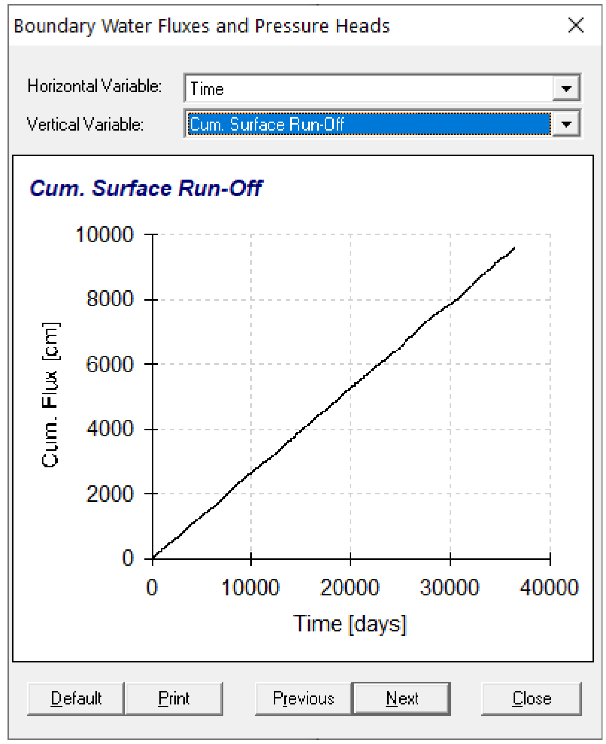


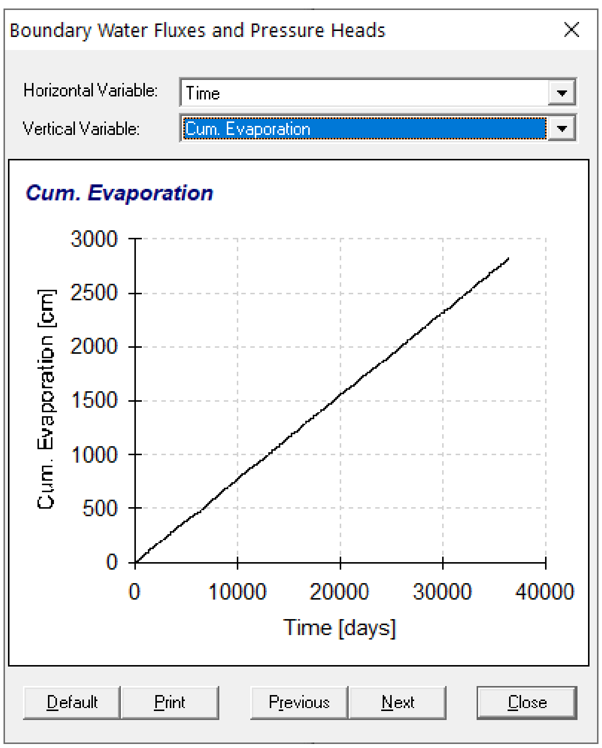


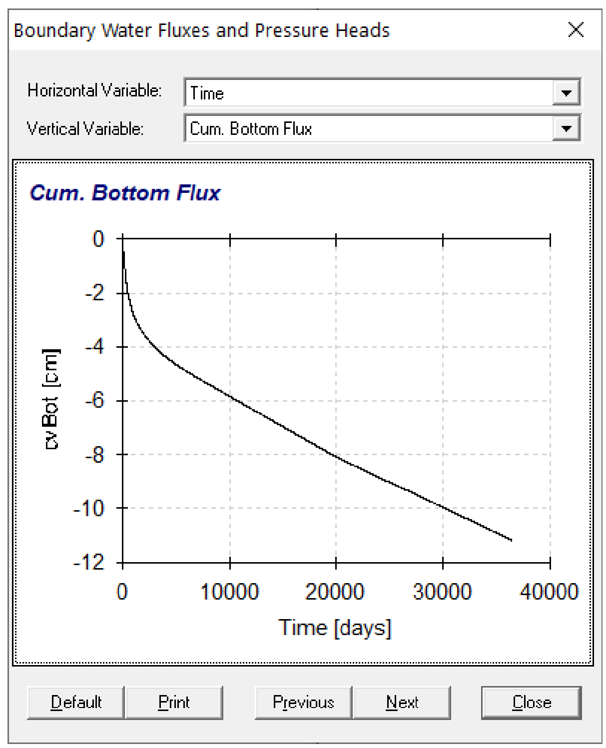
[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Case 3-2b – Institutional Control ($K_{sat\ HDPE}$ = 1.0E-09 cm/sec)



