Proceedings of the Seventeenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 6, Paper 12.4
Civil-Comp Press, Edinburgh, United Kingdom, 2023
doi: 10.4203/ccc.6.12.4

Simulation of Water Flux in an Unsaturated Soil in Boda Village, Hungary

Y. Abduljaleel[1], M. Mihoub[2], Z.F. Ali[2], A. Salem[2,3], M. Amiri[4] and A. Awad[5]

**[1]Department of Civil and Environmental Engineering,
Washington State University, USA
[2]Doctoral School of Earth Sciences, University of Pécs, Hungary
[3]Civil Engineering Department, Faculty of Engineering,
Minia University, Egypt
[4]Geomatics and soil management laboratory,
Faculty of Arts and Humanities,
Université Mohammed Premier Oujda, Morocco
[5]Ministry of Water Resources and Irrigation (MWRI), Giza, Egypt**

Abstract

During the last several decades, the study of the movement of water and solutes in the unsaturated zone has become an issue of great significance due to the profound effects of the physical and chemical processes. In this study, a general methodology has been developed to evaluate the effect of soil water, and temporal variability in precipitation and evaporation on the transport of water and solutes in soils by analyzing 20 soil samples. The analyses were conducted using measurements of precipitation, pressure head, and water content data from the period of 2016-2017 in Boda village, Southwestern Hungary. The HYDRUS program was used to analyze and simulate the data for a period of 225 days. In each location, 4 different soil profiles were chosen (10cm, 25cm, 50cm, and 115cm). The results of the analyses with the help of the measured precipitation, and water content input datum shows that during the study period, the water content of the soil is progressively distributed down from the surface to the bottom, especially in the period of the winter, it gives an overview for getting the proper time for the water supply to the crops.

Keywords: soil water, Boda village, water flux, unsaturated zone, simulation, HYDRUS.

1 Introduction

Most of the processes involving soil-water interactions in the field occur while the soil is in an unsaturated condition, including the supply of moisture and nutrients to plant roots as well as the transport of water and solutes beyond the root zone. Unsaturated flow processes are in general complex and difficult to describe quantitatively since they often entail changes in the state and content of soil water during flow. Such changes involve complex relations among such variables as soil wetness, suction, and conductivity, whose inter-relations are further complicated by hysteresis as well as by spatial variability [1]. In an unsaturated soil, the water phase is bounded partially by solid surface and partially by an interface with the air phase [2,3]. The importance of the unsaturated zone as an integral part of the hydrological cycle has long been recognized. The vadose zone plays an inextricable role in many aspects of hydrology, including infiltration, soil moisture storage, evaporation, plant water uptake, groundwater recharge, runoff and erosion. Initial studies of the unsaturated (vadose) zone focused primarily on water supply studies [4].

In this study, the HYDRUS program is utilized as a tool to simulate water flux in unsaturated soil and solute movement in the vadose zone to develop an understanding of the downward movement of water and solutes under variable boundary conditions. The main aim of this work is to shed light upon moisture dynamics in the vadose zone in Boda village, Hungary. More specific objectives were set to achieve this goal, amongst which examination of temporal variability in precipitation, evapotranspiration, infiltration, and implications of rainfall patterns on the downward movement of water in different depths of the soil, in addition to modeling water flow in unsaturated soils, using HYDRUS program.

2 Materials and Methods

The study site covers a land area of 4 hectares located in longitude of 18°13′59″E and latitude of 46°04′59″N in Boda village in Baranya County, on the southern foothills of the SW part of Mecsek Hills in SW Hungary (Figure 1), with 15.42 km^2 area, elevation between 171.85 and 182.76 meters and maximum slope of 5.41% on the southern, south-western steep. The data was collected from the middle of July 2016 to the middle of Mars March 2017. The long-term average annual precipitation total is 700 mm.

Figure 1: Location of the study site.

Soil samples were gathered from 20 sites within the area. The samples were taken from selected localities in the plot from four sampling depths (0-10 cm, 10-25 cm, 25-50 cm, and 50-115 cm) for the determination of soil properties and to obtain retention curves of soil (Figure 2). The study was performed on two types of soil in accordance with the textural triangle, which determines the percentage of each fraction (% sand, % silt, and % clay particles), While the saturated water content 'θs' was measured, the remaining parameters of the soil water retention curve were optimized using the RETC software by fitting measured data which are water content, water potential, and climatic data.

