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Advances in Hydrus-Based Modelling for Water Flow and Solute Transport in Variably-Saturated Porous Media: A Review

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Abstract: *The HYDRUS program has become an essential tool for modelling water flow and contaminant transport in variably saturated porous media, and is widely used in environmental sciences, hydrology, and agricultural engineering. This review synthesizes recent advancements and applications of HYDRUS, examining how they simulate complex subsurface processes with high precision and adaptability. Special attention is given to HYDRUS-based applications in the agricultural, environmental, and industrial sectors, as well as the model's integration with other technologies, current challenges, and future prospects for enhancing prediction accuracy in sustainable water management. The review observed challenges pertaining to surface type modelling, parameter definition, calibration and validation, and the representation of highly reactive pollutants are given particular consideration. Additionally focus has been given to integration with GIS, machine learning, and artificial intelligence to improve the data uses, precision and effectiveness of simulations. The review also emphasises to enhance user interfaces and promote open-source cooperation in order to increase the application of HYDRUS. Lastly, future prospects for sustainable water and environmental resource management are outlined by exploring how HYDRUS-based simulations can assist policy and decision-making through environmental monitoring and management.*

Keywords: *HYDRUS, Variably Saturated Porous Media, Water Flow, Contaminant Transport, Simulation, Environmental Modelling.*

1. INTRODUCTION

Water flow and solute transport in soil are critical for groundwater recharge and agricultural processes, and at the same time, these processes are responsible for pollutant leaching, which adversely affects soil nutrients and contaminates groundwater. Agricultural fields, municipal and industrial waste dumping yards, and similar sites are major sources of contaminant leaching, where pollutants seep into aquifers through the unsaturated zone (Scanlon et al., 2002). Groundwater is a critical source of potable water, and it is crucial to ensure that it is free from contaminants to protect health.

Accurately exploring water and solute movement is essential for evaluating contaminant leaching risk. This helps assess the timing, concentration, and spread of pollutants, providing key insights for developing planning and mitigation strategies (Šimůnek et al., 2003). It also aids in optimizing irrigation and fertilization practices by simulating nutrient dynamics and water use efficiency in soil (Cote et al., 2003). Such applications require precise predictions of how water and contaminants move under unsaturated conditions (Langergraber & Šimůnek, 2005).

Numerical simulation is a crucial step in designing systems such as landfill liners, wastewater treatment wetlands, and managed aquifer recharge structures. Simulation also helps researchers study the biogeochemical cycling of nutrients and contaminants and assess the influence of climate and land use changes on subsurface hydrology (Šimůnek & van Genuchten, 2008).

Over the past few decades, significant progress has been made in modelling these processes using different finite element method (FEM) tools. HYDRUS is a widely used numerical modelling software specifically designed to simulate water flow and solute transport in variably unsaturated and saturated porous media like soil (Šimůnek et al., 2016; Šimůnek et al., 2024; Beegum et al., 2019; Langergraber & Šimůnek, 2005). The first version is HYDRUS-1D, which is designed for one-dimensional vertical flow systems, such as soil columns, which found its application in small scale simulation works (Basak & Mishra, 2015). Later its 2D and 3D versions were developed, which expanded the capability to two-dimensional and three dimensional simulations. It widened its application field to field-scale agricultural studies, shallow groundwater assessments, and drip irrigation management with much more complexities (Skaggs et al. 2004; Karandish, and Šimůnek, 2017; Morillo et al., 2017; Askari and Shayan, 2021; Domínguez-Niño et al., 2020). HYDRUS utilizes Richards' equation for water flow and the advection-dispersion equation for solute transport simulation. The software finds applications in various environmental, agricultural, and aquifer management fields to study contamination due to pesticide leaching, wastewater treatment, and other hydrogeological processes.

HYDRUS can analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The program can handle flow regions with irregular boundaries and nonuniform soils exhibiting any degree of local anisotropy. Flow and transport can occur in one-dimensional vertical or horizontal directions, two-dimensional vertical or horizontal planes, three-dimensional regions with radial symmetry about the vertical axis, or fully three-dimensional domains. The standard modules (excluding specialized add-on modules) include a Marquardt-Levenberg type parameter optimization algorithm for inverse estimation of soil hydraulic and/or solute transport and reaction parameters from measured transient or steady-state data (Šimůnek et al., 2022).

The main program unit of the HYDRUS graphical user interface (GUI) defines the overall computational environment of the system. This main module controls program execution and determines which optional modules are required for a particular application. The module contains a project manager and both pre-processing and post-processing units. The pre-processing unit includes specification of all necessary parameters to run the HYDRUS FORTRAN codes, grid generators for simple rectangular and hexahedral transport domains, a grid generator for unstructured finite element meshes suitable for complex two-dimensional and three-dimensional domains, a small catalogue of soil hydraulic properties, and the Rosetta Lite program for generating soil hydraulic properties from soil textural data. The post-processing unit provides simple two dimensional graphics for presenting soil hydraulic properties, distributions of variables over time at selected observation points, and actual or cumulative water and solute fluxes across specific boundaries. It also offers options to present simulation results using contour maps, isolines, spectral maps, velocity vectors, and/or animation with both contour and spectral maps.

The HYDRUS program numerically solves Richards' equation for variably saturated water flow and the advection-dispersion equations for both heat and solute transport. The flow equation includes a sink term to account for water uptake by plant roots. The heat transport equation considers both conduction and convection with flowing water. The solute transport equations account for advective-dispersive transport in the liquid phase and diffusion in the gaseous phase. The transport equations also include provisions for nonlinear nonequilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first-order degradation reactions. Additionally, physical nonequilibrium solute transport can be represented using a two-region, dual-porosity formulation that partitions the liquid phase into mobile and immobile regions. Attachment/detachment theory, including filtration theory, is also incorporated to enable simulations of virus, colloid, and/or bacteria transport.

This paper systematically reviews the existing works dealing with simulation of water flow and solute transport through porous media and explores the limitations, challenges and future scope of improvements in the domain.

