



REVIEW ARTICLE

Applications of the HYDRUS model in irrigation management, groundwater recharge and crop studies: A review

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Abstract

The computer software HYDRUS was developed for simulating water movement, heat transport and solute dynamics in variably saturated porous media. HYDRUS was first introduced as SWMS-2D in 1991, followed by HYDRUS-1D in 1995, since then it has been continuously developed and has become one of the most widely used models for vadose zone hydrology applications. In this review, HYDRUS model-based studies reported in the literature are organised under three broad categories: (i) irrigation management and efficiency; (ii) groundwater recharge estimation and (iii) crop growth and root water uptake modelling. Simulation studies using HYDRUS-1D and HYDRUS-2D/3D have reliably reproduced soil water content and soil water potential dynamics under drip, furrow, sprinkler and subsurface irrigation systems. Coefficient of determination (R^2) values frequently exceeded 0.90 across the reviewed studies, which is consistent with findings reported in the majority of irrigation and recharge applications. HYDRUS has also been extensively used to quantify deep percolation fluxes from land surfaces under different land-use and climate conditions to estimate groundwater recharge potential, which is particularly useful for water budget closure in arid and semi-arid regions. Integration of HYDRUS with crop models (such as DSSAT, SWAP and HP2) has helped researchers understand the partitioning of evapotranspiration (ET), nitrate leaching potential and root zone salinity dynamics for precision agriculture applications. The HYDRUS model has recently been coupled with machine learning tools to estimate model parameters, assess climate-change impacts and enable multi-process coupling for modelling constructed wetlands. Some research gaps and rarely explored areas include tropical region applications, where hydrologic data may not be readily available and standardised protocols for model calibration in heterogeneous soils. Future directions identified in this review include coupling HYDRUS with remote sensing inputs and machine learning frameworks to extend vadose zone modelling from plot to regional scales, developing physics-informed neural networks as real-time irrigation advisory tools and building standardised calibration protocols for tropical and data-limited environments where heterogeneous soils and monsoon-driven hydrology currently limit model applicability.

Keywords: crop modelling; groundwater recharge; HYDRUS; irrigation management; root water uptake; solute transport; vadose zone; variably saturated flow

Introduction

Water scarcity and food security are considered two of the most important issues facing humanity in the 21st century (1). Irrigation dominates global water withdrawals, accounting for approximately 70 % of all freshwater use and has placed severe stress on both surface water and groundwater resources (2). Rational irrigation scheduling, accurate estimation of groundwater recharge and crop water use modelling are critical for the sustainable management of water resources. Rational irrigation scheduling avoids both under- and over- irrigation, thereby reducing water waste while maintaining crop yield (3). Accurate groundwater recharge estimation ensures aquifer withdrawals remain within renewable limits (4). Crop water use modelling matches water supply to actual plant demand, minimising unnecessary abstraction (5). Together, these components reduce water loss, protect groundwater resources and

improve allocation efficiency, forming the basis of sustainable water management. Physics-based numerical simulation models that represent water and solute movement in the soil-plant-atmosphere system have emerged as widely used research tools available to scientists working toward these goals. The HYDRUS model suite, developed by Šimůnek, van Genuchten, Šejna and colleagues at the US Salinity Laboratory and PC-Progress is a widely adopted computational platform for modelling water movement, heat transfer and solute transport processes in variably saturated porous media (6–8). HYDRUS models solve Richards' equation and the one-, two- or three-dimensional advection-dispersion equation using Galerkin finite element procedures. HYDRUS has evolved from its early beginnings as SWMS-2D into HYDRUS-1D and HYDRUS-2D and finally into HYDRUS(2D/3D), which is capable of simulating increasingly complex geometries, boundary conditions and coupled processes (9).

HYDRUS has been used extensively since its initial public release with over 10000 registered users worldwide and thousands of publications citing the software (10, 11). Irrigation engineers, vadose zone hydrologists, soil scientists, environmental engineers and agronomists have applied the model in diverse environments ranging from wetlands to deserts. Several reviews have discussed HYDRUS applications within narrowly defined subdomains such as drip irrigation, solute transport or nitrate leaching (12–14). To date, there has been no review that comprehensively synthesises cross-domain applications covering irrigation, groundwater recharge and crop studies together and no prior review has documented the development of HYDRUS through time or identified emerging trends in its application. These trends include climate-change impact studies on recharge and irrigation demand (15). They also include machine learning integration for parameter estimation and surrogate modelling (16, 17). A further trend is precision irrigation scheduling guided by real-time crop water status (18). While several reviews of HYDRUS applications exist covering model development and capabilities, irrigation processes, tree crop drip irrigation, constructed wetlands, groundwater vadose zone coupling, pollutant transport and low-impact development simulation and saline soil water and salt transport, no single review has simultaneously and systematically addressed HYDRUS applications across irrigation management, groundwater recharge and crop growth within a unified framework (11, 19–24). The objective of this review is to fill this gap by: 1) summarising the HYDRUS developmental history and theoretical basis; 2) providing a

systematic review of HYDRUS applications related to irrigation water management; 3) reviewing studies focused on groundwater recharge estimation; 4) reviewing root water uptake studies that HYDRUS simulates directly through the Feddes stress-response function alongside crop growth and yield studies that HYDRUS addresses through coupling with external models such as DSSAT, SWAP and AquaCrop and 5) highlighting major limitations and future research needs. A timeline graphic showing HYDRUS development highlights and publication trends within each of these application domains is provided in Fig. 1.

Methodology: Literature search strategy and screening process

A systematic literature search was conducted in Scopus and Web of Science in December 2025. Both databases were chosen for their broad coverage of the journals in which HYDRUS applications are typically published. The base term “HYDRUS” was searched within the title, abstract and keyword fields and paired with domain-specific co-terms for each review category: irrigation, drip, subsurface drip, furrow, sprinkler and deficit irrigation for irrigation management; groundwater recharge, managed aquifer recharge, infiltration and drywell for recharge; and root water uptake, evapotranspiration (ET) partitioning and nitrogen (N) transport for crop growth. The resulting publication trend across these three domains, together with two further domains tracked in the broader search described below (contaminant transport and wetlands and drainage), which are addressed in Section 6 of this review, is presented in Fig. 1.