The HYDRUS model was used with the data collected from the plots. The program offers graphs of the distributions of the pressure head, water content, water and solute fluxes, and temperature at preselected depths. Also included is a small catalog of unsaturated soil hydraulic properties [5]. It can be used to simulate such processes as precipitation, infiltration, evaporation, transpiration, soil water storage, capillary rise; deep drainage, and groundwater recharge [6].

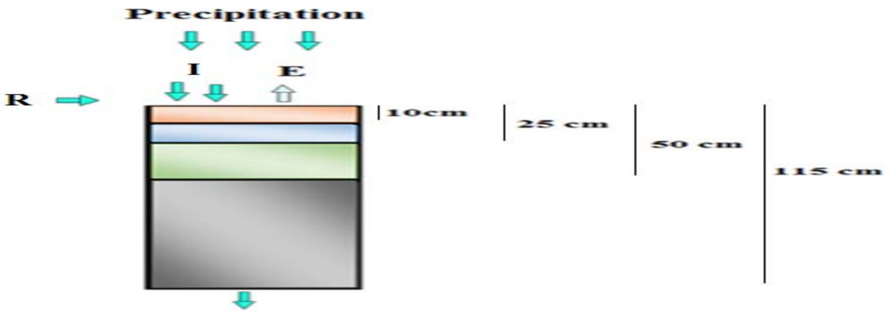

Figure 2: Cross-Sections of the Soil layers.

2.1 Water flow in the unsaturated zone

Water flow in the vadose zone is usually described by integrating the equation of continuity (1) and Darcy– Buckingham equation (2) [7], it is expressed as follows:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_i}{\partial z_i} - S \tag{1}$$

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

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

$$Q = -KA\frac{h_2 - h_1}{\Delta L} \tag{2}$$

where K is hydraulic conductivity, [LT^{-1}].

Firstly, Darcy's law was implemented to the partially saturated flow by Buckingham [8] and he found that in this case, the hydraulic conductivity is a function of water content K= K(θ). This means that a small decrease in θ leads to a significant decrease in K [9]. Darcy's law was developed for an unsaturated medium:

$$q = - K(\theta)\frac{\partial h}{\partial z} \tag{3}$$

Where h is the hydraulic head and defined as:

$$h = H(\theta) - z \tag{4}$$

A combination of equations (3) and (1) and is called Richards' equation and it describes the vertical downward movement of water in an unsaturated zone:

$$\partial\theta / \partial t = \partial / \partial z \, [K(\theta) \, ((\partial H / \partial z) - 1)] - S \tag{5}$$

Where H is the soil water pressure head relative to atmospheric pressure ($H \leq 0$). Richards' equation is partially differential and highly non-linear as θ-H-K has a non-linear relationship in nature, which also indicates its strongly physically based origin. Moreover, boundary conditions at a soil surface are changing irregularly. If relationships between θ-H-K are known, numerical solutions may solve the equation for various top boundary conditions [10].

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} - \cos\alpha\right)\right] - S \tag{6}$$

where H is the water pressure head [L], α is the angle between the flow direction and the vertical axis, and K is the unsaturated hydraulic conductivity (Simunek et al2005).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} - \cos\alpha\right)\right] - S \tag{7}$$

The hydraulic function of van Genuchten [11] for Soil Water Retention Curve (SWRC) and the hydraulic conductivity function of Mualem [11,12] were used in this study and described as:

$$Se(h) = \theta(h) - \theta r / \theta s - \theta r = (1 + \alpha |h| n) - m \tag{8}$$

2.2 Meteorological parameters

Meteorological parameters: Using the HYDRUS 1D and the data gathered off the site of the Institute of Geography and Earth Sciences, University of Pécs, the following figures were given to illustrate the different parameters that influence the soil. The research data was obtained through the university site, mostly daily such as precipitation, wind speed, sunshine, humidity, and the maximum and minimum temperature that were further used to calculate more meteorological parameters through their simulation. Investigation of water transport was done for different climatic conditions and soils with different physical properties. Using the time series of meteorological parameters in the period of 225 days permits us to give a view of its influence on the water flux in the vadose zone.