2. Objective of the Review

This review provides a comprehensive overview of recent advances in HYDRUS-based modelling of solute transport through variably saturated porous media. It reviews the studies highlighting developments in key solute transport processes, model advancements such as improved numerical methods (including enhanced parameter estimation techniques, reaction transport models, and incorporation of GIS, machine learning, and artificial intelligence), applicability in various environmental contexts such as agriculture, ground water contamination, environmental protection etc. The work attempts to summarise the limitations and hurdles faced by different researchers, and recommends future directions for improvements in model algorithms and parameter estimation techniques. These scope of the review are illustrated in a mind map as shown in figure 1. By synthesizing the current knowledge base, this paper aims to inform researchers, practitioners, and decision-makers about the capabilities and limitations of HYDRUS simulations in variably saturated porous media.

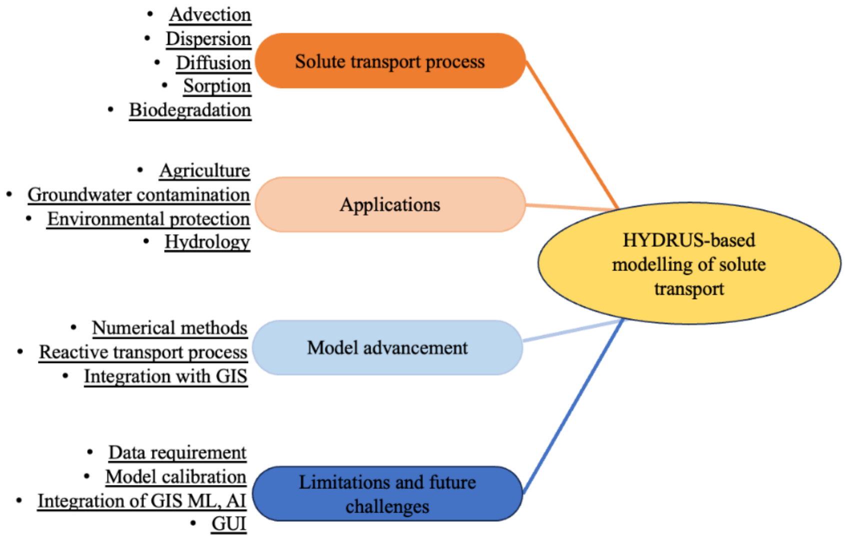

Fig. 1: Mind map of the study

3. Solute Transport Process

HYDRUS-based simulation is founded on fundamental solute transport processes that govern the movement of contaminants and nutrients in variably saturated porous media. Solute movement occurs through processes such as advection, dispersion, diffusion, biodegradation, and sorption. HYDRUS utilizes the Richards equation to simulate water flow, as shown in equation 1 (Richards, 1931). The Richards equation integrates Darcy's law with the principle of mass continuity to describe water flow through heterogeneous media such as variably saturated soil (Lei et al., 1988).

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

Here, θ, t, K, h, and S represent volumetric water content, time, hydraulic conductivity, pressure head, and sink term, respectively. The sink term accounts for water loss due to root uptake and/or evaporation. Solute movement is simulated using the advection-dispersion equation (ADE), as shown in equation 2 (Van Genuchten and Parker, 2013). This equation accounts for the processes of advection, dispersion, and chemical reactions such as sorption and degradation (Saadat et al., 2025). The equation describes how solutes move with water (advection) and spread out (dispersion).

$$\frac{\partial C}{\partial t} = \nabla \cdot (D\nabla C) - \nabla \cdot (vC) + R \qquad (2)$$

Here, C, D, v, and R represent solute concentration, dispersion coefficient, flow velocity, and reaction term, respectively (e.g., sorption, degradation). The dispersion coefficient D accounts for both molecular diffusion and mechanical mixing from flow paths. This combined process description is fundamental for modelling solute transport in variably saturated porous media, as implemented in HYDRUS models.

Advection is the process by which dissolved materials move with the flow of water through porous media. In porous media, advection depends on the hydraulic properties (porosity and permeability) of the medium, as well as the solubility and concentration of the solute (Madie et al., 2022). Dispersion refers to the spreading of solutes away from the main flow path as they are transported through the pores of the medium. It affects solute movement and distribution (Perfect et al., 2002). The dispersivity coefficients of soil in the longitudinal (Disp. L) and transverse (Disp. T) directions, along with solute diffusion in water (ω), are required to define solute flow parameters. Solute transport is also affected by adsorption. The distribution coefficient, Kd, describes how much of the solute is adsorbed by the soil versus how much remains in the water during transport. These properties allow HYDRUS to simulate interactions between water, contaminants, and soil particles, impacting their movement and distribution over time.

The ADE equation balances changes in solute mass concentration over time with the spreading of solutes due to dispersion and their transport by bulk water flow (advection) (Phillip and Castro, 2003). The ADE and its application to solute transport in porous media such as soil have been extensively discussed by van Genuchten and Parker (1984). Diffusion also plays a significant role in solute movement, describing the molecular movement of solutes from regions of high concentration to regions of lower concentration. This process is mathematically described by Fick's first law, which states that the diffusion flux (the amount of solute moving per unit area in unit time) is proportional to the concentration gradient.

$$J = -\omega \nabla C \qquad (3)$$

Here, ω is the molecular diffusion coefficient (unit: L^2/T).

Diffusion is the natural tendency of solutes to achieve equilibrium through molecular motion. It is independent of fluid flow mechanisms such as advection or dispersion. In liquids, molecular diffusion depends on the diffusivity of the solute species and the tortuosity and connectivity of the pore space, which often reduce the effective diffusion coefficient compared to that in free water.

Some solutes which are organic in nature are degraded by microbial activities. This process is known as biodegradation. During this process a gradual reduction in contaminant concentrations takes place over time. Biodegradation depends on solute concentration, microbial populations, and suitable environmental conditions such as humidity and temperature. HYDRUS program offers biodegradation options to simulate natural attenuation and bioremediation processes of solutes.

Another process involved in solute movement is sorption, which refers to the reversible or irreversible attachment of solute molecules onto soil particles. Sorption slows solute transport compared to water movement, as some solutes adhere to solids and stop moving with the water. The extent of sorption depends on soil mineralogy, organic content, and the characteristics of the solute.

4. Modelling of geometric domain, flow parameters, and boundary conditions

4.1 Geometric Modelling

HYDRUS-1D initially began with one-dimensional geometric modelling and has gradually introduced three-dimensional layered and general modelling capabilities. These advancements reduce the need for assumptions and averaging of different flow parameters, thereby improving the precision of movement prediction. HYDRUS models rely heavily on accurate flow parameters, including soil hydraulic and solute transport properties (Inoue et al., 2020). The Van Genuchten (1980) and Mualem (1976) models describe the hydraulic properties of soil by defining parameters that describe the retention and flow of water through soil pores based on soil moisture pressure and texture.