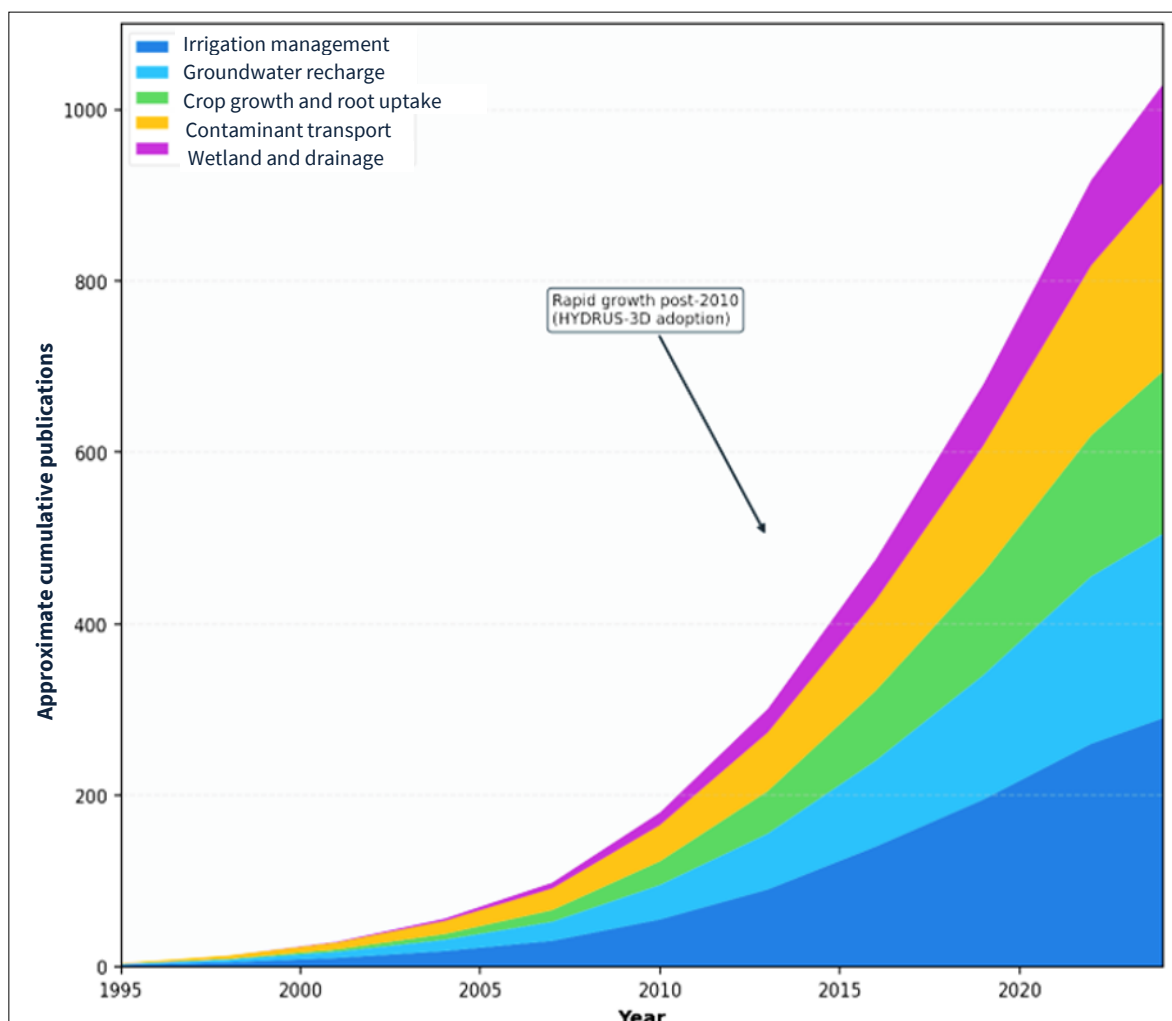


Fig. 1. Cumulative publication trend in HYDRUS applications across six domains: irrigation management, groundwater recharge, crop growth, root uptake, contaminant transport and wetlands and drainage (1995–2025).

Records were screened in two stages. The first stage checked titles and abstracts against the inclusion criteria, which required the use of HYDRUS in its 1D, 2D or 3D form or of a HYDRUS-based coupled model such as HP1, HP2 or HYDRUS-MODFLOW; publication as a peer-reviewed, English-language journal article and the demonstration of clear relevance to irrigation management, groundwater recharge or crop growth. Studies were excluded if they relied on a different vadose-zone model, appeared only as conference proceedings or non-English publications or reported no application-relevant outcome (including non-HYDRUS models, grey literature and abstracts only). The second stage involved reading the full text of each remaining study to confirm eligibility and to extract the irrigation or recharge type, HYDRUS version, soil characteristics and key findings. This two-stage process identified 97 studies that satisfied all inclusion criteria. This focused, criteria-screened set of 97 studies is distinct from the broader bibliometric search summarised in Fig. 1, which tracks publication volume across all five application domains including contaminant transport and wetlands and drainage, without applying full-text screening to every record.

HYDRUS model: Theoretical framework and development history

Governing equations

HYDRUS simulates water flow in variably saturated porous media by solving the modified Richards equation (Eqn. 1) (25):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[K(h) \left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A \right) \right] - S \quad (\text{Eqn. 1})$$

where $\theta(h)$ is the volumetric water content [$L^3 L^{-3}$], h is the pressure head [L], K is the unsaturated hydraulic conductivity [LT^{-1}], K_{ij}^A are dimensionless components of the hydraulic conductivity anisotropy tensor, S is the sink term due to root water uptake [$L^3 L^{-3} T^{-1}$] and x_i denotes the spatial coordinates [L] (7). Soil hydraulic properties are specified using the van Genuchten-Mualem constitutive relationships (Eqn. 2) (26):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \quad \text{for } h < 0 \quad (\text{Eqn. 2})$$

where θ_r and θ_s denote the residual and saturated water contents, respectively [$L^3 L^{-3}$]; α is the shape parameter [L^{-1}]; l is a pore connectivity parameter; n and m are empirical constants related to the pore size distribution index.

Transport of solutes is described by the advection-dispersion equation (ADE) with additional first-order degradation and nonlinear sorption (6–8). Heat transport is calculated simultaneously by solving the Fourier's law (3–5). Root water uptake is calculated using the macroscopic root water uptake model (27). This model decreases water uptake rates under water stress and osmotic stress.

Development history

The HYDRUS model development timeline, highlighting major software releases, is presented in Fig. 2. HYDRUS was originally developed from SWMS-2D, a standalone two-dimensional finite element code published by Šimůnek and van Genuchten for two-dimensional simulation of variably saturated water flow. HYDRUS-1D followed, adding a user-friendly graphical interface and capability for one-dimensional simulation of coupled water, heat and solute transport. HYDRUS-2D followed shortly after, adding two-dimensional flow domains to HYDRUS capabilities (6, 9, 28). HYDRUS (2D/3D) v1.0 was developed in collaboration with PC-Progress, featuring a Windows-based graphical user interface and capability

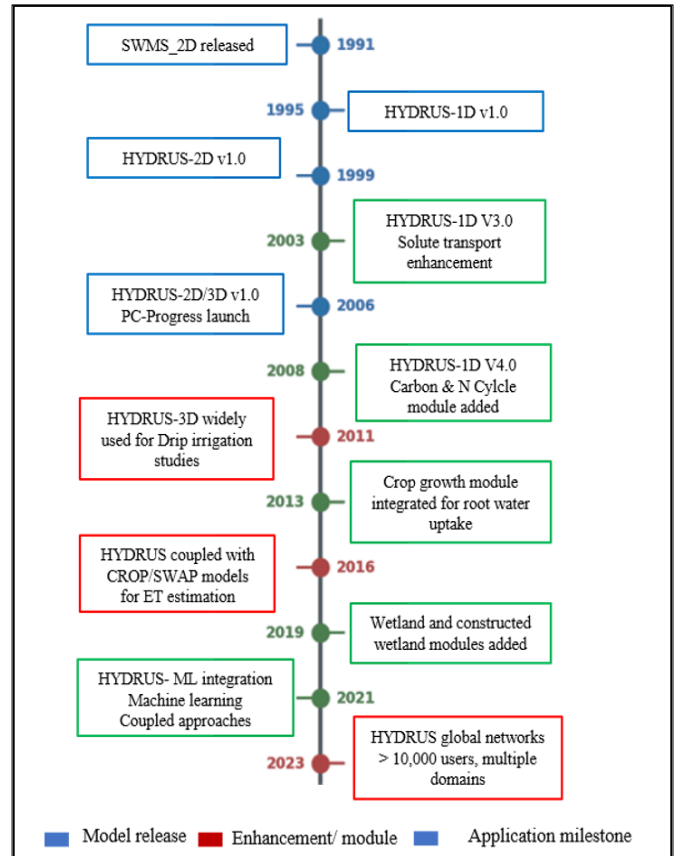


Fig. 2. HYDRUS model development timeline (1991–2023) showing major software releases (blue), module enhancements (green) and key application milestones (red).

for simulating flow and solute transport in complex three-dimensional flow domains (29). Major upgrades since have included the additions of dual-porosity/dual-permeability processes to describe preferential flow pathways, carbon and N cycling processes, plant growth and root architecture processes and interfaces to couple HYDRUS with crop simulation models such as DSSAT and SWAP (13, 30–34). Table 1 presents a summary of the major HYDRUS versions and their capabilities.

HYDRUS development and application trends

The timeline of model development plotted against the cumulative publication trend across the three primary application areas is illustrated in Fig. 1. Publication counts were approximated (search conducted during December 2025) by searching Scopus and Web of Science with HYDRUS as a title, abstract, keyword term with co-terms as irrigation or groundwater recharge or crop studies. The increase in publications accelerated after 2010 due to increased adoption of HYDRUS (2D/3D) after it became available as commercial software through PC-Progress. As shown in Fig. 1, the cumulative HYDRUS publications across the five tracked domains reached approximately 1020 by 2024. Irrigation management studies account for the largest single share, at 28 %, followed by contaminant transport and groundwater recharge studies, each at 21 %. Crop growth and root uptake studies make up 19 %, while wetlands and drainage applications, the smallest category, account for 11 %. Together, irrigation management and groundwater recharge represent nearly half of all HYDRUS publications (approximately 49 %), reflecting their long-established position within the field, while contaminant transport and crop growth studies continue to grow as substantial areas of application.