3 Results and discussions

The stimulation of the program gives each proponent in a separate graph as follows: The precipitation is the most important parameter that influences water flow in the soil. Potential evapotranspiration is the total amount of water that can evaporate and transpire by the plants on a given surface [13]. It is given by the FAO-Penman–Monteith method as follows:

$$ET_o=0.408\ \Delta(R_n-G)+\gamma 900T+273u_2(e_s-e_a)\ /\ \Delta+\gamma\ (1+0.34u_2) \tag{9}$$

where: ET_o is crop reference ET (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s-e_a is saturation vapor pressure deficit (kPa), Δ is slope vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). The daily distribution of precipitation and potential evapotranspiration during the period of 225 are presented in Figure 3.

a) b)

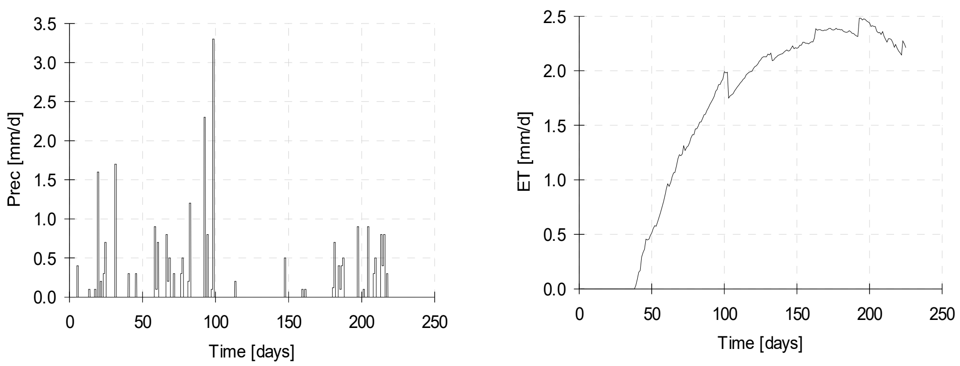

Figure 3: a) Daily Precipitation b) Potential evapotranspiration of 2016-2017.

An important function of soil is to absorb water at the ground surface, and either store it for use by plants or slowly release it to groundwater through gravitational flow. The simulated infiltration and runoff illustrate the amount of water either penetrating the soil or flowing on the surface (Figure 4).

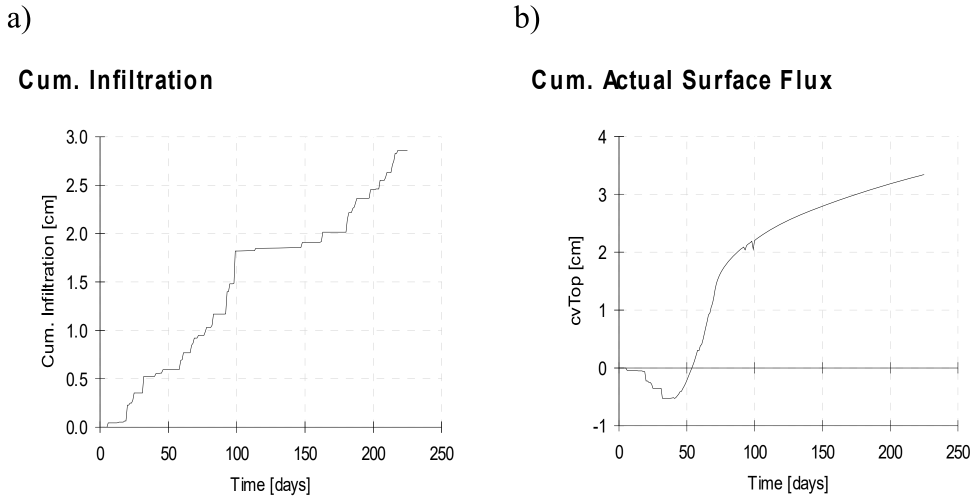

Figure 4: a) Infiltration and b) Runoff (2016-2017).

3.1 Soil properties and unsaturated water flow

The vadose zone is bounded by the soil surface and joins with groundwater in the capillary fringe. The main forces which are responsible for holding water in soil are capillary and adsorptive forces. Hydraulic conductivity is the essential parameter that influences the movement of fluid in the soil profile, where water moves either due to gravity or capillary forces. Using the HYDRUS 1D the soil profile at different depths is characterized by various hydraulic conductivity (Figure 5), where the 25cm depth is the most conductive layer which indicates that the second layer is the wettest layer in comparison to the other layers.

As it is presented in Figure 6, the results Cum. Potential Surface Flux and Cum. Bottom Flux are opposite to each other in the first two depths 10 cm and 25 cm, whereas Soil Water Storage is entirely related to the rate of rainfall upon the study site.