The soil water retention curve and unsaturated hydraulic conductivity are described by the Van Genuchten model. It involves parameters such as residual water content (Qr), saturated water content (Qs), alpha (inverse of air entry pressure, 1/L), the pore size distribution coefficient (n), the pore connectivity factor (I-value) (Tian et al., 2018), and hydraulic conductivity (Ks). Ks exhibits a nonlinear relationship with moisture content, and HYDRUS requires input on how this conductivity varies under unsaturated conditions (Mawer et al., 2015).

Solutes and water move through the soil's interconnected pores and internal fissures. The single porosity model is the fundamental flow model. It is a traditional method that makes the assumptions that water flows through the porous medium uniformly and that soil pores are homogeneous. It works well in soils without fractures where water flows in a single, continuous phase and hydraulic conductivity and suction pressure are connected by constitutive relationships. With subsequent versions of HYDRUS, several advanced modelling options for hydraulic characterization and simulation of water flow in porous media have been introduced, enabling more accurate and precise flow modelling. These models include dual-porosity and dual-permeability models. The dual-porosity models account for soil heterogeneity by representing the soil matrix and macropores or fractures as two interacting pore domains which increase permeability. Water and solute flow occur mainly in through the macropores, while the micropores primarily acts as a storage domain. The dual-permeability models builds on the dual-porosity concept, to simulate water flow through two overlapping pore networks, each with its own hydraulic conductivity and flow regime, connected by exchange terms. The dual permeability model treats soil as consisting of two interacting pore networks, the soil matrix (micropores) and macropores (fractures or preferential flow paths). Water flow and solute transport are assumed to occur separately in both domains, which allows exchange of water and solutes between the matrix and macropores. This approach captures complex flow and transport phenomena in soils with highly heterogeneous structures, such as aggregated soils or fractured rocks.

These basic models can be supplemented by mechanistic or empirical models that address temperature-dependent hydraulic properties, root water uptake, and soil water retention hysteresis. A thorough characterisation and highly accurate simulation of variably saturated water flow and solute movement in complex soil systems are made possible by the proper combination of these options.

4.2 Boundary Conditions And Initial Conditions

Boundary and initial conditions are critical in defining how the fluid system, including solutes, interacts with the variably saturated soil domain in HYDRUS models (Rocha et al., 2006). These conditions determine how the fluid system enters and exits the soil. HYDRUS provides several boundary types, including no-flux, constant flux, time-variant, free, and atmospheric boundaries (Okereke & Keates, 2018).

A no-flux boundary condition specifies that no fluid enters or leaves the soil. A constant flux boundary defines fluid discharge or inflow at a constant rate. Initial conditions, such as initial moisture levels, solute concentrations, or temperature within the soil stratum, must be specified before simulation calculations start in order to create a baseline for simulations (Cichota et al., 2021). Properly defining these boundary and initial conditions is essential for simulating realistic field scenarios. Two major points are observed in the way boundary conditions are defined, one is handling of ponding, and another is handling of run offs. It is observed that HYDRUS is unable to simulate ponding when irrigation or precipitation exceeds the soil's infiltration capacity because it restricts the actual boundary flux in these circumstances (Šimůnek et al., 2012). Simultaneous modelling of surface runoff and leaching is inaccurate; instead, it treats the excess water of infiltration capacity independently, and does not quantify run off (Caiqiong & Jun, 2015).

4.3 Numerical Equation Solver

In HYDRUS, the soil profile is discretized spatially (meshed) into N−1 adjoining finite elements, bounded by N nodal points. This spatial discretization is consistently applied for simulations of both water flow and solute transport. During simulation, water balance calculations are performed to track volumes and inflow/outflow rates within user-defined subregions, supporting mass conservation checks and detailed hydrologic analysis. Water flow is governed by the mixed form of Richards' equation, as previously described, which is discretized using a mass-lumped linear finite element scheme. This scheme is equivalent to a standard finite difference approach (Vogel et al., 1996), enabling robust numerical solutions for transient variably saturated flow. Boundary conditions, whether Dirichlet (pressure head dependent) or Neumann (flux dependent), are incorporated with matrix rearrangements to maintain symmetry and numerical stability. Atmospheric boundaries are dynamically managed following criteria from Neuman (1974), where prescribed flux or head conditions are adaptively applied to realistically simulate infiltration and evaporation.

To solve the coupled time-dependent partial differential equations governing flow and transport, HYDRUS employs the Crank–Nicolson method. This finite difference method is well known for its high accuracy and unconditional stability in numerically solving parabolic PDEs, such as the heat equation and solute transport equations. In HYDRUS, the Crank–Nicolson approach is combined with the Galerkin finite element method, upstream finite element (FE), or Galerkin finite element with artificial dispersion (GFE) to construct the finite element spatial discretization and weighting. This hybrid method effectively controls numerical dispersion and oscillations, enabling accurate and stable simulation of solute movement through porous media over time and space. HYDRUS adjusts the equation-solving iterations using specified tolerance levels for different parameters, employing root mean square, R-square, and Nash-Sutcliffe efficiency metrics (Roberts, 2023; McCuen et al., 2006; Barrett, 1974).

Any numerical simulation process requires calibration, validation, and verification with field data to ensure that model outputs are reliable (Gupta et al., 2006). Several experimental studies have been conducted to calibrate and validate HYDRUS simulations.

Zhang et al. (1994) conducted a comparative study of classical convention-dispersion equation (CDE), and stochastic convection dispersion equations (SCDE) for predicting solute transport in homogeneous and heterogeneous soil columns. The study found that the later equation more accurately predicted experimental data due to its ability to model scale-dependent dispersion. But, the study erroneously assumed that pore water velocity is constant in homogeneous soil. Accurate prediction of pore water velocity is required to fit CDE and SCDE.

Bonanno et al. (2022) studied the solute transport and water exchange with storage zones, which may include dead zones, sediments, and nearby groundwater by utilising the Transient Storage Model (TSM). The study iteratively combined global and dynamic identifiability analyses to improve parameter identifiability in tracer breakthrough experiments. The study observed that application of TSM leads to more reliable interpretations of solute exchange and residence times.