Table 1. Major HYDRUS versions, key capabilities and primary application domains (6–8)

Version	Year	Key capabilities	Primary applications
SWMS-2D	1991	2D variably saturated flow	Subsurface drainage, basic vadose zone
HYDRUS-1D	1995	1D water, heat, solute transport, root uptake	Irrigation scheduling, leaching
HYDRUS-2D	1999	2D variably saturated flow and transport	Furrow irrigation, subsurface drainage
HYDRUS-2D/3D	2006	3D variably saturated flow, GUI-based	Drip irrigation, GW recharge, wetlands
HYDRUS (2D/3D) v3+	2016	C/N cycle, crop growth, dual-permeability	Precision agriculture, climate change studies

Data inputs, model outputs and evaluation standards for HYDRUS applications

Reproducible HYDRUS simulations require complete documentation of inputs, boundary conditions and outputs across all activated modules. For the water flow module, mandatory inputs are the soil texture class and measured bulk density for each horizon. Van Genuchten parameters (θ , θ_s , α , n , K_s) must be reported with the fitting method stated, whether laboratory retention curve, inverse modelling or pedotransfer function. The domain geometry must specify whether a one-dimensional profile, two-dimensional cross-section or axisymmetric domain was used. The upper boundary condition must state whether atmospheric forcing, constant flux or constant head was applied. The lower boundary must specify free drainage, seepage face, prescribed pressure head or water table condition. A measured initial soil water content or pressure head profile is required at the start of the simulation. Key outputs are soil water content profiles at observation depths, cumulative actual ET partitioned into transpiration and evaporation and drainage flux at the lower boundary. These outputs should be evaluated using standard performance metrics such as root-mean-square error (RMSE), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and coefficients of determination (R^2), which together provide the tools needed to judge model reliability and acceptability (35, 36).

When the solute transport module is activated, additional inputs are required alongside the water flow parameters. Measured soil bulk density (ρ_b), longitudinal dispersivity (D_L) and molecular diffusion coefficient (D_w) must be reported with their measurement basis. The D_L varies by orders of magnitude across soil types and must be measured rather than assumed (7). For reactive solutes such as nitrate, the distribution coefficient K_d and first-order degradation rates in liquid (μ_w) and solid (μ_s) phases must be reported with the experimental or literature source from which they were derived. The initial solute concentration profile for each horizon must be measured at simulation start. Key outputs are solute concentration profiles at selected depths, cumulative leaching fluxes and the depth of the solute front at specified times. Model performance against measured concentration data should be evaluated using the same suite of statistical metrics applied for water flow.

For groundwater recharge simulations including managed aquifer recharge, basin infiltration and stone-filled drywell systems, additional boundary condition information is required. Where a reservoir or drywell is represented using a variable head or seepage face boundary, the time-variable ponding depth or water level series must be provided as measured field input. The initial vadose zone water content profile surrounding the structure must reflect measured pre-event field conditions. Key outputs for recharge applications are cumulative infiltration volume, wetting front depth over time, lateral spread of the wetting zone and recharge flux reaching the water table. These should be validated against

measured observation well water levels, surface ponding depth records and field soil water content profiles using standard statistical performance metrics for consistent cross-study comparison.

For studies incorporating root water uptake, the Feddes stress parameters h_1 , h_2 , h_3 and h_4 must be reported for each simulated growth stage. Their source must be stated whether the Feddes database, direct measurement or inverse estimation (37). The Vrugt root distribution parameters maximum rooting depth (Z_m), maximum lateral extent (X_m), depth and position of peak root density (Z^* and X^*) and empirical shape coefficients p_z and p_x must be stated alongside the irrigation management and growth stage for which they were calibrated. For salinity studies, Maas-Hoffman threshold and slope must identify whether species level or cultivar specific values were used. The calibration period must span at least one complete growing season. Validation must use an independent period or site dataset. Outputs of actual transpiration, root zone water depletion and crop water stress index should be validated against sap-flow measurements, weighing lysimeter data or eddy covariance estimates using the same statistical tools applied across all modules.

HYDRUS applications in irrigation management

Subsurface drip irrigation

Irrigation is one of the most prominent application areas of HYDRUS, with drip/subsurface drip irrigation (SDI) being the most common physical scenario HYDRUS has been applied to experimentally. This stems largely from the fact that physically based analytical solutions do not exist for describing two-dimensional (or three-dimensional) wetting patterns arising from point-source emitters, so numerical solutions are required to study this process. HYDRUS-2D was first validated for simulating soil wetting patterns under SDI in loam and clay loam soils (12). Measured versus simulated soil water content profiles compared favourably, with R^2 often exceeding 0.92. Spatial patterns of water depletion were adequately simulated by the root water uptake model included in HYDRUS (27).

Point-source emitter wetting bulbs were also simulated using HYDRUS-2D and 3D compared against analytical solutions (38). HYDRUS performed much better for soils with heterogeneous properties when compared to empirical formulas predicting wet bulb shape. The authors were also able to show through simulation that emitter discharge rate, soil texture and initial moisture content jointly control the horizontal-to-vertical ratio of wetting extent, information important for emitter spacing recommendations. HYDRUS-2D was used to simulate water and N distribution under trickle fertigation of onion in a field experiment and validated against measured ammonium and nitrate concentrations in the root zone (39). Fertigation applied at the beginning of the irrigation event concentrated N within the upper 30 cm of the soil profile, while fertigation applied at the end of the irrigation event caused greater nitrate displacement toward deeper layers. This demonstrated that HYDRUS-2D can reliably represent the effect of fertigation timing on N distribution under trickle irrigation.

This result was independently supported by validation of HYDRUS-2D for N uptake under furrow-irrigated maize, which reported R^2 above 0.95 and normalised RMSE below 18.60 % for simulated crop N uptake confirming that HYDRUS reliably captures N dynamics across both furrow and trickle delivery systems (40).

A modified FAO-56 dual crop coefficient approach was coupled with HYDRUS-2D to estimate actual transpiration and evaporation for subsurface-drip-irrigated wine grapes across four deficit irrigation treatments (51–92 % of normal application) (18). Seasonal actual crop evapotranspiration (ETc) varied between 239 and 382 mm, deep percolation accounted for 35–40 % of total applied water and actual crop coefficients (mean $K_c = 0.27$) matched literature values, demonstrating HYDRUS-2D's reliability for assessing deficit irrigation in perennial crops.

Furrow and surface irrigation

Surface and furrow irrigation presents unique simulation challenges due to the transient ponding, infiltration and redistribution processes that occur. HYDRUS was coupled with a surface irrigation hydraulic model to simulate infiltration and redistribution under furrow irrigated wheat and maize cropping systems in France (5). HYDRUS-2D was able to successfully reproduce infiltration rates and soil water contents after irrigation events. Simulations of wheat and maize yields was also improved with the coupled HYDRUS-surface irrigation simulations over standard crop models. Water use efficiency and deep percolation for sprinkler and surface irrigation practices in semi-arid Portugal were assessed using HYDRUS-1D (14). Simulation results show that HYDRUS-1D can estimate seasonal ET within 8 % of field measurements. A review of HYDRUS simulations under different surface boundary conditions found that using atmospheric boundary conditions with surface runoff routing allowed realistic ponding and redistribution during and after irrigation events (41). Time-variable flux or head boundaries are easily prescribed to simulate realistic irrigation schedules such as deficit or alternate furrow irrigation.

