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Fate and Transport of Pathogen in Sub Surface Environment-A Review

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ABSTRACT: Micro-organisms are a threat to water quality and human health due to its large-scale distribution in the aquatic environment. The cause of health risk is due to the discharge of untreated / partially treated wastewater from various sources. The wastewaters are also used for irrigation during lean seasons in many parts of the urban environment. It is essential to understand the impact of wastewater usage in agriculture due to lack of investigations on the movement of microorganisms. Several research gaps exist in the studies related to fate and transport of pathogens in the vadose zone. Microbial transportation in the unsaturated zone poses many challenges which comprises the tracing of pathogens in the unsaturated zone because of uneven preferential flow conditions. The estimation of survival rates of microorganisms in the subsurface environment is significant as it directly affects the health risks of living organisms. The hydraulic properties of soil are critical in the movement of pathogens in the vadose zone. The retention predictions of microbes are highly variable due to the presence of colloids, dissolved organic matter, and variable solution chemistry (pH and ionic strength) which changes the surface charge of the media and the microbes. There is a scarcity of field scale data representing different soil layers which is a major constraint in model prediction of preferential flow paths and survival of pathogens in the vadose zone. Review focusses on pathogen transport processes, decay rates. This review is about the process of attachment, detachment, undergoing straining action of pathogens when they are bound with complex organic matter.

1. INTRODUCTION

Background and Relevance of subsurface Pathogen contamination

Pathogens are defined as bacteria, viruses, or other microorganisms that can cause disease. Pathogens are responsible for most all episodic disease outbreaks (USEPA2026), and are present in many groundwater supplies (Mattar et al., 2025).Better understanding of pathogen source and transport can only serve to facilitate improved human health and associated economic benefits. Pathogen transport has been extensively investigated (Bekoe et al., 2025), where it often focused on easy to measure targets (bacteriophage, other inorganic tracers) because other targets such as viruses were both difficult and expensive to analyze (Heffron et al., 2024).

Microbial contamination of groundwater is a pressing concern worldwide, particularly in regions with high agricultural activity, poor sanitation infrastructure, and increasing urbanization. The elevated contamination is attributed to the large numbers of viruses released into the environment, their longer survival times in water, and their resistance to common disinfection techniques (Mustafa et al., 2025). Pathogenic viruses are the primary concern when assessing fecal contamination in groundwater. Key factors influencing the transport and attenuation of viruses in aquifers include virus size, shape, motility, surface charge, and inactivation rate, as well as physical processes such as adsorption and filtration (Jat Baloch et al., 2026).

Monitoring and Prediction

Indicator- related monitoring has been extensively used as practical approach for assessing microbial water quality still, its faith in predicting pathogen presence remains limited. Fresh studies indicate that traced organisms (E-coli, F-RNA bacteriophage MS2) show weak and inconsistent correlations with pathogens due to differences in survival rates with different survival conditions, transport motion, and environmental continuity (Richiardi et al., 2023). In groundwater systems, particularly under conditions of preferential inflow, pathogens may bypass natural filtration mechanisms, exhibiting their occurrence (Bivins et al.,2020).These limitations stress the need for integrating molecular tools and multi-marker approaches to enhance the delicacy of microbial threat assessment.

The limitations of index- related monitoring and prediction relate to the incapability of generally used microbial pointers. However, such processes constantly and directly represent the presence, transport, and threat of pathogenic micro-organisms, leading in misgivings in water quality assessment and threat Prediction. There is no connection between the indicator presence and pathogen fate. Also, there is a huge gap between traditional indicator based monitoring and actual real time behaviour (Pérez Guillemette & Albrechtsen, 2025). Therefore, it is important to develop a framework to understand its survival rates, microbes' attachment (adsorption)-detachment(desorption) along with seasonal variations (based on wet and dry cycles) and real time field investigations. However, there are certain limitations in such cases which are presented in a flow diagram.