A similar study was carried out by Sadaat et al. (2025), which explored the effectiveness of the TSM for predicting how contaminants spread in rivers. The study made two major observations regarding contaminant exchange between storage zones (dead zones and pools) and the river. It was observed that the simpler ADE model is more effective in approximating contaminant distribution when the exchange rate is low. However, when the exchange rate is high, the ADE model gives erroneous predictions, and the TSM provides better results. The TSM explicitly accounts for transient storage processes (temporarily holding and then releasing of contaminants). Including TSM can help better identify sources and predict contaminant movement under realistic hydrodynamic conditions.

Li et al. (2013) used a simple soil column method to evaluate soil phosphorus leaching risk. The study determined phosphorus leaching but excluded the lateral movement of the solute to simplify the experiment. The study found that coarse-textured soils had significantly ($p < 0.05$) higher levels of phosphorus accumulation than fine-textured soils. This study observed that this difference was a result of coarse-textured soils' poor chemical and physical retention of dissolved phosphorus and particulate phosphorus, respectively. Phosphorus leaching was also found to be accelerated by the high saturated hydraulic conductivity of coarse-textured soils. There is need for further verification on more soils with a wide range of physical and chemical properties.

Comacho et al. (2023) conducted a study tracking solute transport using a bromide tracer. The study observed subsurface lateral movement of bromide along the soil slope, with the solute spreading along the boundary over time and accumulating at the bottom. While the study effectively explored solute movement along the slope, further research is needed to develop methods to quantitatively differentiate the magnitude of surface and subsurface lateral movement under different soil conditions, especially when solute concentration is high at the inlet.

Jeng et al. (2010) investigated the poro-elastic behavior of porous soils in relation to solute transport using Darcy’s law, demonstrating that poro-elastic soil deformation can reduce or slow solute movement. Although the study presented only the preliminary results, there is scope for more physical verification of the flow parameters with numerical analysis. Several other studies, including those by Ellsworth et al. (1996), Neuman et al. (2018), and Kanzari et al. (2018) also made similar observations.

Morianou et al. (2023), have also extensively examined solute transport through soil and observed that HYDRUS 2D/3D program is reliable for simulating flow dynamics along with solute transport and root uptake. Although, three different types of crops are taken for consideration, there is need to study different types of irrigation schemes. There is challenge to simulate root uptake in three dimensional domain. A major limitation of the study is relating the lab scale experimental model to landscape problem, which may have come with over simplification of parameters.

Coquet et al. (2005) conducted a field study on the effects of soil structure heterogeneity, generated by farming practices, on water flow and solute transport. The study found that independently measured soil hydraulic parameters (from lab-tested samples) were insufficient to fully simulate soil heterogeneity and required minor adjustments for accurate simulation. These adjustments were attributed to possible air entrapment during infiltration, hysteresis, and reduced permeability in compacted soil. It is similar observation as made by Simunek and Van Genuchten (1999).

A study by Busheva and Polezhaeva (2024) on solute mass transfer in an oscillating flow in a two-dimensional channel found that increased solute transfer is linked to the average fluid flows caused by uneven water oscillation amplitudes in the pores between randomly packed hard spheres. It is observed that as the time averaged flow velocity is sensitive to pore shape, the results should be compared with other studied.

Wang et al. (2018) calibrated and validated HYDRUS-1D to simulate infiltration dynamics in layered water-repellent soils, demonstrating satisfactory performance in modelling sand/silt loam and silt loam/sand layered soils. The study observes that further research is needed to assess the capability of HYDRUS to simulate heterogeneous water repellent soils.

Pazoki et al. (2017) conducted two pilot studies to simulate leachate movement and predict changes in nitrogen and phosphorus concentrations in landfill soils. HYDRUS-1D successfully simulated these processes using reverse estimation methods with empirical solutions to determine soil hydraulic parameters. The authors noted that sufficient data are required for improved simulation results. After initial purification, the resultant leachate entered the pilot system and was collected after passing through the soil. Finally, HYDRUS-1D was used to model leachate flow and changes in nitrogen and phosphorus concentrations in the soil.

Kanzari et al. (2018) calibrated water flow and salt transport in HYDRUS over seven days and then validated the process over 383 days. They concluded that HYDRUS simulated water and saline profiles with field-measured data to a sufficient level of accuracy. It is observed that the study ignored the effect of rainfall and evaporation.

The advanced of numerical methods, and greater computing power has led to significant advances in HYDRUS-based modelling. These advances include improvements in simulating key transport processes such as advection, dispersion, diffusion, biodegradation, and sorption, which facilitate a more realistic simulations. A defining strength of HYDRUS is its ability to integrate different modules, which allows tailored simulations based on specific environmental requirements. Several modules such as UNSATCHEM for major ion chemistry, HPx and PHREEQC for simulation of complex geochemical reactions (including transient water flow, transport of multiple solutes, biogeochemical reactions, and heat transport in soils), CW2D and CWM1 for wetland, enable specialized applications across various fields (Langergraber & Šimůnek, 2005; Šimůnek et al., 2024). These modules have been successfully applied in contexts ranging from nitrate leaching in agricultural works to reactive transport in landfills as well as in evaluating wetland performance. The latest version of the program, HYDRUS Version 5, integrates all previously separate 1D, 2D, and 3D modules into a unified software platform, which has enhanced the user accessibility, computational efficiency, and workflow consistency (Šimůnek et al., 2024).

5. Applications

Understanding of water flow and solute transport in variably saturated soil is relevant across diverse environmental contexts, such as agriculture, aquifer management, wastewater treatment, and environmental problems. A brief review of HYDRUS simulation applications in these environments has been described in the following paragraphs.

5.1 Agriculture

Agriculture requires frequent irrigation and fertilizer application. Two basic needs of agricultural system simulation are to determine the frequency and effectiveness of irrigation, fertilizer or pesticide penetration, and the associated risk of leaching into deeper soil and ultimately the water table. HYDRUS based studies assist in optimizing fertilizer and irrigation frequencies, rates, and quantities for high yields, and to reduce chemical leaching and prevent contamination of soil and groundwater (Lazarovitch et al., 2023; Ranjbar et al., 2017; Voulanas et al., 2022). Recent research focuses on coupling HYDRUS simulations with geographic tools to access publicly available soil, ground water and precipitation data to get a more precise water and nutrient flow patterns. This improves water and fertilizer use efficiency, and minimize pesticide leaching through judicious dosing for different crops (Wang et al., 2024; Liang et al., 2025; Kumar et al., 2025).