Recent experimental studies have extended HYDRUS-based furrow and surface irrigation research to diverse crops, soils and climates. HYDRUS-2D was validated for furrow-irrigated maize over two growing seasons (42). Model predictions of N uptake achieved R^2 above 0.95 across all three N application rates. Simulations showed that N concentration was consistently greater under ridges than furrows because drier ridge soil retains mobile nitrate during and after the irrigation event. A two-season field experiment was conducted on wide ridge and furrow-irrigated winter wheat in China (43). HYDRUS-2D reproduced soil water content with R^2 above 0.68 and RMSE below $0.10 \text{ cm}^3 \text{ cm}^{-3}$ in both horizontal and vertical directions. The optimal management combination was 220 kg ha^{-1} of N with irrigation to 70 % of field capacity. Controlled furrow infiltration experiments on clay loam and sandy loam under fertiliser solution application were conducted and simulated with HYDRUS-2D (44). HYDRUS-2D reproduced cumulative infiltration with RMSE of 0.66 cm and soil water content with RMSE of $0.027 \text{ cm}^3 \text{ cm}^{-3}$. The study also showed that fertiliser solution concentration modified the soil saturated hydraulic conductivity. Furrow irrigation with urea was investigated using HYDRUS-1D and HYDRUS-2D in a controlled infiltration study (45). Inversed parameters were reliable and simulations showed urea was completely hydrolysed to ammonium within 5 days of redistribution. The infiltration rate increased with urea concentration, water depth and furrow width but decreased with initial soil water content.

HYDRUS-2D was evaluated for seven irrigation and tillage strategies in a field experiment on wheat in India during the 2022–2023 rabi season (46). Strategies included furrow irrigation in raised beds, conventional flood irrigation and zero-tillage flood irrigation. HYDRUS-2D accurately simulated soil water dynamics across all treatments during the critical 30-day growth window. Surface and drip irrigation were compared in a two-season field experiment on carrot grown on saline soil in arid Tunisia (47). HYDRUS 2D/3D produced lower normalised RMSE for surface irrigation than for drip irrigation at the same measurement depths. These studies collectively confirm that HYDRUS-2D reliably simulates water and N dynamics under furrow and surface irrigation across crops and climates. Fertigation timing relative to the irrigation event and soil texture are the primary factors governing N distribution within the root zone. HYDRUS-2D is the only widely available model that resolves both the water flow and coupled solute transport needed to optimise these management decisions.

Irrigation scheduling and water use efficiency

HYDRUS has been used as a virtual lysimeter in numerous studies for assessment and optimisation of irrigation scheduling strategies. HYDRUS-2D was used to create trigger-threshold-based irrigation schedules for pepper and tomato production systems in Israel (3). Optimal depths of sensors were determined such that drainage losses were minimised while maintaining acceptable root zone water status. Results showed sensor-based SDI systems calibrated using HYDRUS used 20–30 % less water than conventional irrigation schedules. HYDRUS-2D was used to assess nitrate leaching under three different micro-irrigation strategies and found that emitter depth is a strong control on nitrate movement relative to root-zone volume (48). Overall deeper emitters improved nitrate uptake efficiency by 12–18 %.

HYDRUS has been validated for sprinkler irrigation across sandy loam to clay loam soils in Korea, Morocco, India, Iran and China. Soil water content was reproduced with RMSE of $0.023 \text{ cm}^3 \text{ cm}^{-3}$ for soybean and R^2 of 0.86 for wheat across seven irrigation strategies (46, 49). Actual ET matched eddy covariance within 8 % for winter wheat in semi-arid Morocco (50). Return flow under sprinkler irrigation was quantified as negligible compared with 13.3 % under furrow irrigation on the same crop and soil, demonstrating that irrigation method selection governs groundwater recharge potential beyond field-scale water use efficiency (51). Deficit schedules derived through HYDRUS reduced applied water by 22 % while sustaining crop yield above 90 % of the well-watered control (46, 52).

Boundary condition setup remains the principal challenge in sprinkler simulation. When canopy interception is not separated into stemflow and throughfall components, inter-row soil water content is overestimated by up to 40 % in row crops (53). HYDRUS-2D/3D resolves this by prescribing spatially explicit canopy flux boundaries at the soil surface. Centre-pivot systems, sprinkler fertigation and tropical monsoon environments have not yet been addressed in validated HYDRUS studies. These gaps limit current applicability to temperate and semi-arid contexts, represent the most important directions for future research. Examples of HYDRUS applications to irrigation management studies published in the peer-reviewed literature and organised by author(s), type of irrigation and main findings was listed in the Table 2.

Table 2. Summary of published HYDRUS studies in irrigation management

Year	Irrigation type and soil type	Crop/ cropping systems	Performance metrics	Key findings	HYDRUS version	References
2008	Surface drip; Multiple soil texture	Multiple crops (review)	R^2 generally > 0.85 across cited field studies in review	Root zone soil moisture dynamics simulated under arid conditions	HYDRUS-2D/3D	(7)
2004	Drip (subsurface); Loam, clay loam	Cotton	$R^2 > 0.92$; RMSE < 0.04 cm ³ cm ⁻³	Soil wetting patterns well simulated; deficit irrigation modelled	HYDRUS-2D	(12)
2011	Sprinkler and furrow; loam, sand clay loam	Maize; Cereals	$R^2 > 0.88$ for E and T partitioning; seasonal ET_a within 8 %	ET and deep percolation estimated under Mediterranean conditions	HYDRUS-1D	(14)
2017	Drip, deficit irrigation; sandy loam	Wine grapes	RMSE < 0.03 cm ³ cm ⁻³ ; actual K_c within ± 5 % of reference values	Soil water, nitrate and chloride dynamics under deficit irrigation	HYDRUS-2D	(18)
2010	Subsurface drip; Sand; loam; Clay	Generic row crop	Wetting bulb dimensions within ± 10 % of field measurements	Wetting bulb geometry validated with field experiments	HYDRUS-2D/3D	(38)
2022	Furrow fertigation; clay loam	Maize	$R^2 > 0.95$; NRMSE < 18.60 % for crop N uptake	HYDRUS captures N dynamics under furrow delivery consistent with trickle fertigation results	HYDRUS-2D	(40)
2019	Furrow fertigation; Silty clay loam	Maize	$R^2 > 0.95$; NRMSE < 18.60 % for N uptake across all treatments	N consistently greater under ridges than furrows because dry ridge soil retains mobile nitrate	HYDRUS-2D	(42)
2023	Wide ridge and furrow; sandy loam	Winter wheat	$R^2 > 0.68$; RMSE < 0.10 cm ³ cm ⁻³ for soil water content and N	Optimal management: 220 kg N ha ⁻¹ with irrigation to 70 % field capacity	HYDRUS-2D	(43)
2025	Sprinkler and flood; Clay loam	Winter wheat	$R^2 = 0.86$; RMSE = 0.019 cm ³ cm ⁻³ (pooled across all strategies)	Sprinkler raised-bed combination achieved highest LAI and root growth; HYDRUS captured narrower wetting front under sprinkler vs flood irrigation	HYDRUS-2D	(46)
2021	Sprinkler; Sandy loam	Soybean	RMSE = 0.023 cm ³ cm ⁻³ ; $R^2 = 0.663$	Post-irrigation capillary redistribution improved root-zone water uniformity by 8–15 % within 48 hr; application non-uniformity effects on root-zone water distribution quantified	HYDRUS-1D	(49)
2021	Sprinkler; Sandy clay loam	Winter wheat	NSE > 0.80; ET_a within 8 % of eddy covariance; RMSE < 0.04 cm ³ cm ⁻³	Actual ET matched eddy covariance within 8 %; deep percolation 12–18 % of applied water under over-irrigation; ET partitioned at daily resolution across two seasons	HYDRUS-1D	(50)
2015	Sprinkler; Silt loam	Maize	$R^2 = 0.75$ (calibration); $R^2 = 0.66$ (validation); RPD = 1.45	78 % of sprinkler rainfall intercepted by maize canopy as stemflow	HYDRUS-2D/3D	(53)

R^2 : coefficient of determination; NSE: Nash-Sutcliffe efficiency; NRMSE: normalised RMSE.