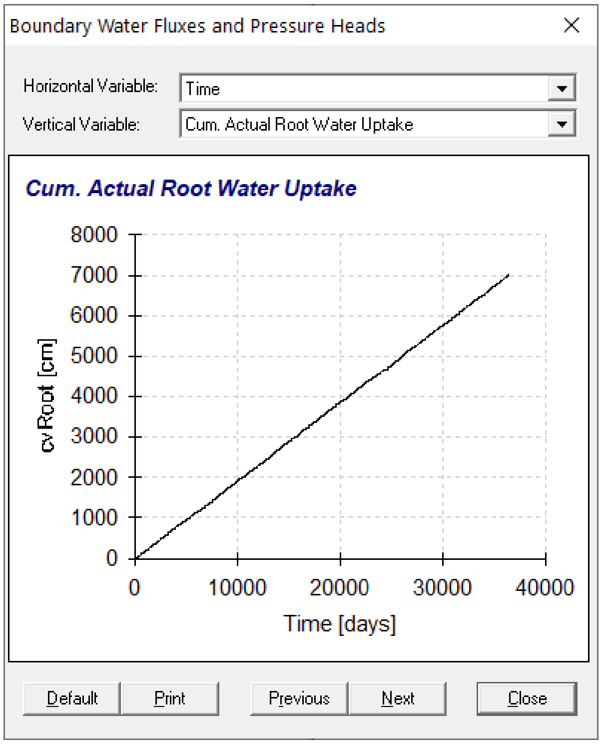


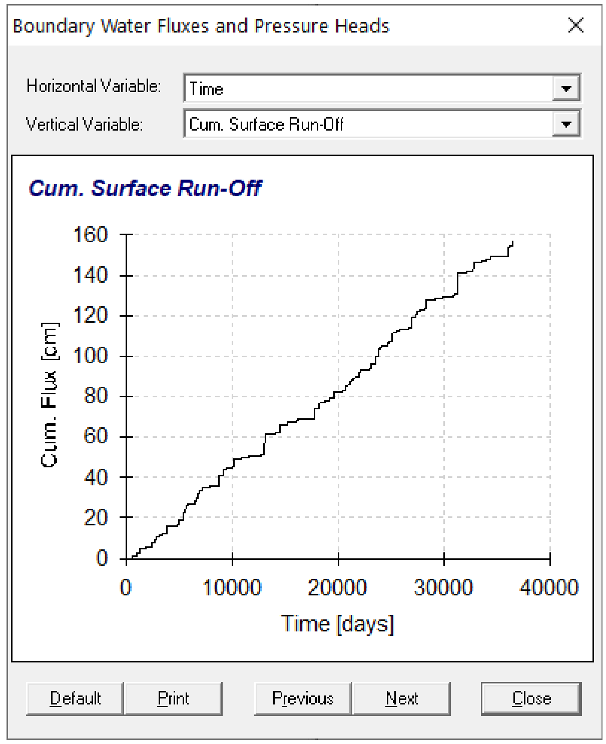


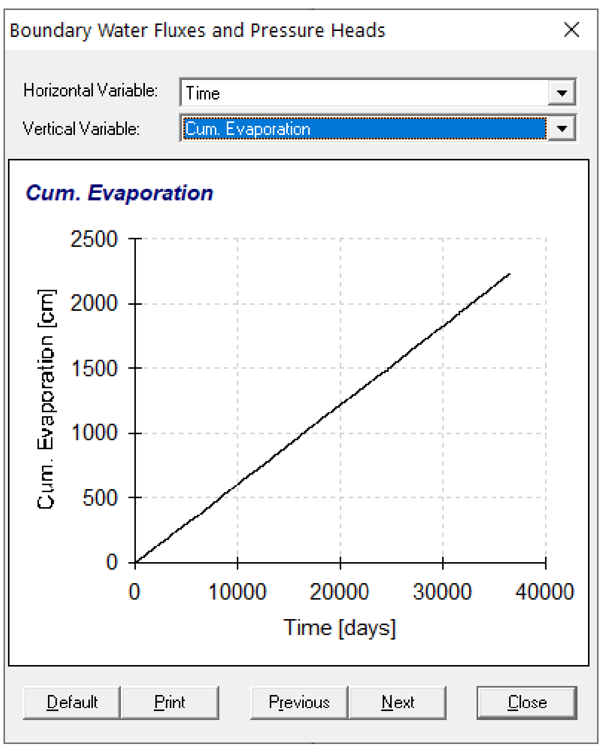