However, several challenges remain to be solved such as accurate field data collection, soil heterogeneity (including flat, and furrow surfaces), and climate variability (temperature, humidity, and precipitation), all of which complicate the application of HYDRUS. It is observed that a greater integration is required between simulations and practical management to maximize the program's benefits (Lazarovitch et al., 2023; Voulanas et al., 2022; Wang et al., 2024).

Karandish & Šimůnek (2017) calibrated the HYDRUS-2D model using data from a two-year field experiment in a drip-irrigated field. The study reported that HYDRUS-2D was able to capture temporal and spatial trends in soil water content. Earlier, Karandish and Šimůnek (2016) used of HYDRUS-2D to develop optimal irrigation scheduling, which can save water.

Phogat et al. (2014) observed that small differences in results obtained from HYDRUS could arise because the numerical model uses point-based parameter values, while field-observed values are often representative of averages over a certain soil volume. Additionally, due to irrigation, the gradient of soil water content is high but may not be linear, showing higher concentrations near the water source (Mguidiche et al., 2015).

A similar conclusion was made by Mmolawa et al. (2003), who observed that the HYDRUS-2D analytical model overestimates root water uptake at some locations. This may result from the lack of consideration of water stress effects due to changing saturation levels on uptake intensity in the analytical model, and also because the analytical model may be sensitive to the choice of linearizing interpolation of hydraulic parameters. Other studies have used HYDRUS-2D for simulating saturated soil under different irrigation conditions (Assouline et al., 2006; Crevoisier et al., 2008; Mubarak, 2009; Tafteh and Sepaskhah, 2012; Ramos et al., 2012).

Nie et al. (2020) and Sun et al. (2022) studied HYDRUS-2D simulations of fertilizer transport, such as nitrate nitrogen and potassium, under fertilizer solution infiltration during furrow irrigation. The studies observed that soil water content, the n-parameter, and hydraulic conductivity increase with higher potassium nitrate concentrations.

Karimov et al. (2025) examined the efficiency of drip irrigation in amaranth production using the HYDRUS-1D model and found that it facilitated proactive adjustments of drip irrigation, which could be helpful in designing precise irrigation technologies. But, the study over looked lateral component of water flow which is a major component of irrigation.

Similar study was conducted by Ghilassi et al. (2024) to explore the drip irrigation efficiency in sandy loamy soil. One major flaw in the study was not consideration of lateral flow of water which is a major component of water and fertilizer flow. This review indicates that simulation accuracy requires precise modelling of related parameters. For better results, hydraulic parameters such as hydraulic conductivity should allow the addition of curves. Modelling of three dimensional distribution of water and fertilizer would help in simulating real world irrigation situations. Reduction of fertilizers concentration with water with different types of soil condition should be explored further. Addressing these issues will ensure that HYDRUS-derived agricultural strategies effectively reduce environmental risks while supporting sustainable cultivation practices.

5.2 Groundwater Contamination

HYDRUS is being used extensively for environmental investigations to assess risk of soil and ground water contamination at industrial units, and dumping yards. The ability to simulate variably saturated zones with realistic characterization of solute transport at the interface between unsaturated and saturated media has made HYDRUS popular among practitioners. For instance, Qu et al. (2022) applied HYDRUS-1D to simulate lead migration in fluctuating groundwater zones. The studied observed the solute movement, and provided insights for heavy metal pollution remediation in soil and groundwater. Šimůnek et al. (2013) highlighted the program’s capability to model and simulate the transport of multiple chemical contaminants, considering physical and chemical interactions in soils. Recent applications have studied nitrate leaching risk mapping by integrating HYDRUS with GIS tools to predict spatial probability in groundwater contamination (Nebraska, 2025).

Voulanas et al. (2022) used the HYDRUS-1D model to study soil water balance in agricultural fields in river basin. The model incorporated meteorological data, soil data, and soil moisture measurements. After calibration via HYDRUS-1D’s inverse solution, model results were used to evaluate the irrigation activities applied in the pilot fields in terms of irrigation dose, irrigation interval, and soil moisture variation during the cultivation period. To measure the efficiency of the evaluated irrigation method, water productivities for all three fields were compared with productivities from similar applications and experiments, as well as precision irrigation experiments in climates similar to that of Nigrita. The study observed that simulated soil water content changes in the root zone responded well to rainfall and irrigation events, varying relatively quickly with abrupt increases during any water input. HYDRUS-1D has proven to be a reliable tool for evaluating water movement in agricultural fields under various irrigation schemes and different crops globally, despite its considerable demand for input data. Additionally, HYDRUS-1D was found useful in evaluating water balance components of the pilot irrigation application.

A study by Slama et al. (2010) extensively investigated salt accumulation in soil through experimental and analytical methods. The study explored the impact of rainfall structure on solute leaching in soil and groundwater and observed that both annual rainfall amounts and temporal distribution structure affect solute fluxes leaching into groundwater and soil concentrations.

Li et al. (2022) and Qu et al. (2022) investigated the effect of groundwater level fluctuations on lead migration through coarse and medium sand using experimental and analytical simulations.

Wang et al. (2024) focused on subsurface pipe drainage in the Shanghai coastal area using HYDRUS-2D/3D. Their study explored the dynamic changes in soil–water–salt interactions under various subsurface conditions. Some limitation is observed in the methodology of the study. The ground water influence was not considered assuming that it has limited impact on the flow process, also the effects of temperature should have been taken into consideration.

Similarly, Liang et al. (2025) studied leaching of phosphorus from rice cultivation, using HYDRUS and observed that the simulated results showed good agreement with R-square values ranging from 0.62 to 0.8. While these results show good agreement with field data, there is still a scope for improvement in the HYDRUS mechanism for high precision. The study does not account for time dependent chemical reactions, and also, a long term study to calibrate the model would be better to draw meaningful conclusions. Despite its strengths, challenges such as the need for precise soil hydraulic data, scale issues, and integration with field data limit its applicability across different fields. Nevertheless, HYDRUS remains a valuable tool for engineers to design effective remediation and protection management strategies for drinking water sources.