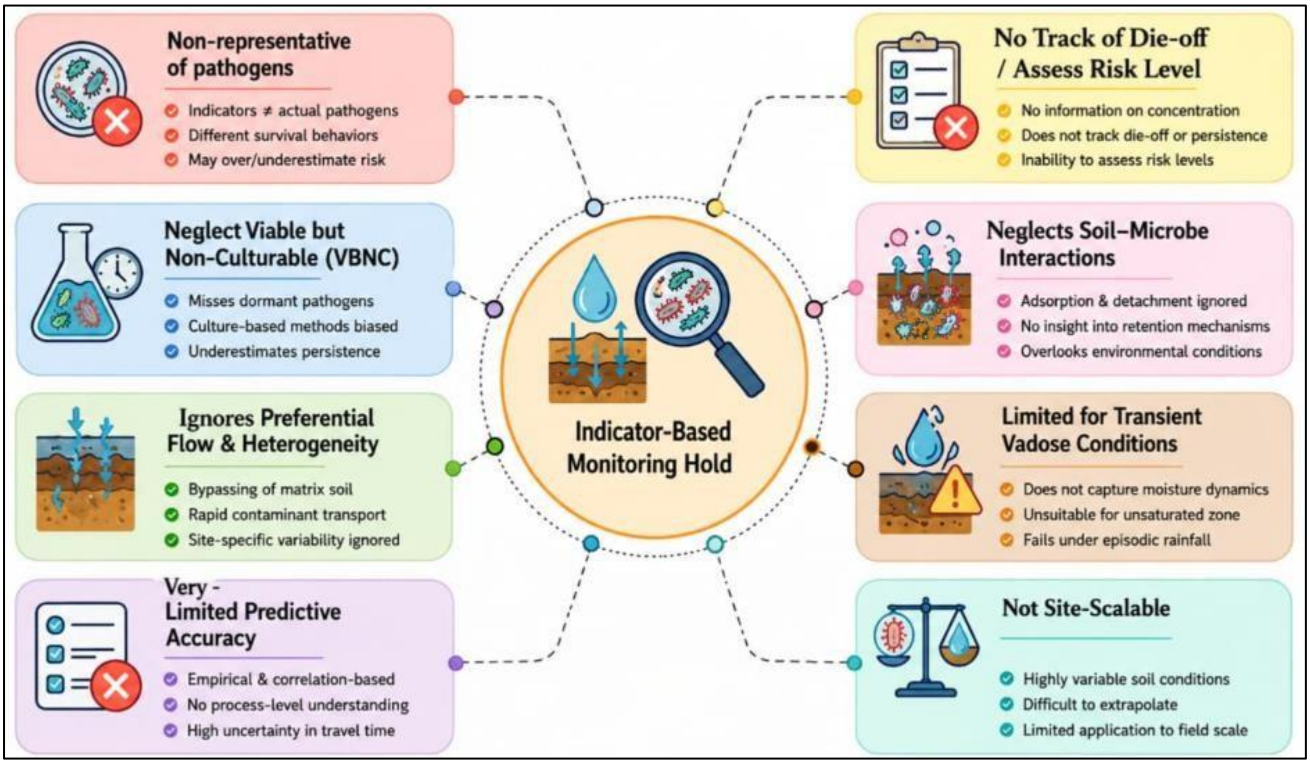

Figure1: Conceptual figure of limitation of indicator-based monitoring

Need For integrated understanding of Transport, Survival and Modelling

"Pathogenic viruses are of major concern for faecal contamination of groundwater because they are widely released into the vadose zone and often stay longer than bacterial indicators. Their transport and movement in aquifers are controlled by **(a)** virus intrinsic properties — size and shape (affecting straining and mobility), capsid surface chemistry/charge and isoelectric point (controlling electrostatic adsorption and aggregation), and inactivation rate (temperature, UV, biotic/abiotic decay) — and **(b)** physical and geochemical processes in the subsurface — adsorption (attachment), filtration/straining, advection/dispersion, detachment, and solid-phase inactivation**.** Recent reviews and field studies (2023–2025) summarise experimental evidence and surveillance data supporting these mechanisms and provide quantitative persistence/inactivation ranges (Rusinol, 2023). With reference to the above-mentioned chemical processes, it is necessary to discuss the occurrence and distribution of microorganisms and bacteria in soils. These are the primary indicators of pollution and also acts as the carriers of various polluted contaminants through the aqueous system. Most important factors that control their persistence in this complex environment are temperature, soil media and moisture content, sunlight, pH, organic matter, type of bacteria, and antagonistic microflora (Iqbal et al., 2025).