The results of Cum. Potential Surface Flux and Cum. Bottom Flux in the two next depths 50 cm and 115 cm are different from the former ones, in that the surface flux progressively is increasing from 0 cm/day until it reaches 200cm/day, on the other hand, it is decreasing from approximately 20 cm/days to 150 cm/ day. The Soil Water Storage is also related to the rate of rainfall thus it is fluctuational (Figure 7).

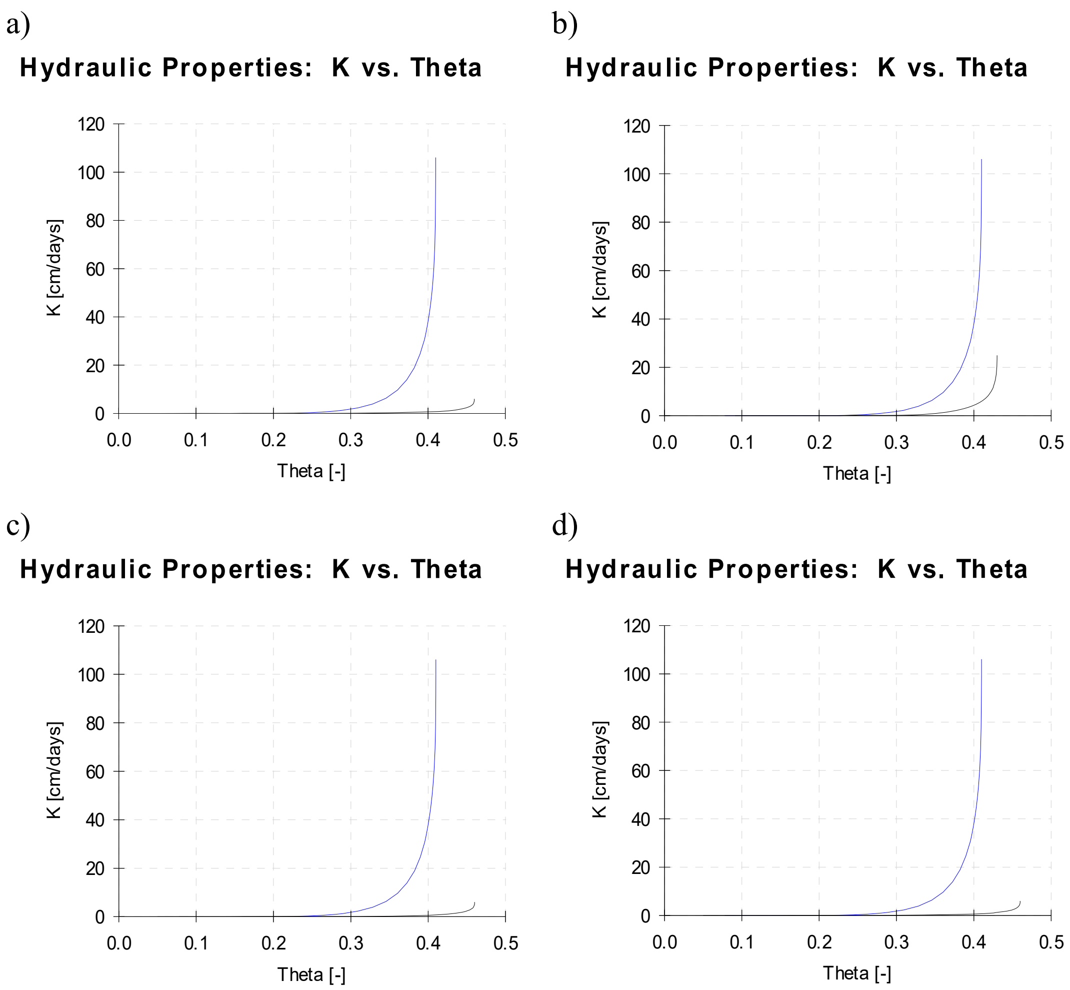

Figure 5: Hydraulic properties K vs Theta for different depths at a) 10, b) 25, c) 50, and d) 115 cm.