5.3 Environmental Concerns

Leaching of pollutants into the soil and contamination of groundwater or water bodies is a significant environmental concern. It is useful for simulating the natural attenuation of contaminants, their accumulation, and for understanding interactions between water, soil, and solutes. Several studies have used HYDRUS to investigate the leaching risk of pollutants from various sources, such as industrial and pharmaceutical wastes. The integration of reactive solute transport processes enables HYDRUS to assess biogeochemical reactions and contaminant transformations in aquifers. Many environmental systems involve the transport of multiple pollutants, each with unique chemical behaviours, such as different transport rates, sorption characteristics, or chemical reactions (Pereira et al., 2015). This advancement has enhanced the capability of HYDRUS to simulate real-world environmental conditions, where multiple contaminants often interact, accumulate, or degrade at different rates (Liu et al., 2024). The HYDRUS framework also used to simulate the transport of nutrients, pesticides, heavy metals, and pharmaceutical wastes, simultaneously (Siphiwe et al., 2024). By understanding these processes, stakeholders can make plans to address environmental challenges (Dou et al., 2022). Some research exploring the leaching of pharmaceutical and personal care product pollutants is reviewed and described here. Wydro et al. (2023) did a review on the pharmaceuticals and personal care products residues in the aquatic environment and possibilities. The review highlighted the accumulation, toxicity, and removal processes of these compounds, but ignores the persistence of these compounds.

Gillis et al. (2012) observed that pharmaceuticals are an emerging class of environmental contaminants that have received widespread attention, yet their environmental effects remain largely unknown. The study used HYDRUS-1D to model water and solute transport and to explore the leaching of diazepam and iopromide. The results showed that iopromide transport was not well described by HYDRUS-1D, with an error of 157% in mass recovery. It was assumed that poor fit distribution factors for the solute may have led to reduced sorption and higher water solubility. Additionally, when the distribution factor was adjusted to match the field pattern of iopromide transport, it introduced errors in the solute mass balance calculation.

García-Santiago et al. (2017) studied the risk of leaching of seven pharmaceutical and personal care product compounds with different physicochemical properties using the buckets model and HYDRUS-1D. The study indicated that most of the compounds have a low potential to contaminate groundwater through silty loam, although some tended to accumulate in the top layers of the soil. The study also observed differences between the experimental and numerical results, which could be attributed to the high reactivity of the studied compounds that may not have been well modelled.

Martínez-Hernández et al. (2017) investigated the natural attenuation of selected pharmaceutical compounds, including caffeine, acetaminophen, sulfamethoxazole, naproxen, and carbamazepine, during vadose zone infiltration using HYDRUS-1D. They observed that attenuation of the detected pharmaceuticals could be reproduced by a combination of retardation and removal approaches. The study observes that there is need of further investigation on input concentration on removal rates. The study also recommends that further study should be conducted to understand chemical transformation of pharmaceutical wastes.

Lyu et al. (2019) studied reclaimed water from municipal wastewater treatment plants in Beijing and observed that pharmaceuticals and personal care products can leach into soil and contaminate groundwater through the irrigation of urban green fields. This process can cause root elongation and introduce carcinogens. The study did not explicitly explains how different personal care products were differentiated and how they reduce into end-substances.

Deng et al. (2019) studied the concentration distribution of radioactive compounds in the soil column using a three-dimensional numerical model of nuclide migration (HYDRUS-3D), considering both the porosity and flow velocity of the solid phase. It is observed that the lateral distribution of solutes were ignored in the study.

Pei et al. (2022) also raised concerns about the pollution of water bodies by pharmaceuticals and personal care products (PP), noting their tendency to accumulate in soil and aquatic environments. The study raised some major concern like difficulty in determining the exact rate of infiltration of PP products. As the work becomes interdisciplinary, there is limited knowledge among engineers about the PP product characteristics such as composition, decay rate, and sedimentation etc.

Meffe et al. (2021) studied the natural attenuation, plant uptake and human health impact of pharmaceutical and transformation products during unplanned water reuse in field conditions. It is observed that while most study claim testing under field conditions, most of these studied are conducted under controlled lab conditions. For proper field effect, the soil sample should be undisturbed during the testing.

An et al. (2022) investigated the adsorption and migration characteristics of Acid in river sand using sand column experiments and the HYDRUS-1D model. They found that the model could quantitatively describe water flow and solute reactions during the migration process. A major flaw in the study is not integrating the effect of particle size, and ion strength, and only relying on the Ph values for adsorption.

Dibyanshu & Scheytt (2025) examined the transport behavior of four pharmaceutically active compounds using column experiments in both unsaturated and saturated porous media. These compounds were, caffeine, carbamazepine, diclofenac, and ibuprofen, under neutral pH conditions. The study underscored that there is a need for monitoring and management to prevent groundwater contamination from pharmaceutical wastes. It is observed that long term contamination risk should be studied to explore the real world scenario of microbial interaction.

The removal of contaminants in soil and nutrient concentrations in wetland can be done using HYDRUS, which can help in conservation efforts (Šimunek et al., 2012).

A similar study was done by Castaño-Triase et al. (2024) to study the pharmaceuticals of concern in reclaimed water for crop irrigation in the Mediterranean area.

Other industrial wastes, such as agro-based cardboard wastewater, have also been studied using HYDRUS. Research by Masto et al. (2020), Singh et al. (2012), Ladu and Zhang (2011), Caiqiong and Jun (2015), Ansari (2004), Mathur et al. (2004), and Conkling and Blanchar (1989) has successfully explored effluents from the paper industry. HYDRUS can model pollutant leaching and predict potential contamination of surrounding areas, and provide crucial data for designing safe waste containment systems (Faisal et al., 2015).

Hydrus has been used in many environmental studies in a variety of contexts due to its strong framework and versatility. Hydrus's use in geographically dispersed analyses of water resources and contaminant transport is further improved by combining it with Geographic Information Systems (GIS) and remote sensing data. Hydrus helps researchers forecast hydrological shifts and guide sustainable land management strategies by modelling soil-water-plant interactions under different climate scenarios (Wu et al., 2019).