Viruses have been recovered by eluting soil with deionized water and concentrating the Carrier by sorption onto aluminum hydroxide (AI[OH]3). Soil temperature and moisture are the primary factors affecting virus survival in soil treated with waste water effluents or sludge. Soil type may also influence survival, although the effect is probably related to the degree of viral adsorption. There is considerable variation among virus types in their ability to survive in subsurface environments(Farmer-Diaz et al., 2025).

Preferential flow allows much faster contaminant transport and creates significant consequences for ground-water quality and has direct impacts on drinking water and human health, animal waste nutrient and pesticide management, and watershed management (Sasidharan & Bradford, 2025). Simulation of the Transport and environmental factors like soil moisture, absorption, desorption studies can be Integrated using models. This will improve the predictions accuracy including the contamination risk analysis as well reliable framework

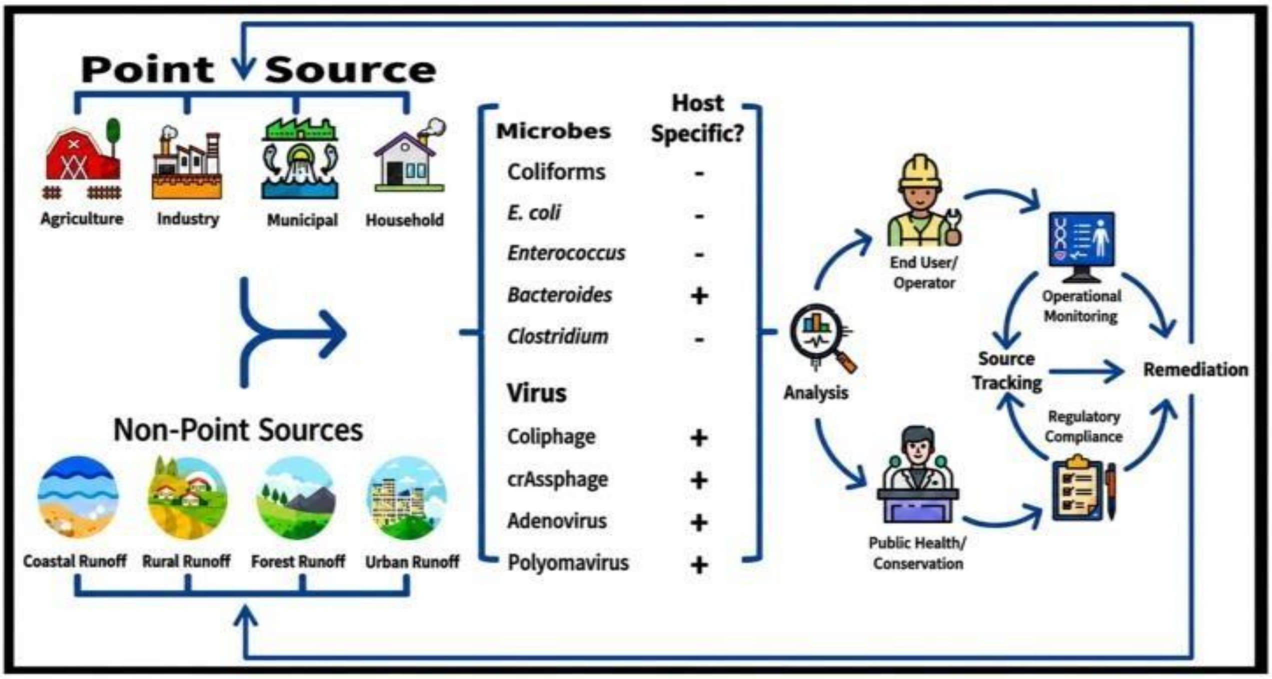

Figure 2. Methodology and Conceptual framework of pathogen fate and transport in subsurface environment.