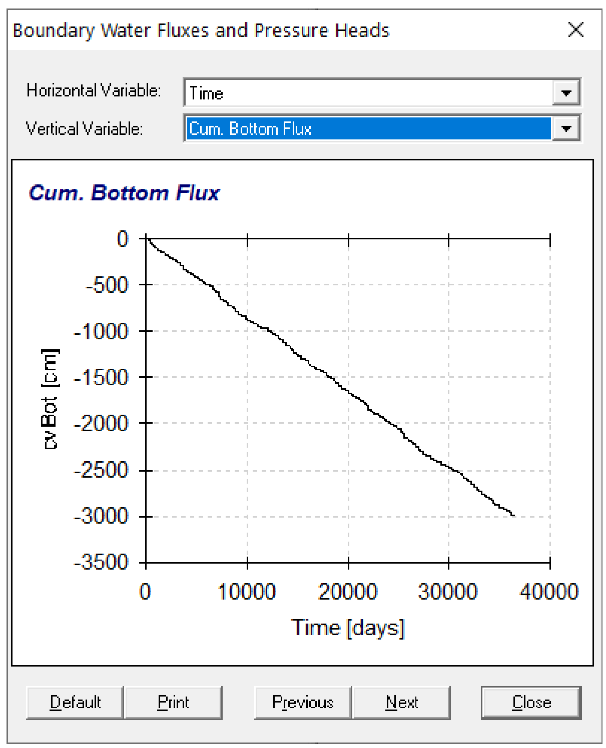
[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Case 3-3 – Upper Three Layers of Intact Multilayer Cover



