Proc. 3rd International Conference on Advancements in Engineering Education (iCAEED2024)
20-23 Nov 2024, Sydney, Australia
ISBN: 978-1-7636843-3-1

Groundwater engineering education: an application of HYDRUS 1D modelling to study groundwater flow and solute transport in some selected locations of NSW

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Abstract

This study which is a part of groundwater engineering education investigated water and solute transport using HYDRUS 1D for unsaturated zone of three distinct geographical locations of NSW situated in the proximity of Australia's largest groundwater reservoirs. The diverse climatic conditions ranging from subtropic moderate of Albury and Singleton to semi-arid of Lightning Ridge with significant variations in the meteorological parameters were researched and analysed to simulate the solute concentration along the soil profile of 100 m considering root water uptake. The results showed variations in solute concentration peaks based on the input of rainfall suggesting that frequent rainfall reduces the concentration accumulation. These simulations thus, were useful in deducing the effect of salt accumulation on solute residence times and concentration distributions in relation to climate, temperature, soil properties, land practices and irrigation methods. It has been helpful to understand their influence on groundwater quality to make informed decisions on the use of Australia's most valuable water resource.

Keywords: Groundwater, Solute transport, HYDRUS 1D, Salinity, Concentration, Residence time.

1. INTRODUCTION

Solutes in groundwater refer to the particles present in the water because of its interaction with the natural materials such as rocks or the human induced contaminants such as fertilizers, toxic substances and inorganic chemicals released on to the topsoil of the unsaturated zone. However, some solutes that are present in the unsaturated zone potentially seep into the groundwater aquifers through advection, sorption and biological degradation contaminating the groundwater resources. As most of the pollution problems arise in unsaturated region, this region is termed as the base for capture, storage and release of contaminants and are of utmost importance in preventing groundwater pollution.

Considering the importance of groundwater management holds, solute transport modelling techniques are widely used to analyse the groundwater quality problem by speculating the distribution and concentration of solutes in the subsurface over time. HYDRUS 1D is one of the computer models that solves deterministically the modified Richards equation for groundwater flow and the convection-dispersion equation for heat and solute transport using the Galerkin finite element method (Simunek, Genuchten & Sejna 2005). This model considers a simple single porosity flow model to consider uniform flow within the permeable media, and design complicated triangular mesh grids using finite element techniques and simulate nanoparticle movement giving more optimized simulation results.

As a part of groundwater engineering education, in this study HYDRUS 1D version 4.17 has been used to understand water and solute movement in unsaturated zone in three different geographical locations of New South Wales (NSW) in Australia by investigating the effects of its land practices into groundwater salinity and solute transport by analysing the general patterns of concentration profiles along the soil depth. The major objective of this study is to understand the effect of salt accumulation in solute residence times, its reactions and concentration distributions.

2. MATERIALS AND METHODS

2.1 Theory of water flow in unsaturated zone

Richard's equation is widely used to govern the flow of water in unsaturated soils. It is a partial differential equation that considers the effect of gravity, capillary rise, and effect of hydraulic conductivity on water movement in the unsaturated region. The equation (1) is given as:

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

Where, θ= volumetric water content, K= unsaturated hydraulic conductivity, t = time, h = pressure head, S= sink term, z = depth

This equation describes how water content in the soil changes over time and location in response to pressure head changes and external disturbances. To account for water adsorption by plant roots, a sink factor is included in the flow equation which may also consider dual porosity type flow (Pachepsky, Timlin & Rawls 2003). In this study, HYDRUS 1D numerically solves the infiltration equation by modelling it as one-dimensional vertical flow. Further, the model is used to understand water behaviour in unsaturated soils using van Genuchten formula that describes the soil hydraulic properties in uniform flow conditions (Saifadeen & Gladneyva 2012).

2.2 Study area

Australia has some iconic groundwater reserves such as the Great Artesian Basin covering one fifth of the continent and the Murray Darling Basin that supports Australia's food production and many other alluvium aquifers spread across the continents sustaining the communities, agricultural practices and the Australian economy. For this study, focus has been given along the southern, eastern and northwestern part of NSW that are part of historic riverbanks along the groundwater basins. The study areas in NSW have been selected as Lightning Ridge, Singleton and Albury.

2.3 Meteorological and hydraulic data

The software requires input of time variable boundary conditions and meteorological data for the selected locations. Secondary data on precipitation, radiation, temperature, evaporation and climate have been obtained from the Australian Bureau of Meteorology (2022). Approximate soil composition percentages for the varied climatic and geographic locations within NSW were used to run the simulations.

2.4 Modelling in HYDRUS 1D

As the average depth of unsaturated soils varies along different geographical locations within Australia, assumed depth of 100 cm was taken below the soil surface to model the simulations for a total of 365 days. Inbuilt Van- Genutchen hydraulic coefficient was used while considering the root water uptake to account for water absorption for plants. Upper and lower water flow boundary conditions were considered to be atmospheric with surface layer and free drainage respectively. Equilibrium model of solute transport was incorporated with concentration flux and zero gradient concentrations as the respective upper and lower boundary conditions.