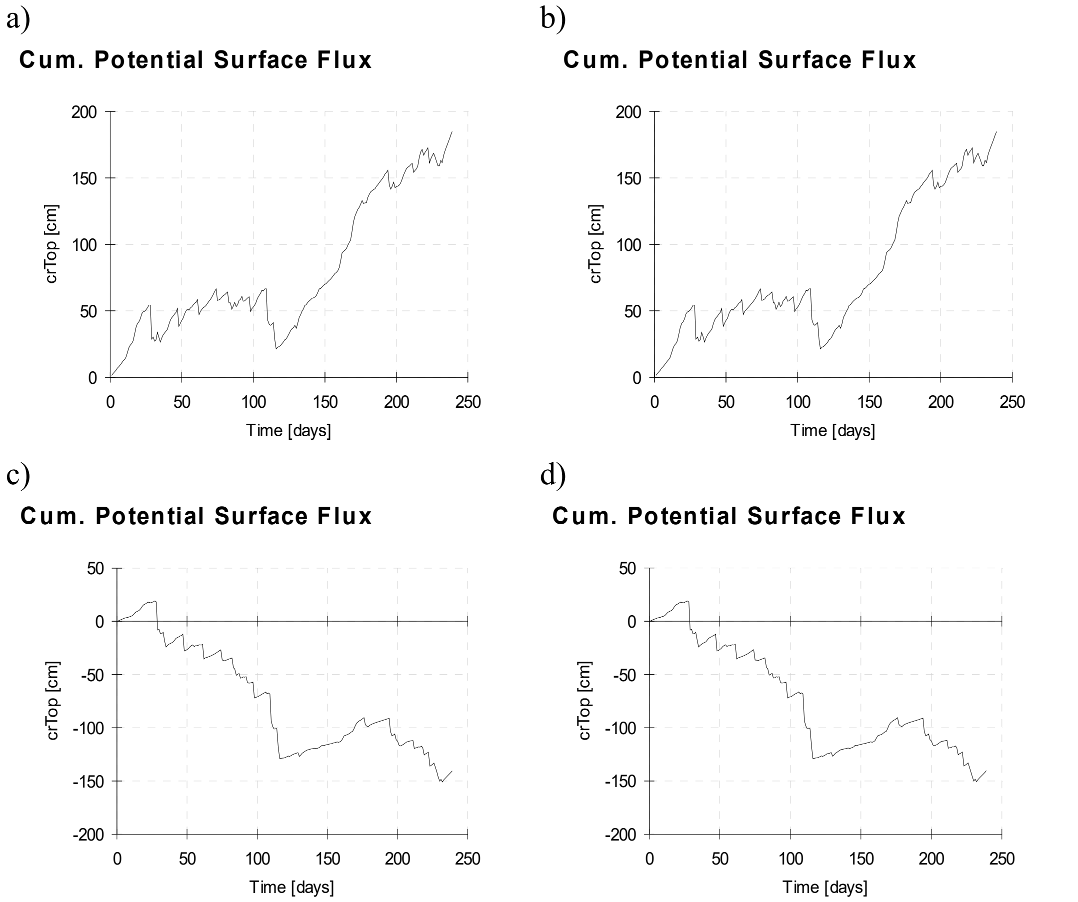

Figure 6: Cum. Potential Surface Flux for different depths at a) 10, b) 25, c) 50, and d) 115 cm.