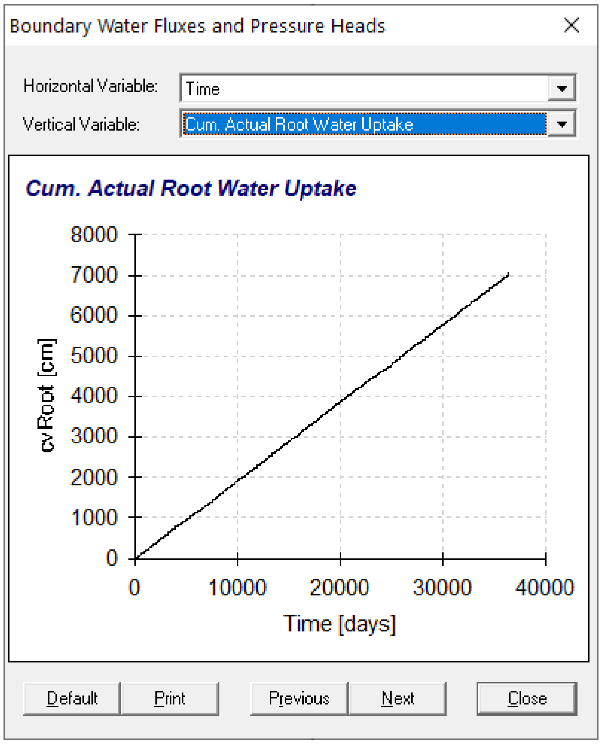


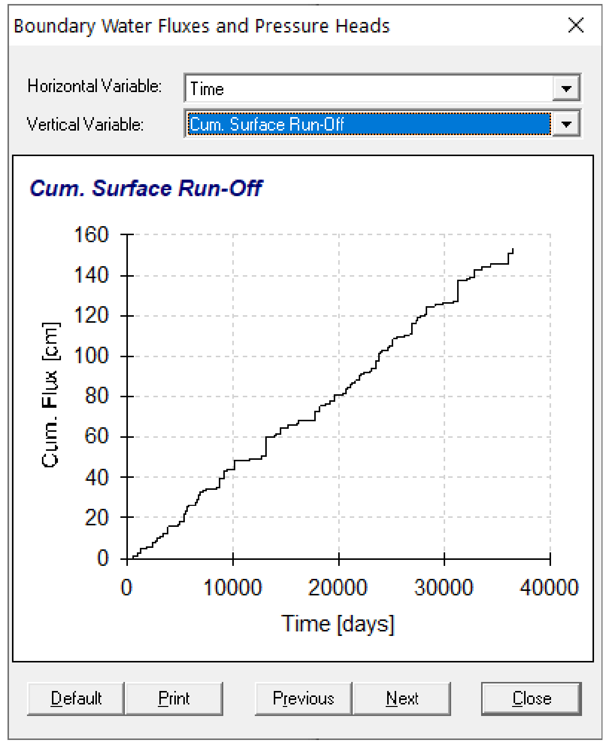


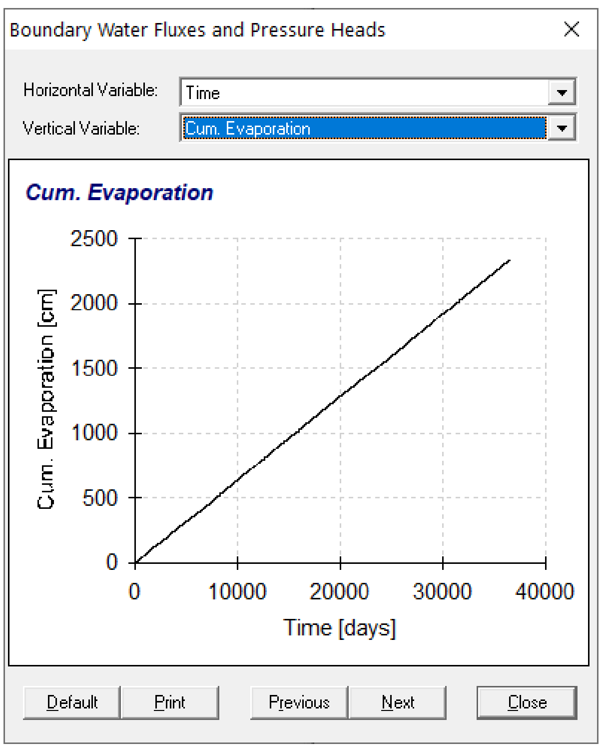


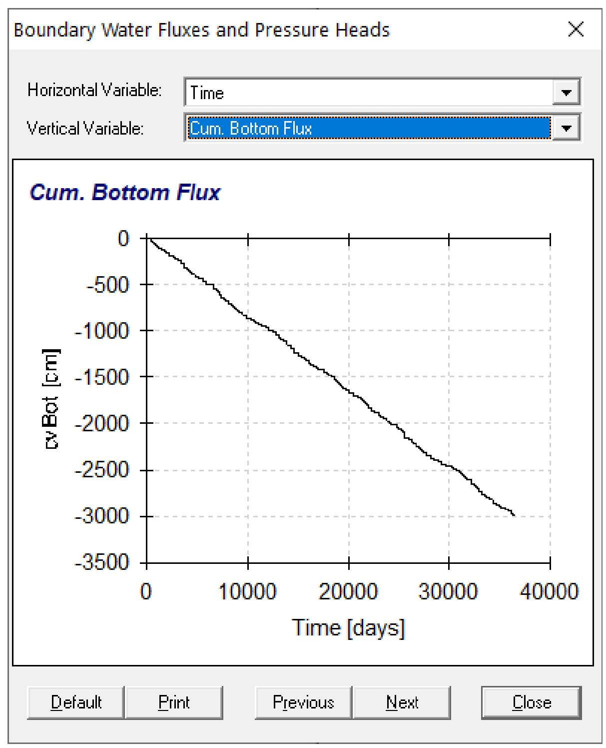
[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Case 3-4 – Upper Four Layers of Intact Multilayer Cover