5.4 Integration with Geographic Information Systems (GIS)

Modelling with large-scale, real-time spatial data requires GIS data. HYDRUS-GIS integration enables the use of real-world spatial data, such as soil properties, topography, land use, precipitation, and hydrological features, to simulate processes over larger areas (Elsersawy & Kamal, 2017). This integration broadens HYDRUS applications to fields such as aquifer management, runoff estimation, and environmental monitoring with real-time data (Zhou & Li, 2020). Coupling Hydrus with GIS provides more accurate and realistic spatial representations, supporting better decision-making in land management, agricultural planning, and environmental remediation (Haj-Amor & Bouri, 2020). For example, in a study by Haj-Amor and Bouri (2019), the HYDRUS-1D model was coupled with GIS to explore the effects of climate change on soil salinization and to develop irrigation practices that desalinate soils. A schematic diagram of GIS integration with HYDRUS, is shown in Figure 2. By integrating HYDRUS with GIS data, can form a monitoring system for regional level environmental issue relating to leaching of pollutants, and support decisions making on land use, contamination remediation, and environmental protection policies (Li et al., 2024; Dou et al., 2022; Zhou & Li, 2020; Locatelli et al., 2019).

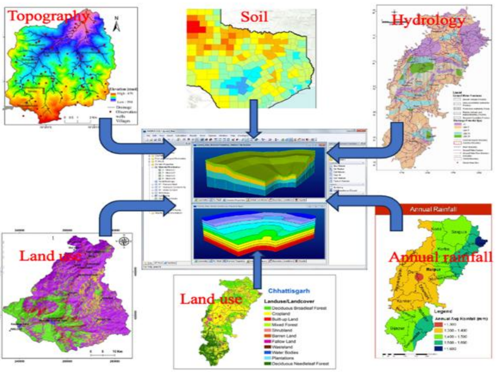

Fig. 2: Integrating HYDRUS with GIS

6. Findings From Reviews

Significant development have been made into the HYDRUS program since it was first introduced in the early 1990s, to address various issues related to related to solute and water flow related to agriculture, groundwater, and pollution leaching. These developments have improved its versatility, accuracy, and precision, which has resulted in broadening its applicability across different fields. Some key findings from the extensive review are presented in the Table 1.

Table 1: Major findings of the review

Objective	Findings
Inoue et al. (2020)	• Need accurate flow parameters, including soil hydraulic and solute transport properties.
Van Genuchten (1980) Mualem (1976)	• Defining parameters that describe the retention and flow of water through soil pores based on soil moisture pressure and texture.
Rocha et al. (2006) Šimůnek et al. (2012)	• Unable to simulate ponding when irrigation or precipitation exceeded the soil's infiltration capacity.
Bonanno et al. (2022) Sadaat et al. (2025)	• When the exchange rate between storage zones (dead zones, pools, and sediments) between the river is high, the ADE model give erroneous predictions. • The TSM explicitly accounts for transient storage processes and can handle high exchange rates between storage zone and rivers. • The TSM inclusion can help to better identify sources and predict contaminant movement under realistic hydrodynamic conditions.
Caiqiong & Jun (2015)	• Simultaneous modelling of surface runoff and leaching is inaccurate.
Li et al. (2013)	• Need for further verification on more soils with a wider range of physical and chemical properties
Comacho et al. (2023)	• Need to consider movement along the slope. • Further research is needed to develop methods to quantitatively differentiate the magnitude of surface and subsurface lateral movement under different soil conditions.
Zhang et al. (1994)	• Study erroneously assumed that pore water velocity is constant in homogeneous soil. Accurate prediction of pore water velocity is required to fit CDE and SCDE
Jeng et al. (2010)	• Study presented only the preliminary results, there is scope for more physical verification of the flow parameters.
Coquet et al. (2005) Simunek & Van Genuchten (1999)	• Required minor adjustments for accurate simulate of soil heterogeneity. These adjustments were attributed to possible air entrapment during infiltration, hysteresis, and reduced permeability in compacted soil.
Morianou et al. (2023)	• There is challenge to simulate root uptake in three dimensional domain. • A major limitation is relating the lab scale experimental model to landscape problem, and over simplification of parameters.
Wang et al. (2018)	• Further research is needed to assess the capability of HYDRUS to simulate heterogeneous water repellent soils.
Pazoki et al. (2017)	• Sufficient data are required for improved simulation results.
Kanzari et al. (2018)	• Study ignored the effect of rainfall and evaporation.
Lazarovitch et al. (2023) Voulanas et al. (2022) Wang et al. (2024)	• Several challenges remain to be solved such as accurate field data collection, soil heterogeneity (including flat, and furrow surfaces), and climate variability (temperature, humidity, and precipitation). • A greater integration is required between simulations and practical management to maximize the program’s benefits
Phogat et al. (2014)	• Small differences in results obtained from HYDRUS could arise because the numerical model uses point-based parameter values, while

	field-observed values are often representative of averages over a certain soil volume
Mguidiche et al. (2015)	• Due to irrigation, the gradient of soil water content is high but may not be linear, showing higher concentrations near the water source
Mawer et al. (2015)	• HYDRUS-2D analytical model overestimates root water uptake at some locations. • Lack of consideration of water stress effects due to changing saturation levels. • Linearizing interpolation of hydraulic parameters
Nie et al. (2020) Sun et al. (2022)	• Hydraulic conductivity increase with higher potassium nitrate concentrations.
Wydro et al. (2023)	• Accumulation, toxicity, and removal processes of these compounds, but ignores the persistence of these compounds.
García-Santiago et al. (2017)	• Observed differences between experimental and numerical results, which could be attributed to high reactivity of studied compounds that may not have been well modelled.
Martínez-Hernández et al. (2017)	• There is need of further investigation on input concentration on removal rates. • Further study should be conducted to understand chemical transformation of pharmaceutical wastes.
Lyu et al. (2019)	• Need to study reduction of personal care products into end-substances.
Deng et al. (2019)	• Lateral distribution of solutes were ignored in the study.
Pei et al. (2022)	• Raised some major concern like difficulty in determining the exact rate of infiltration of PP products. • As the work becomes interdisciplinary, there is limited knowledge among engineers about the PP product characteristics such as composition, decay rate, and sedimentation etc.
Meffe et al. (2021)	• Most study claim testing under field conditions, most of these studied are conducted under controlled lab conditions. • For proper field effect, the soil sample should be undisturbed during the testing.
An et al. (2022)	• Did not integrate the effect of particle size, and ion strength. • Only relied on the Ph values for adsorption.
Dibyanshu & Scheytt (2025)	• Underscored that there is a need for monitoring and management to prevent groundwater contamination from pharmaceutical wastes. • Long term contamination risk should be studied to explore the real world scenario of microbial interaction.
Karimov et al. (2025)	• Over looked lateral component of water flow.
Ghilassi et al. (2024)	• Not consideration of lateral flow of water which is a major component of in irrigation.
Voulanas et al. (2022)	• Despite its considerable demand for input data, its scares.
Qu et al. (2022)	• Groundwater level fluctuations on lead migration through coarse and medium sand using experimental and analytical simulations
Wang et al. (2024)	• Ground water influence was not considered assuming that it has limited impact on the flow process, also the effects of temperature
Liang et al. (2025)	• Does not account for time dependent chemical reactions. • A long term study to calibrate the model would be better to draw meaningful conclusions. • Need for precise soil hydraulic data, scale issues, and integration with field data limit HYDRUS applicability across different fields.