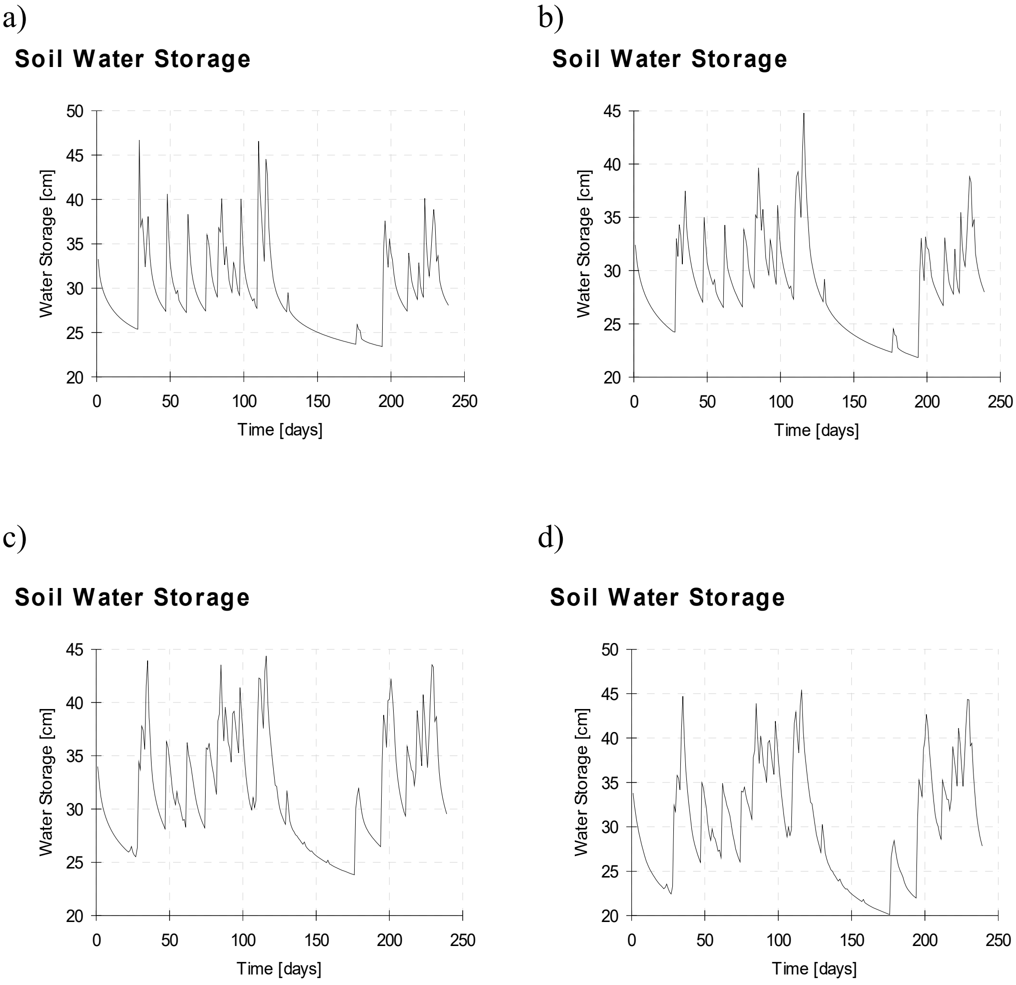

Figure 7: Soil water storage for different depths at a) 10, b) 25, c) 50, and d) 115 cm.

3.2 Water flow using HYDRUS 2D

In this study water flow was simulated using the HYDRUS 2D/3D, a software program capable of simulating water, solute, and heat flow in variable saturated porous media, and was chosen for this study for its ability to represent the unsaturated zone. The program was numerically solving Richard's equation for saturated-unsaturated flow in two dimensions. The HYDRUS-2D model can solve non-uniform and anisotropic flow domains, delineated by irregular boundaries. The model can handle atmospheric boundary conditions given by meteorological values at time intervals, where the model calculates the actual evapotranspiration taking into account the prevailing root zone soil moisture conditions.

The size of the model domain for both sites was 200 cm in width and 150 cm in depth. The time simulation period was 225 days, with the help of site measurements (Precipitation, water content…..etc), calculation of the evapotranspiration using the FAO-Penman–Monteith method, van Genuchten-Mualem model, RETC values, -Boundaries condition (atmospheric condition in the top free seepage in the bottom), materials distribution of soil. The developed second-dimension model illustrates the dynamic of water in an unsaturated soil in the study site.

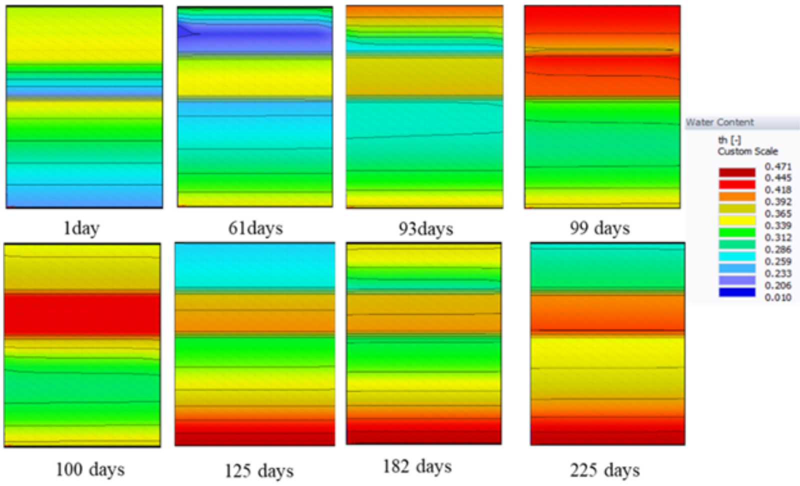

Figure 8: Water distribution in study samples at different times.