[a] Inches/year = Cumulative [cm] / 100 years / 2.54 cm/inch
[b] Cum. Precipitation = Cum. Root Water Uptake + Cum. Evaporation + Cum. Surface Run-Off + Cum. Bottom Flux
[c] Cum. Bottom Flux ≡ Cum. Percolation Rate
[d] Cum. Evaporation ≡ Cum. Evapotranspiration

Appendix D. HELP Model Input Parameters for Slit-and-Engineered-Trench Cases used in HYDRUS-1D Comparisons

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Table D-1. HELP Model Input Data for Case 3-1 – Operational Soil Cover (ST_OpCover.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.0689 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	**CN Input Parameter Value**
Slope =	1 %
Slope length =	80 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 53.06	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	48		0.396	0.109	0.047	0.109

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)

Table D-2. HELP Model Input Data for Case 3-2 – Institutional Control (ST_IC.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.0689 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
GCL	2	4 (geomembrane liner)
Topsoil	3	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	0.0001		0.396	0.109	0.047	0.109
2	4	0.06		0.75	0.747	0.4	0.75
3	1	48		0.396	0.109	0.047	0.109

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.0E-03					
2	4	5.0E-08					
3	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
2	4	1	4	3	

Table D-3. HELP Model Input Data for Case 3-3 – Upper Three Layers at Time of Cap Installation (ST3L00.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	6		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)

Table D-4. HELP Model Input Data for Case 3-4 – Upper Four Layers at Time of Cap Installation (ST4L00.D10).

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	2 %
Slope length =	585 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 46.2	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer	4	2 (lateral drainage layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	6		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	12		0.417	0.045	0.018	0.045

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	5.0E-02	585	2			

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)

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Distribution:

timothy.brown@srnl.doe.gov
alex.cozzi@srnl.doe.gov
david.crowley@srnl.doe.gov
c.diprete@srnl.doe.gov
a.fellinger@srnl.doe.gov
samuel.fink@srnl.doe.gov
connie.herman@srnl.doe.gov
patricia.lee@srnl.doe.gov
Joseph.Manna@srnl.doe.gov
john.mayer@srnl.doe.gov
daniel.mccabe@srnl.doe.gov
Gregg.Morgan@srnl.doe.gov
frank.pennebaker@srnl.doe.gov
Amy.Ramsey@srnl.doe.gov
William.Ramsey@SRNL.DOE.gov
michael.stone@srnl.doe.gov
Boyd.Wiedenman@srnl.doe.gov
bill.wilmarth@srnl.doe.gov
sebastian.aleman@srnl.doe.gov
paul.andrews@srs.gov
dan.burns@srs.gov
tom.butcher@srnl.doe.gov
kerri.crawford@srs.gov
Thomas.Danielson@srnl.doe.gov
kenneth.dixon@srnl.doe.gov
James.Dyer@srnl.doe.gov
peter.fairchild@srs.gov
luther.hamm@srnl.doe.gov
thong.hang@srnl.doe.gov
tim.jannik@srnl.doe.gov
daniel.kaplan@srnl.doe.gov
steven.mentrup@srs.gov
verne.mooneyhan@srs.gov
ralph.nichols@srnl.doe.gov
Virgina.Rigsby@srs.gov
Jansen.Simmons@srs.gov
Frank.Smith@srnl.doe.gov
Brooke.Stagich@srnl.doe.gov
Ira.Stewart@srs.gov
Tad.Whiteside@srnl.doe.gov
Jennifer.Wohlwend@srnl.doe.gov
Records Administration (EDWS)