3. RESULTS AND DISCUSSION

The HYDRUS 1D results have been simulated for a period of November 2022 to November 2023 as the weather observations were available for the past 13 months. The results have been generated using most of the accurate data available from the sources, such as the meteorological data, however, for soil related parameters approximate estimates have been made based on the reports generated by Australian Government Bioregional assessment reports of 2014 and the publications of Department of Planning and Environment of NSW.

The results have been used to analyse the salinity patterns of selected locations and to discuss the effect of climate and land practices. The graphs provided in Figure 1 show the results obtained from HYDRUS 1D simulations for variable solute concentrations and water movement patterns over the simulation period in the selected observation nodes. For the simplicity of the analysis, water with electrical conductivity of 0.83 dS/m was irrigated to monitor the concentration changes in relation to time for different locations.

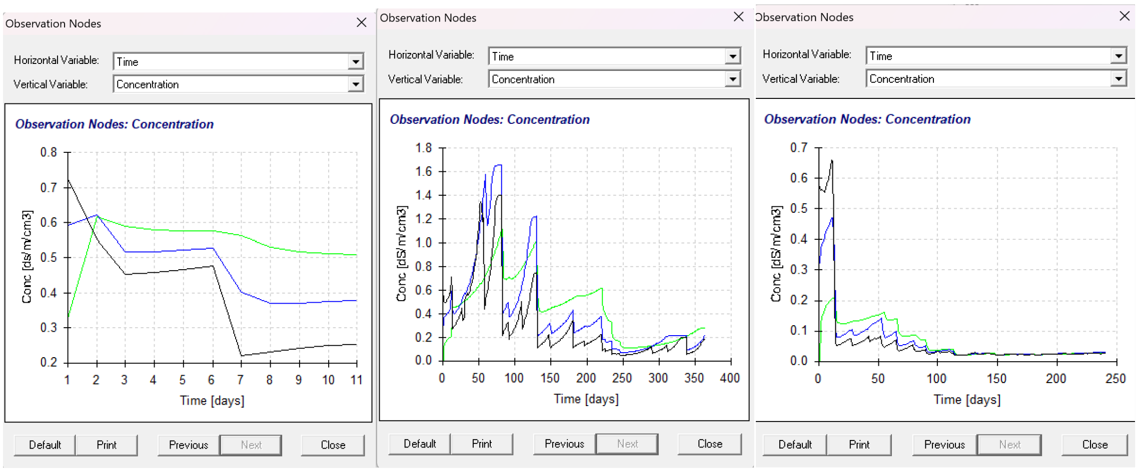

Figure 1. Concentration at different observation nodes of Albury, Lightning Ridge and Singleton respectively (left to right)

Graphs in Figure 1 show the initial increase in concentration, possibly because of the solutes introduced into the soil system via the irrigation process which later decreases with time, indicating possibilities of adsorption, solubility of the substance or interactions with the microorganisms leading to degradation. The effect of root water uptake on solute concentrations at the surface and the root zone were also analysed and are presented in Figure 2 and 3.

Surface concentration of solutes denote the solutes present near the soil surface which could be constantly changing due to the patterns of rainfall, irrigation schedules and release of other toxics into the land. However, root zone concentrations show the concentration of solutes at the plant root region, where there is potential of root uptake. The graphs in Figures 2 and 3 show decrease in solute concentration relative to time, which is distinct while analysing for Albury within a shorter time duration. This is possibly because of the addition of solutes in the land or increased availability of solutes in the root zone through irrigated water, which gradually decreases over time due to solute seepage. Similarly, Singleton also follows a similar pattern of surface concentration, however, Lighting Ridge shows multiple fluctuations in its solute concentration suggesting the effect of climate and soil properties that differs from the other two locations.

Out of many solutes present in the soil profile most is comprised of naturally dissolving salts such as NaCl which have percolated through to groundwater aquifers contaminating them while also having a profound effect on the orientation, plant variety and water flow through soils (Artiola et al. 2019). Climatic patterns such as precipitation, can increase salt concentration on the surface however, higher mean rainfall can dissolve salts or leach it further downwards to the soil horizon. Albury and Singleton have subtropical climate with wet and mild winters which possibly demonstrates the decrease in root zone solute concentrations during wet seasons, suggesting downward movement and dilution of solutes. However, the semi-arid climate of Lighting ridge shows higher concentration fluctuations due to climate irregular rainfall and droughts.