HYDRUS applications in groundwater recharge estimation

Natural and diffuse recharge

Groundwater recharge, defined as the downward flux through the soil profile and vadose zone that replenishes groundwater, is exceptionally difficult to quantify directly. HYDRUS-1D has become the go to model for quantifying recharge fluxes based on vadose zone process simulation. For example, one of the first spatially distributed studies of vadose zone recharge using HYDRUS-1D was conducted in semi-arid Texas, USA (54). It was shown that recharge beneath native brush vegetation was nearly zero because actual ET was essentially equal to precipitation. By contrast, conversion to cultivated cropland resulted in recharge that was 1–2 orders of magnitude greater than native vegetation recharge. This variability in recharge spatially across the study area strongly influenced groundwater management decisions in the region.

Spatially distributed monthly groundwater recharge for a temperate glacial-outwash watershed in Wisconsin was estimated using HYDRUS-1D and benchmarked against water table fluctuation and base flow separation methods (55). Annual recharge estimates

from HYDRUS-1D ranged from 80 to 320 mm yr⁻¹ across soil texture and land cover classes, with sandy soils yielding recharge rates 2–4 times greater than silt loam soils under identical precipitation inputs. HYDRUS-1D consistently outperformed simple water balance models because it explicitly resolved transient vadose zone water storage and the lag time between surface precipitation and water table response that ranged from days in coarse-textured soils to several weeks in fine-textured profiles. The study concluded that HYDRUS-1D is the most appropriate approach for spatially distributed recharge estimation in glacial-outwash landscapes where soil texture heterogeneity is the dominant control on recharge variability and where water balance models that assume instantaneous vertical drainage produce systematic overestimates of recharge during low-intensity rainfall periods. HYDRUS-1D applied on the heavily irrigated North China Plain to quantify irrigation return flow recharge, showing that irrigation returned more than 70 % of groundwater recharge to the aquifer during the growing season. This had important implications for groundwater sustainability in one of China's most intensively cultivated regions.

Managed aquifer recharge

Managed aquifer recharge (MAR) includes intentional recharge processes through infiltration basins, injection wells and spreading grounds. HYDRUS-1D and HYDRUS-2D were applied to model flow and clogging mechanisms in infiltration basins, showing that biological clogging could be accounted for by using a temporally variable saturated hydraulic conductivity, which yielded better agreement with observed infiltration rates (56). The numerical simulation explained temporal trends in clogging recovery observed during drying periods. HYDRUS-1D was applied on dryland cotton fields in Texas to compare recharge estimates derived from vadose zone chloride mass balance and HYDRUS-1D simulations, concluding that recharge estimates from HYDRUS-1D were consistently 15–25 % greater than those from chloride methods due to the presence of preferential flow pathways (57). HYDRUS-2D was used to model flow and transport through stony soils in Mediterranean Italy, showing that recharge is significantly greater when macropore flow is included in the simulation versus models assuming a homogeneous soil texture (58).

Standard analytical infiltration methods, including Green-Ampt, Philip and Kostiakov, treat the soil as a homogeneous one-dimensional medium. Green-Ampt assumes a sharp wetting front advancing through a uniformly wetted soil above a dry zone and calculates infiltration rate from capillary suction head and saturated conductivity. Philip derives a power series solution to the Richards' equation for ponded infiltration into a uniform soil profile and expresses cumulative infiltration as a function of time and two fitted parameters. Kostiakov uses a purely empirical power function fitted to observed cumulative infiltration measurements without any physically based soil property as input. All three treat the soil as a homogeneous one-dimensional medium and cannot represent the lateral redistribution or stratification effects that govern recharge in heterogeneous field soils, which HYDRUS addresses through its numerical solution of the Richards equation in up to three spatial dimensions (59). However, accuracy gain depends critically on the quality of site-specific hydraulic characterisation.

The most systematic HYDRUS-based drywell project was conducted by Sasidharan and colleagues across five studies from 2018 to 2025. Three design-relevant findings emerged. First, the lateral flow component at the drywell perimeter accounts for 20 to 35 % of total recharge. Analytical methods that treat flow as purely vertical consistently underestimate recharge capacity, leading to oversised and costlier infrastructure (60). Second, fine-textured lenses within otherwise coarse profiles reduce effective recharge by 30 to 50 % relative to homogeneous predictions. Bulk-averaged hydraulic properties are therefore insufficient for accurate design in stratified soils (61, 62). Third, viral transport modelling showed that drywell siting relative to aquifer depth poses a quantifiable public health risk. Virus concentrations exceeded regulatory thresholds where the vadose zone was shallower than approximately 3 m under typical inactivation rates (63). A comparison of alternative MAR infrastructure showed that lined canals maximised spatial recharge uniformity, while gravel-packed wells achieved the highest per unit recharge rate under identical conditions (64). These findings are internally consistent and methodologically valuable. However, they derive predominantly from USA arid-climate sandy soils. Generalisation to humid tropical or fine-textured contexts requires independent validation.

Independent validation across diverse hydrogeological contexts reinforces the core drywell findings while revealing consistent site dependencies. Flood-recharge volumes for alfalfa in San Joaquin Valley were reproduced to within 8 % of the observed values using HYDRUS-2D (65). Accuracy was highly sensitive to antecedent soil water content; a parameter rarely measured at management-relevant temporal resolution. An R^2 above 0.88 for tank-fed recharge was achieved across three soil types in India and Africa, with site-to-site variability dominated by textural heterogeneity rather than climate or tank geometry, independently confirming heterogeneity as the cross-regional dominant uncertainty source (66). The same conclusion was reached for stormwater ponds: stratified layering reduced recharge 30 to 45 % below homogeneous predictions regardless of pond geometry (67). Inverse optimised parameters reproduced Cape Town MAR volumes within 8 % in a data limited urban setting, provided that soil characterisation extended to adequate depth (68).

HYDRUS-1D was applied to evaluate low-impact development stormwater infiltration systems across three contrasting soil textures in Canada, showed that the model captured seasonal vadose zone recharge dynamics with NSE above 0.80 and RMSE below 15 mm for monthly recharge flux predictions (69). Projected rainfall intensification under RCP 8.5 climate scenarios increased peak recharge events by 20 to 35 % in sandy soils but by less than 10 % in clay profiles, confirming that soil texture rather than precipitation change magnitude controls how strongly urban infiltration systems respond to future climate intensification. A comparative summary of HYDRUS applications in groundwater recharge estimation was presented in Table 3.

A coupled HYDRUS-MODFLOW framework demonstrated that vadose zone transit time dynamics governed seasonal transitions between hydraulically disconnected and connected river-aquifer states in a semi-arid alluvial system (70). In losing stream reaches the time-variable unsaturated zone flux simulated by HYDRUS reduced streamflow depletion estimates by 18 to 40 % relative to MODFLOW-only predictions (70). It shown that omitting vadose zone processes systematically overestimates stream depletion in aquifer systems where the depth to the water table is sufficient to sustain an unsaturated zone of significant thickness. HYDRUS-based vadose zone transit time predictions were further shown to support polycyclic aromatic hydrocarbon (PAH) contamination risk assessment from soil core concentration profiles, reducing dependence on groundwater monitoring infrastructure (71). Across all studies, soil heterogeneity characterisation and initial soil water content measurement emerge as the primary targets for reducing HYDRUS recharge prediction error, regardless of infrastructure type or climate region.