Figure 8 illustrates the distribution of the water below the study samples in a period of 225cm through 115 cm depth. The chosen days show the most effective pictures that best illustrate the dynamics of water, where the lowest degree of wetness is expressed with blue color and the highest degree of wetness is expressed with red color. The period of the end of summer and the beginning of autumn (July, August, and September) is represented in the simulation from 1 to 61 days where we can see that the moisture is low at the bottom and higher at the surface, it is progressively getting higher at the bottom due to the dynamic of water movement in the soil. Later on from the 93 to the 99 days, the moisture is at the top of the chart due to rainfall events in the month of autumn and progressively it is observed that the moisture is penetrating the soil profile until it reaches greater depths. Rainfall events occur repetitively in the winter period which is represented from the 125 days to the end of the study period, thus more penetration of water moisture will be present in the soil.

4 Conclusions and Contributions

Soil water content plays a key role in planning and carrying out field operations, obtaining field information on soil water content to determine soil water management systems can take a long period. Several measurement techniques for soil water content measurement in the field are available. Modeling field hydrological processes is vital for improving soil water dynamics for field operations. The HYDRUS (2D/3D) model was used to simulate water flow through a study site surface of silty and silty loam soil. The ability of the model to account for root water uptake was also used to better show the water dynamics in the simulation exercise. The evapotranspiration was calculated through the Thornthwaite formula (ETP = 16 (10t/I)a.k) and the values were set as an input in the HYDRUS (2D/3D) mode. The model was used to simulate water flow through a 2-D model domain of 200 cm width × 115 cm depth. The results show that the maximum water penetration depth at the end of the simulation period was high in comparison to the beginning of the period due to rainfall events accruing through the duration of the study which is 225 days. Moreover, seasonal timing plays an extremely important role in determining water dynamics and soil properties. The hydraulic conductivity is mostly high beneath the surface layer with the soil characteristics below the landfill having a great impact on it.

References

[1] D. Hillel, "Introduction to Soil Physics", Elsevier Science, 2013.

[2] Q. Wang, S. Wang, W. Su, W. et al. "Interpretation of grouting characteristics in unsaturated sand from the perspective of water–air interface", Acta Geotech. 17, 2943–2954, 2022. https://doi.org/10.1007/s11440-021-01375-7

[3] W.A. Jury, R. Horton, "Soil Physics", Wiley, 2004.

[4] J.Šimůnek, M. Šejna, H., Saito, M., Sakai, M. TH. van Genuchten, "The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media", Version 4.17, HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 2013.

[5] R.F. Carsel, R.S. Parrish, "Developing joint probability distributions of soil water retention characteristics", Water Resour. Res. 24 755–769, 1988. https://doi.org/10.1029/WR024i005p00755

[6] J. Simunek, M.Th. van Genuchten, M. Sejna,"Hydrus: model use, calibration and validation.Transactions of the ASAE. American Society of Agricultural Engineers", 55, 1261-1274, 2012.

[7] A. Saifadeen, R. Gladnyeva, "Modeling of solute transport in the unsaturated zone using HYDRUS-1D", TVVR 12/5020, Water Resources Engineering, Lund University, Sweden, 2012.

[8] E. Buckingham, "Studies on the movement of soil moisture", Bull. 38. USDA, Bureau of Soils, Washington D.C, 1907.

[9] W. Brutsaert, “Hydrology: An Introduction", Cambridge University Press, 2005.

[10] J. C.van Dam, G. H. de Rooij, M. Heinein, F. Stagnitti, "Concepts and dimensionality in modeling unsaturated water flow and solute transport. Unsaturated Zone modelling: Progress, Challenges and Applications", Frontis Ser., vol 6., edited by Feddes R. A., Fooji G. H. et van Dam J. C., 1-36. Springer, New York, 2004.

[11] M.T. van Genuchten, "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils", Soil Sci. Soc. Am. J. 44 (5), 892–898, 1980.

[12] Y. Mualem, "A new model for predicting the hydraulic conductivity of unsaturated porous media", Water Resources Research 12, 513–522, 1976.
[13] R.G. Allen, L.S. Pereira, D. Raes, M. Smith, "Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage", paper 56. FAO, Rome, 1998.