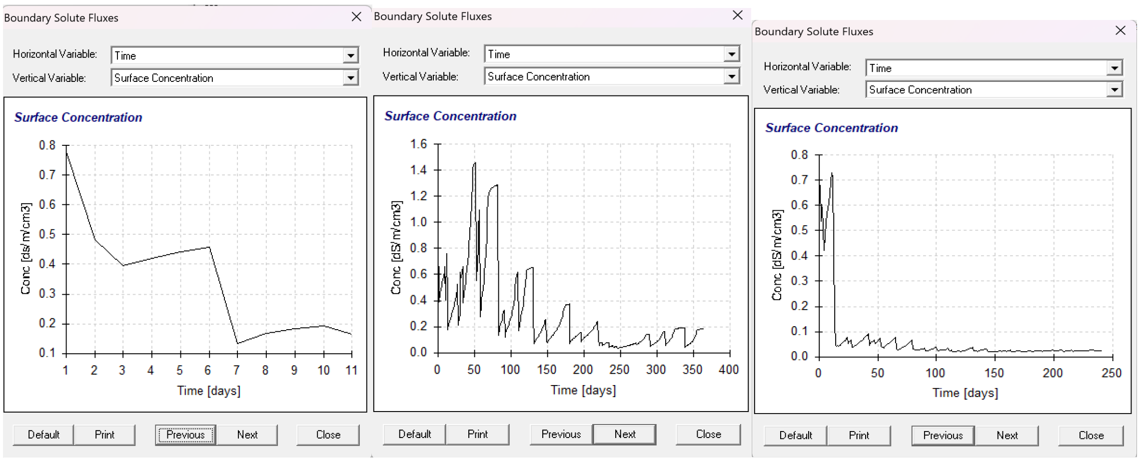

Figure 2. Surface concentration of solutes at Albury, Lightning Ridge and Singleton respectively (left to right)

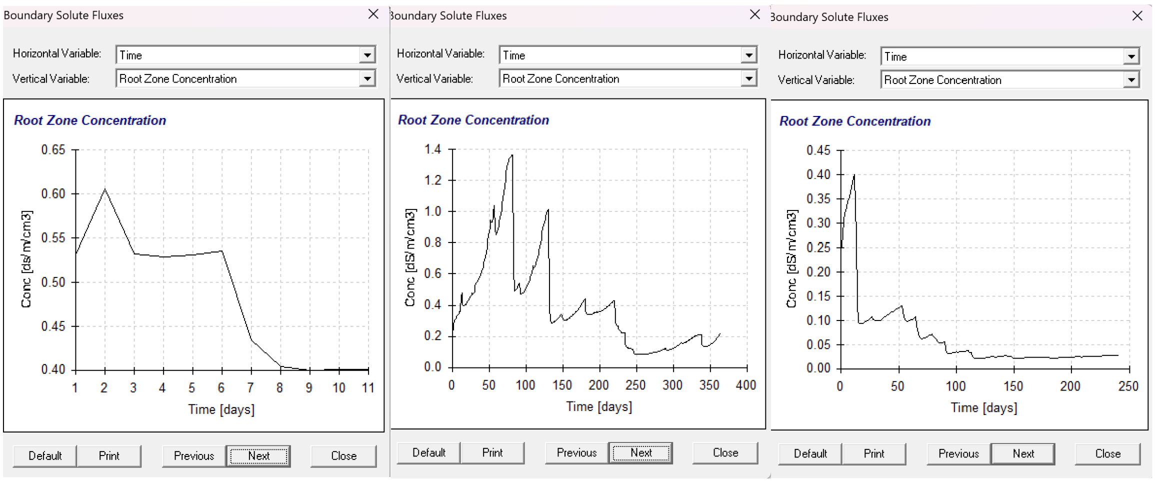

Figure 3. Root Zone concentration of solutes at Albury, Lighting Ridge and Singleton respectively (left to right)

Moreover, soil composition, orientation, conductivity and the organic content of the soil can decide on the fate of solutes concentration and their residence times. This can be evident from the simulations that the loamy soil of Albury has moderate concentration and residence times while the fluctuations in Lighting Ridge's stony soil shows shorter residence time compared to stable concentrations in Singleton's sandy loam soil.

Singleton is famous for its vineyards, which requires altering soil compositions while Albury located on the Murray basin is regarded as the food bowl for Australia. These regions, therefore, use both fertilizers and irrigation water, which transports the nutrients like phosphorus and nitrate to the soil profile and dissociates to form salt ions after reacting with water increasing the salt content.

4. CONCLUSIONS

This study, as a part of groundwater engineering education, primarily examines the effect of rainfall, temperature and soil properties on solute concentrations and their residence times. It further explores the effect of human induced activities in relation to agriculture and irrigation have contributed to soil salinity. The three selected locations Albury, Singleton and Lighting Ridge vary widely in their meteorological parameters. Albury has hot summers and wet winters, while Singleton has hot summer and mild winters, and Lighting Ridge has a dry climate with minimum precipitation among the three selected locations.

Soil properties along with the meteorological parameters were simulated by HYDRUS 1D to analyse vertically uniform flow along the soil depth, which was elaborated to deduce the solute concentration and residence time in three different soil types. Loamy soil of Albury demonstrated moderate solute concentration and residence times with the graphical trends while the fluctuations in Lighting Ridge suggested the solute concentrations spike and fall due to the rainfall variations and soil structure. The study also postulates that HYDRUS 1D is a powerful tool for groundwater engineering education and thus in simulating water and solute movement in unsaturated medium.

5. ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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