7. Summary

The study extensively reviewed several existing literatures to explore the advances in HYDRUS-based modelling for water flow and contaminant transport in variably-saturated porous media. The study focused on the challenges, difficulties, shortcomings, and forced assumptions faced by different researchers. Based on the major findings of the review, some recommendations for further development in the domain are described in the following paragraphs.

7.1 Numerical solver

It is observed that when ponding, pooling or some other kind of storage takes place between before the flow merge into water streams, inclusion of the Transient Storage TSM mode with the ADE in HYDRUS may improve the program's ability to predict pollutant flow in rivers or ground water. By integrating TSM, HYDRUS could provide more precise contaminant tracking and better support environmental management and pollution control decisions in rivers where exchange between storage zones and the main channel is significant.

7.2 Parameter definitions

Large amounts of input data are needed for hydraulic models, especially for parameters like environmental conditions, contaminant characteristics, and soil hydraulic properties. Although these data are necessary for precise simulations, they are frequently hard to come by, particularly in field settings (Dahunsi et al., 2025). The type, moisture content, and depth of the soil all have a significant impact on its hydraulic characteristics, including the water retention curve and hydraulic conductivity. Specialised laboratory or field measurements are frequently needed to obtain accurate data for these properties. The accuracy of model predictions may be lowered by the absence of such data or the requirement to estimate values from sparse information (Durner & Flühler, 2006).

Texture, porosity, and hydraulic conductivity are just a few of the characteristics that make soil fundamentally diverse. These elements are critical to hydrological behaviour in larger fields with more soil heterogeneity, water table variations, and topographic variability (Vilim et al., 2024). When working with models at larger scales, these problems become more complicated (Wada et al., 2017). Consequently, several studies have noted the need for higher precision in modelling. Rather than relying solely on point-to-point data for different parameters, incorporating options for parameter curves may improve simulation accuracy and yield more reliable results.

7.3 Calibration and validation

Modelling soil strata requires several properties, such as residual water content, natural soil water content, hydraulic conductivity, and diffusion coefficients. Researchers often rely on soil libraries developed by others. However, soil strata characteristics vary across regions, highlighting the need for more studies from developing economies to create additional soil property libraries. This would help researchers use HYDRUS more effectively. During calibration, including uncertainties associated with flow parameters (including those for soil and solutes) could introduce a probabilistic approach to simulation results, leading to greater precision in modelling. A HYDURS-data sharing community could be helpful in creating a collaborative environment.

7.4 Modelling of surface type

Green space surfaces often include vegetation, spaced brick lanes, and other features that influence precipitation runoff and water percolation into the ground. Therefore, providing a distinct option to define different types of soil surfaces would make modelling more realistic and accurate.

7.5 Modelling of highly reactive pollutants

Studies such as Lyu et al. (2019) have observed that some pharmaceutical pollutants are highly reactive and exhibit strong adsorption in soil. Some of these pollutants may coagulate while some can get adsorbed in the top soil layers in the process of moving through the soil. HYDRUS should be able to account for this precipitation and incorporate the time-dependent coagulation characteristics into simulations, as the flow may not be uniform or steady. The distribution of chemicals can change the pore size and permeability of the soil.

7.6 ML and AI integration

In order to improve HYDRUS modelling accuracy and efficiency, machine learning (ML) techniques are being incorporated into it more and more (Saha & Pal, 2024). HYDRUS models can be made more effective, adaptable, and able to manage big datasets by integrating machine learning, which will speed up model development and produce predictions that are more accurate (Dai et al., 2025). In order to address flow issues, studies like Šimůnek et al. (2024), Li et al. (2025), and Zhu et al. (2024) have combined

HYDRUS with a variety of data analysis methods, such as neural networks and machine learning models. ML models increase model accuracy and decrease the amount of computation needed for calibration (Xia et al., 2021; Kumar et al., 2023; Ahmad et al., 2024). The application of artificial intelligence (AI) in a variety of fields is a recent technological trend. The HYDRUS program could adopt parameters appropriate for accurate simulation by integrating AI, which would lower modelling error and improve model precision (Zhao et al., 2024). AI can also identify patterns in simulation results, potentially alerting users to unforeseen modelling errors and thereby improving the simulation process (Shukla, 2024).

7.7 Enhancing GUI and integration with GIS

If the GUI is improved further, it will be easier for different groups of practitioners, including researchers, engineers, and students, to adopt the program without requiring a lot of computational training (Šimůnek et al., 2024). Making editing and viewing options (such as chamfering, boring through soil, rotation and movement of the model) more accessible would benefit users. Additionally, enabling the import and export of data to and from other programs would make HYDRUS more accessible and attract a wider user base (Samborska-Goik & Pogrzeba, 2024).

7.8 Policy and management applications

The review points out towards integration of HYDRUS with GIS in a monitoring system for environmental, agricultural, and aquifer management (Li et al., 2024; Dou et al., 2022; Zhou & Li, 2020; Locatelli et al., 2019). The review underscores that Hydrus-based simulations can play a larger role in policy and decision making by timely disseminating the relevant data and raising alarm, for example if a certain level of pollutant is observed in the ground water, or if the soil of some region is experiencing lower than usual water content.

The review concludes that HYDRUS-based modelling for water flow and contaminant transport in variably saturated porous media has made significant strides, but it also identifies important challenges in terms of parameter definition, calibration, surface and pollutant modelling, and integration with new technologies such as machine learning. The HYDRUS's potential for environmental and agricultural applications can be improved through better data collection, community collaboration, improved user interfaces, and coupling with decision-support systems. The usefulness of HYDRUS in policy, management, and sustainable resource planning could be significantly increased by future research concentrating on improving real-time data assimilation, expanding pollutant interaction representations, and improving model accuracy.

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