Recharge under climate change scenarios

Climate change affects recharge by changing precipitation intensity and timing, as well as demand for ET. HYDRUS has been coupled with outputs from climate models in increasing frequency to make predictions of future recharge. Downscaled precipitation from a global climate model was used as input into HYDRUS-1D order to project recharge changes in the southwestern USA (72). Recharge was predicted to increase under future warming scenarios even if annual precipitation decreases, due to more intense precipitation leading to faster infiltration rates that exceed ET demand during storms. HYDRUS-1D was coupled with outputs from the SWAT

Table 3. Summary of published HYDRUS studies on groundwater recharge

Year	Region/context	Key findings	HYDRUS version	References
2003	Arid, North China Plain	Irrigated agriculture major driver of GW recharge; HYDRUS well reproduced	HYDRUS-1D	(4)
2003	Semiarid Texas, USA	Recharge estimation under native vs. cultivated land cover contrasted	HYDRUS-1D	(54)
2007	Temperate, Wisconsin	Monthly recharge estimation using HYDRUS improved accuracy vs. WTF method	HYDRUS-1D	(55)
2008	Arid zones, USA	Deep percolation and recharge fluxes estimated under MAR scenarios	HYDRUS-1D	(56)
2011	Dryland, Texas	HYDRUS-1D recharge estimates compared with chloride mass balance	HYDRUS-1D	(57)
2009	Mediterranean, Italy	HYDRUS-2D used to simulate recharge under stony soils	HYDRUS-2D	(58)
2018	Arid, USA	2D simulation enables accurate drywell sising below analytical predictions; direct cost saving	HYDRUS-2D	(60)
2019	Drywell in heterogeneous soil, USA	Fine lenses reduce recharge 30–50 % below bulk averaged predictions; layer position governs outcome	HYDRUS-2D	(61)
2021	Drywell virus transport, USA	Virus concentrations exceed regulatory threshold when vadose zone < 3 m under typical inactivation rates; Colloid transport module provides site specific public health risk framework	HYDRUS-2D	(63)
2025	Canal and well MAR comparison, USA	Lined canals: most uniform spatial recharge; gravel packed wells: highest per unit recharge rate; drywell is a better recharge structure than canals	HYDRUS-2D	(64)
2023	Flood based MAR, California, USA	Recharge volumes reproduced to within 8 % of the observed values; strongly sensitive to initial soil water content	HYDRUS-2D	(65)
2025	Stormwater pond, semi-arid region	Stratified layering reduces recharge 30–45 % below homogeneous 1D predictions; infrastructure-type independent	HYDRUS-1D	(67)
2024	Infiltration basin, Canada	HYDRUS captured seasonal recharge dynamics under projected rainfall intensification scenarios	HYDRUS-1D/2D	(69)

MAR: Managed aquifer recharge; WTF: Water table fluctuation method.

terrestrial model to assess the impact of afforestation on groundwater recharge in the UK (73). Conversion of pastureland to woodland decreased annual recharge by 40 to 55 mm yr⁻¹ due to increased water losses from interception and transpiration.

HYDRUS applications in crop growth and root water uptake studies

Root water uptake modelling

Root water uptake couples soil hydrology to plant physiology. HYDRUS uses the macroscopic root water uptake approach, whereby potential transpiration is allocated to each soil layer based on normalised root length density and multiplied by dimensionless stress response functions that reduce potential uptake due to water and/or salinity stress (27). A comprehensive review of root water uptake parameters for many crops standardised the parameterisation approach followed by HYDRUS model users and showed reasonable comparisons between simulated and observed transpiration for many different soil-crop conditions (37). Šimůnek and progress in modelling root water and nutrient uptake with HYDRUS was documented, including the three-dimensional root distribution model that can represent asymmetric root architectures and capture declining root density with depth and lateral distance from the plant stem (41, 74). This three-dimensional root model was used with HYDRUS-2D/3D to simulate competition between plant rows for soil water.

The spatial pattern of root extraction in HYDRUS is defined by the Vrugt function using five parameters: Z_m , X_m , Z^* , X^* , p_z and p_x (74). Accurate estimation of these parameters requires understanding their interaction with h_3 , the Feddes threshold that defines the onset of crop water stress. Soil water pressure head is a negative value that becomes more negative as soil dries. When pressure head is above h_3 the crop transpires at full potential. Once it falls below h_3 actual transpiration declines proportionally and stops at the wilting point h_4 . The central estimation problem is that a deep root distribution drawing water from greater depth

produces soil moisture profiles identical to a shallower distribution with a more sensitive h_3 . This makes Z_m and h_3 statistically indistinguishable from soil moisture sensor data alone (75). This was quantified in medium textured soils the 95 % confidence interval for estimated Z_m spanned 60.5 to 136.4 cm (76). The issue was resolved by adding tensiometers that measure pressure head directly, which uniquely constrained both root distribution and soil hydraulic parameters simultaneously (77).

The advantage of HYDRUS over empirical approaches for crop water requirement design is fully realised only when root distribution parameters are grounded in field evidence. For annual crops a synthesis of 568 root profiles from 64 published studies established that effective rooting depth for wheat and maize is 50 to 100 cm (78). This provides a reliable field-based constraint for Z_m . A field experiment with 35 wheat lines showed that root length density must be at least 1 cm cm⁻³ in the topsoil to drain all available water (79). This sets a lower bound for Z^* and p_z . When Z_m and p_z are constrained within these bounds HYDRUS-2D reproduced soil water content within ± 3 % of field measurements in a drip irrigated cotton experiment (80). For tree crops the static Vrugt distribution becomes inadequate because root architecture redistributes toward emitters as management changes. In applications to competitive row crops using HYDRUS-2D/3D the three-dimensional root distribution model improved predictions of inter-row soil water depletion by 15 to 20 % relative to models using a uniform root distribution, with measured and simulated soil water content profiles agreeing within RMSE of 0.02 cm³ cm⁻³ across multiple crop and soil combinations (74). The author proved that prescribing asymmetric root architectures with declining root length density with depth reproduced observed soil water depletion patterns under maize that a uniform root distribution model failed to capture, particularly in the 20 to 50 cm depth zone where the contrast between actual and assumed root density was greatest.

In a 30-year-old apple orchard, 81 % of root uptake was found to concentrate within the top 50 cm (81). Reducing emitter discharge from 4 to 2 L hr⁻¹ shifted root uptake by 5.08 % and reduced deep percolation by 2.18 %. HYDRUS-2D reproduced soil water content at RMSE 0.014 to 0.019 cm³ cm⁻³ only after scenario specific recalibration of Vrugt parameters for each management condition. The same management dependence was confirmed in olive orchards and vineyards (18, 82). HYDRUS is therefore limited not by its physical formulation but by parameter identifiability. Reliable root zone simulation and crop water requirement design require Z_m , Z^* , p_z and p_x to be independently constrained by root measurements and tensiometer data rather than inferred from soil moisture sensors alone. Taken together these studies confirm that HYDRUS coupled water and N simulations provide a physically consistent basis for designing fertigation schedules that maximise N retention within the active root zone and minimise leaching losses, a capability that purely empirical N balance models cannot deliver because they do not resolve the spatial distribution of N relative to the root density profile. Root architecture in HYDRUS is currently specified as a static spatial distribution at sowing; dynamic root growth toward water and nutrient sources, which is critical for accurate water extraction modelling in deficit irrigation and saline conditions, is not represented and remains an important development priority

Evapotranspiration partitioning

Partitioning ET into soil evaporation and plant transpiration is necessary to schedule irrigation more effectively, since transpiration is directly linked to biomass production and yield formation. HYDRUS can partition ET by using its surface boundary condition method: potential evaporation and transpiration are imposed as boundary conditions based on the Penman-Monteith equation, which are then multiplied by user-specified factors to account for soil water availability and root density, respectively. Irrigation of maize in Portugal was simulated using HYDRUS-2D and it was observed that HYDRUS was able to predict E and T separately ($R^2 > 0.88$), whereas simpler, single-layer models could not predict the partitioning between E and T accurately. The results indicated that soil mulching decreased E by as much as 60 %, resulting in increased water use efficiency. Soil water content and root uptake in mature olive orchards under SDI were simulated using HYDRUS-2D and 3D (82). HYDRUS-2D was unable to represent the anisotropic root distribution and its impact on depletion patterns; HYDRUS-3D was therefore used and estimated sap-flow based transpiration within 9 % accuracy over an entire season. In HYDRUS, root water uptake is governed by two Feddes thresholds: h_3 , the soil pressure head at which actual transpiration begins to decline and h_4 , the wilting point where uptake stops. Both shift with crop stage yet most studies apply fixed values all season, creating systematic errors. A study across four sunflower growth stages using HYDRUS-1D showed that h_4 was dominant at flowering and maturity but not at seedling stage (83). A meta-analysis of 216 field experiments found that 40 % water reduction reduced maize yield by 39.3 % and wheat by 20.6 %, with both crops significantly more sensitive to stress during flowering than during vegetative growth (84). Because h_3 and h_4 determine when HYDRUS triggers water stress, assigning stage specific values is necessary for accurate crop water requirement simulation.

HYDRUS provides a foundation for representing plant scale physiological responses. Stomatal conductance is captured through the Feddes h_3 threshold, defining the pressure head at which actual

transpiration declines; field studies confirm this reliably reproduces seasonal water use across crops (85). Osmotic adjustment under salinity is addressed through the Maas-Hoffman threshold, which shows agreement with measured crop water use in field experiments (86). Hydraulic redistribution is approximated by the compensatory root water uptake module, capturing redistribution benefits of 10 to 30 % of daytime water use (41, 87). Stage specific h_3 and h_4 values can already be prescribed using time variable files and future stomatal model coupling would directly advance HYDRUS into an integrated crop water requirement tool (83).

Nitrogen and solute dynamics in the root zone

Nitrogen is the nutrient most strongly correlated with crop yields and is most vulnerable to leaching losses from the root zone. HYDRUS can simulate nitrification and denitrification directly through its built-in sequential first-order decay chain in the standard solute transport module (6, 14). Full N cycling, including kinetic mineralisation and broader biogeochemical reactions, requires coupling with the HP1 (1D) or HP2 (2D) modules, which link HYDRUS to the geochemical code PHREEQC (13). In constructed wetland applications, N transformation is instead handled by the CW2D model within the HYDRUS Wetland Module (21, 88). HYDRUS-2D was used to simulate water and N movement in almond and stone fruit orchards receiving variable-rate fertigation and showed that applying N when roots were most active instead of on a fixed schedule decreased nitrate leaching losses by 25 to 40 %. HYDRUS-2D simulation of N movement in a trickle-fertigated field in Iran (39, 89) replicated observed ammonium and nitrate concentrations within the root zone (RMSE < 8 mg L⁻¹). Results from the coupled water-N simulations showed that frequent irrigation with trickle irrigation keeps N within the shallow root zone where root density is highest, decreasing N leaching losses when compared to conventional surface irrigation. HYDRUS applications related to crop growth and root-zone dynamics was summarised in Table 4.

Coupled HYDRUS-crop model frameworks

HYDRUS provides a physically rigorous and computationally efficient framework for simulating coupled water solute and heat transport across a wide range of agricultural and hydrological settings, from subsurface drip irrigation design to managed aquifer recharge assessment and crop root zone management. HYDRUS has been coupled with agronomic crop models to provide soil physics and root water uptake subroutines to these models. Implementations and evaluations of HP2 (a HYDRUS-PHREEQC reactive transport coupling module, distinct from dedicated crop growth frameworks) and coupling HYDRUS to SWAP and DSSAT are documented in the literature (32, 90).

HYDRUS-coupled frameworks consistently improve yield prediction in annual crops by replacing simplified tipping-bucket water balance routines in standalone crop models with a physically rigorous solution of the Richards equation, thereby providing more accurate root zone water availability at daily timescales. Field experimental evidence across multiple crops and environments confirms this mechanism. A 12 % improvement in maize yield prediction was reported when HYDRUS-2D was coupled with the PILOTE crop model compared to a standalone simulation in France (5). HYDRUS-1D linked to AquaCrop sustained 94 % of potential maize yield at 80 % of full crop water requirement under deficit irrigation in Iran, a result dependent on accurate HYDRUS partitioning of total ET into soil evaporation and transpiration

Table 4. Summary of published HYDRUS studies in crop growth and root zone applications

Year	Crop/system	Key findings	HYDRUS version	References
2015	Pepper, tomato	Trigger-based subsurface drip irrigation optimised using HYDRUS	HYDRUS-2D	(3)
2011	Wheat, maize	HYDRUS-2D coupled with crop model for furrow irrigation scheduling	HYDRUS-2D	(5)
2001	Various crops	Root water uptake model embedded in HYDRUS widely validated across crops	HYDRUS-1D	(37)
2009	Maize, sunflower	Coupled crop-HYDRUS simulations improved ET partitioning	HYDRUS-1D/2D	(41)
2018	Olive trees	Root zone dynamics under SDI optimised using HYDRUS-3D	HYDRUS-2D/3D	(82)
2016	Almond, stone fruits	Water and N uptake by tree crops simulated under variable irrigation	HYDRUS-2D	(89)

Note: SDI: subsurface drip irrigation; ET: evapotranspiration; N: Nitrogen.

components (91). In a two-year drip-irrigated maize field experiment evaluating 176 N and water management combinations, HYDRUS-2D was validated against measured soil water content (RMSE 2.3–5.1 mm, MBE 1.6–4.9 mm) and crop N uptake (RMSE 3.9–8.9 kg ha⁻¹, MBE: 5.3–6.3 kg ha⁻¹) (92). For wheat, AquaCrop driven by HYDRUS-simulated soil water dynamics was validated across full and deficit irrigation treatments in southern Iran, reporting soil water RMSE of 18 mm with Willmott's index of agreement $d = 0.84$ under full irrigation and RMSE 19 mm with $d = 0.93$ under deficit, with normalised RMSE below 10 % for grain yield across all treatments (93). Further independent confirmation across multiple experimental sites showed that the DSSAT-HYDRUS-1D framework improved root zone water content predictions over the DSSAT tipping-bucket approach (32).

Species-specific drought sensitivity sets an important context for interpreting these yield prediction results. A global meta-analysis synthesising 216 field experiments from 1980 to 2015 showed that at approximately 40 % water reduction, maize grain yield declined by 39.3 % while wheat declined by only 20.6 %, with maize significantly more sensitive during the reproductive phase (84). These contrasts confirm that accurate yield prediction requires resolving the timing of water deficit relative to phenological stage, a requirement HYDRUS satisfies more reliably than simplified crop model water balances. For perennial tree crops, yield formation depends on carbohydrate reserves and alternate-bearing cycles that no current HYDRUS-coupled framework simulates. Studies have therefore adopted actual ET as the primary validation target: seasonal transpiration agreement within 9 % of sap-flow measurements was achieved in mature olive orchards using HYDRUS-3D and actual ETc was reproduced across four deficit levels in vineyards with strong statistical agreement (18, 82). Both studies confirm HYDRUS reliability for crop water use quantification, but neither extended results to yield prediction. Yield forecasting in perennial orchard systems therefore remains the most consequential unresolved gap in the HYDRUS crop modelling literature.

Multi-process and coupled applications

Contaminant transport and water quality

Applications of HYDRUS also extend beyond agriculture to the simulation of contaminant fate and transport in the vadose zone. For example, a complete coupling of HYDRUS with the geochemical code PHREEQC, known as HP1, enables complex reactive transport simulations including mineral dissolution-precipitation, cation exchange and microbially mediated reactions (13). HP1 has been applied to simulate trace metal transport in acid mine drainage systems and pesticide fate in agricultural soils, illustrating that HYDRUS-based reactive transport can compete with standalone

geochemical simulators (13). Herbicide transport in structured clay soils was simulated with HYDRUS-2D using the dual-permeability module to represent macropore flow (94). Those simulations showed that failure to account for preferential flow resulted in herbicide leaching being underestimated by factors of three to four, with direct implications for pesticide risk assessment performed by regulatory agencies.

Constructed wetlands and drainage systems

HYDRUS has been extended to simulate constructed wetlands (CW) with the addition of modules to simulate clogging and biogeochemical transformations. The CW2D and CWM1 reactive transport modules simulate degradation of organic matter, nitrification, denitrification and phosphorus removal in subsurface-flow constructed wetlands (21, 88). The CW2D and CWM1 have been calibrated to field data from both horizontal-flow and vertical-flow constructed wetlands located in Europe. Comparison of modelled effluent biological oxygen demand (BOD) and ammonium concentrations to measured data from CW sites shows that HYDRUS-based models of CWs can simulate effluent BOD and ammonium concentrations within acceptable uncertainty ranges (e.g., NSE > 0.65, PBIAS within ± 25 %, RMSE < 0.05 cm³ cm⁻³). HYDRUS-2D/3D has been used to design agricultural tile drainage systems. Tile drainage outflow and nitrate leaching from a tile-drained field in Croatia were simulated using HYDRUS-3D (95). Using the software, they found HYDRUS can be used as an inexpensive virtual tile drainage testing platform that allows evaluation of how altering drain spacing affects drainage outflow and nitrate leaching.

Machine learning and HYDRUS hybrid approaches

Although HYDRUS simulations are computationally inexpensive for individual runs, this requirement remains too computationally expensive for large ensemble simulations or for applications where rapid evaluation of thousands of models is necessary. Machine learning surrogate models built from HYDRUS simulations present a computationally inexpensive alternative. A random forest model trained on HYDRUS-1D outputs was used to estimate groundwater recharge over various soil-climate combinations (16). That method reduced RMSE by 30 to 45 % compared to traditional regression models while taking only a fraction of the computational time. A physics-informed neural network surrogate method was proposed that uses the Richards equation as part of the neural network training loss function (17). This approach can be used in place of HYDRUS for forward simulations of infiltration while maintaining physical consistency with the underlying process. HYDRUS-derived hybrid modelling approaches like these are a future direction in vadose zone modelling.

Limitations, research gaps and future perspectives

Model limitations

While HYDRUS continues to enjoy broad popularity and usage because of its demonstrated capabilities, there are notable limitations with the model. First, HYDRUS assumes isothermal conditions by default. Although temperature-dependent flow is an available option within HYDRUS, parameterising this functionality requires lab-scale thermal characterisation data, which are rarely available. Second, HYDRUS is deterministic by default. Although stochastic variants/extensions of HYDRUS exist, as well as methods for handling parameter uncertainty, these features are rarely implemented in applied studies. Consequently, HYDRUS cannot easily account for spatial heterogeneity in soil hydraulic properties that is ubiquitous in field soils without resorting to effective homogeneous parameters that may poorly represent vadose zone behaviour (96). Third, HYDRUS does not contain an integrated crop growth module. Crop growth and yield simulation instead requires coupling with standalone crop models. These include DSSAT, among others. Such models generally provide more advanced crop-process simulation than anything built directly into HYDRUS (32). As such, biomass and yield estimates from HYDRUS are less accurate when crop physiology is the primary question of interest. Coupling HYDRUS tightly with sophisticated crop models remains an active frontier of research (33). Fourth, parameterisation of HYDRUS generally requires soil hydraulic characterisation data generated from laboratory or *in situ* devices such as tension infiltrometers or pressure plates. These approaches can be costly or otherwise unfeasible in data-poor regions of the world (particularly in the Global South).

Research gaps

There are a few key gaps in knowledge identified from this review. Firstly, published HYDRUS case studies are dominated by work completed in North America, Europe and Australia, while HYDRUS modelling studies from tropical or monsoonal climates like those found in South Asia, Sub-Saharan Africa and Southeast Asia are lacking despite presenting different challenges like complex rainfall irrigation interactions and more highly variable soils. Furthermore, standard van Genuchten-Mualem parameters and HYDRUS default root water uptake parameterisations may not be appropriate or require validation across these regions and environments. Secondly, calibration and validation procedures used with HYDRUS have not been standardised across studies. Calibration targets (soil water content (SWC), pressure head (Ψ), drainage flux and solute concentration), methods (manual, HYDRUS-parameter estimation module, external optimizer) and validation metrics (R^2 , NSE, RMSE and PBIAS) differ from study to study which makes cross-study comparisons challenging. Minimum dataset and reporting standards would greatly improve reproducibility. At minimum, studies should report: 1) soil texture and bulk density; 2) van Genuchten parameters with fitting method specified; 3) upper and lower boundary conditions; 4) initial soil water content profile; 5) calibration period length; and 6) validation metrics (NSE > 0.65, PBIAS $\pm$ 25 %, RMSE < 0.05 cm³ cm⁻³). Thirdly, linkages between HYDRUS-simulated vadose zone dynamics with shallow water table conditions are often neglected by using a free drainage lower boundary condition when, in fact, capillary rise can be an important addition to root zone moisture in shallow water table systems. Coupled HYDRUS-MODFLOW packages exist that can simulate this process but are seldom used in crop water

management research (97). Centre pivot irrigation, which irrigates the largest pressurised area globally, has not yet been validated against HYDRUS simulations in any published field study, because the continuously moving wet boundary of a rotating pivot cannot be approximated as steady-state in a static HYDRUS domain; this represents the most significant gap in the HYDRUS sprinkler irrigation literature.

Future research directions

Coupling HYDRUS to high-resolution remote sensing inputs such as Sentinel-1 SAR-derived soil moisture, MODIS-derived leaf area index (LAI) and SEBAL or PT-JPL-derived ET can enable spatially distributed modelling of the vadose zone at field-to-watershed scales that were not possible before. Spaceborne or airborne platforms providing soil moisture data averaged over the footprint such as time-domain reflectometry networks or cosmic-ray neutron sensors can be used to assimilate observations into HYDRUS ensemble runs. Physics-informed neural networks and Gaussian process emulators of HYDRUS have the potential to yield online irrigation advice and HYDRUS ensemble uncertainty quantification at scales relevant for decision support. The quantification of climate change impacts with HYDRUS using global and regional climate model data can be leveraged to study groundwater recharge and crop irrigation demand under future climate change scenarios. Combining HYDRUS with SWAT, MODFLOW and economic optimisation in multi-model ensembles will be necessary to upscale plot-scale insights to make basin-scale management decisions. In future modules a framework that allows for sensitivity analysis of the input parameters should be developed in the HYDRUS.

Conclusion

The soil-water-plant continuum that governs irrigation losses, groundwater recharge and crop uptake has rarely been modelled within a single physically based framework at the operational scale. HYDRUS fills this role through its numerical solution of variably saturated flow across one, two and three spatial dimensions. Over three decades it has grown to a community of more than 10000 practitioners worldwide. No prior review had synthesised its performance across irrigation management, groundwater recharge and crop water use simultaneously. This review addresses that gap.

Under drip, furrow, sprinkler and subsurface drip irrigation systems, HYDRUS reproduced field-measured soil water content with R^2 exceeding 0.90 and NSE exceeding 0.80. This performance extends to two-dimensional wetting front geometry under point-source emitters, fertigation timing effects on root zone N distribution and return flow quantification across irrigation methods. Deficit scheduling strategies derived through HYDRUS reduced applied water by 22 % while sustaining crop yield above 90 % of the well-watered control. No empirical water balance tool provides this combination of irrigation design and groundwater accounting within a single framework.

For groundwater recharge, HYDRUS-1D resolved vadose zone fluxes more accurately than water balance and tracer methods across natural land cover, irrigated farmland and managed aquifer recharge infrastructure. Soil texture and antecedent moisture content governed prediction accuracy in all recharge settings. A special reservoir boundary condition HYDRUS 2D/3D can be used to quantify the groundwater recharge of wells, ponds, basins and many similar recharge systems. For crop and root zone processes root

water uptake is simulated directly through the Feddes stress-response function while full crop growth and yield estimation requires coupling with external models such as DSSAT, SWAP and AquaCrop since no crop growth module is built into the software itself. This coupled approach has improved ET partitioning and N management including reductions in nitrate leaching of 25 to 40 % under optimised fertigation timing

Irrigation engineers, groundwater managers and agronomists stand to benefit most directly from this synthesis. Each profession depends on vadose zone process resolution that empirical tools cannot supply. Machine learning surrogates trained on HYDRUS outputs and remote sensing data assimilation offer the most viable route to scaling field-scale insights to regional management. HYDRUS is the only validated framework that resolves irrigation system design, groundwater recharge accounting and crop N management within a single physically rigorous vadose zone model. Future research should focus more on coupling machine learning algorithms with HYDRUS and data assimilation of remote sensing datasets. Machine learning and HYDRUS modelling could allow for larger spatial extents, higher temporal resolutions and lower computational demand for vadose zone simulations.

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Authors' contributions

All authors collectively contributed to the preparation of this review manuscript. D prepared the original draft of the manuscript. RV supervised the writing of this manuscript. SS, RK and BK contributed to data analysis, graphical visualisation and language editing. BA carried out literature collection and preliminary analysis. All authors have read and approved the final manuscript.

Compliance with ethical standards

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