2. SOURCES AND SUBSURFACE PATHWAYS OF PATHOGENS

Anthropogenic and Natural sources

Natural environments exhibit heterogeneity both at the laboratory scale and field-scale. Various authors have reported with regards to heterogeneity in soil properties, surface topography, temperature and water inputs. However, limited field research is available on microbes and preferential flow paths which is likely to vary with the spatial and temporal scales (Bradford et al., 2015).Intense rainfall events can generate runoff, preferential flow, and transients in water saturation that can rapidly transport microbes in agricultural settings (Türk et al., 2025). Pathogens and subpopulations that survive longer, undergo the probability of being subjected to rapid-transport events(Ning et al., 2023). In the case of land-applied animal manure and bio piles of slaughterhouse residuals are potentially important sources of microbial pathogens in the environment. Pathogens and indicators can be released from such sources to flowing water during precipitation and irrigation events. (Kidane, 2023) and (X. Wu et al., 2024)examined pathogen sources and its impact after releasing into the open land. Studies in the past focused on point sources non-point sources and contaminants in ground water and the transport of pathogens. Recent studies have focused on pathogenic aerosols and Managed aquifer Recharge (MAR) in heterogeneous vadose conditions which will definitely lead to specific conclusions on environmental degradation and remediation techniques.

Transport through vadose and saturated zones

Pathogen transport in the vadose and saturated zones is governed by a combination of fault hydrology(Cook et al., 2022),physical and physico-chemical processes. In the vadose zone, transport occurs via matrix or preferential flow (through macropores), and unstable soil conditions resulted due to adsorption, filtration, and die-off. However, preferential pathways can bypass these mechanisms, enabling rapid vertical migration. In contrast, transport in the saturated zone is dominated by advection and hydrodynamic dispersion, with additional contributions from colloid-facilitated transport and fracture flow in heterogeneous aquifers. Pathogens, particularly viruses, exhibit greater mobility and persistence in saturated conditions, resulting in long-distance migration

Transport through vadose and impregnated zones highlight how pollutants enter, move, and persist in subterranean surroundings (vadose and saturated zones). It identifies major contamination sources analogous as septic systems, wastewater, and land- applied waste, and explains that viral transport is brisk in saturated media due to continuous flux, whereas unsaturated(vadose) conditions limit movement through air – water interfaces and adsorption(Saeibehrouzi et al., 2024). Review synthesizes pollution transport mechanisms in submersed and unsaturated porous media, showing that mobility is enhanced in impregnated zones but limited in the vadose zone due to interfacial and adsorption processes. It identifies pivotal environmental controls on contaminant durability and highlights the need for stylish directly prognosticating models that value for adulterant-specific action in subsurface systems (Jat Baloch et al., 2026). In the past approach was simple with solute transport in homogeneous soil. While the future scope has to include transport simulations in transient environment conditions with QMRA into the process.

Role of Preferential flow, Macropores, fractures and karst

Heterogeneity of soil exists in almost all field soils which influences preferential flow paths enabling the easy movement of large quantity of solutes (X. Chen et al., 2024). These pathways are usually macro-pores formed by worms, burrowing insects and animals, plant roots, cracks and fissures (You et al., 2022), or cultivation practices that alter subsoil structure. Preferential flow affects infiltration rates and solute movement by allowing water to bypass large areas of porous soil (M. Li et al., 2020). Studies have observed infiltration via preferential flow to be greatest following the first couple of rainfall or irrigation events (Katuwal et al., 2021)

Table 1. Typical infiltration rates of different soil textures. (from The Montana Irrigator’s Pocket Guide, NCAT, 2003)

Different Types	Texture Infiltration Rate (inches/hour)
Very coarse sands	3.75
Coarse sands, fine sands, loamy sands	2
Sandy loams, fine sandy loams	1.75
Loams, silt loams, silts	0.75
Sandy clay loams, clay loams, silty clay loams	0.5
Sandy clays, silty clays, clays	0.25

The preferential flow happens through non-structured soils (soils which do not show visible structural elements, large pores or voids) is most often related to wetting front instability. Instability of the wetting front results in movement of water and solutes in columnar structures or "fingers”. This columnar structure is usually referred to as "fingering" (Cueto-Felguroso et al., 2020).

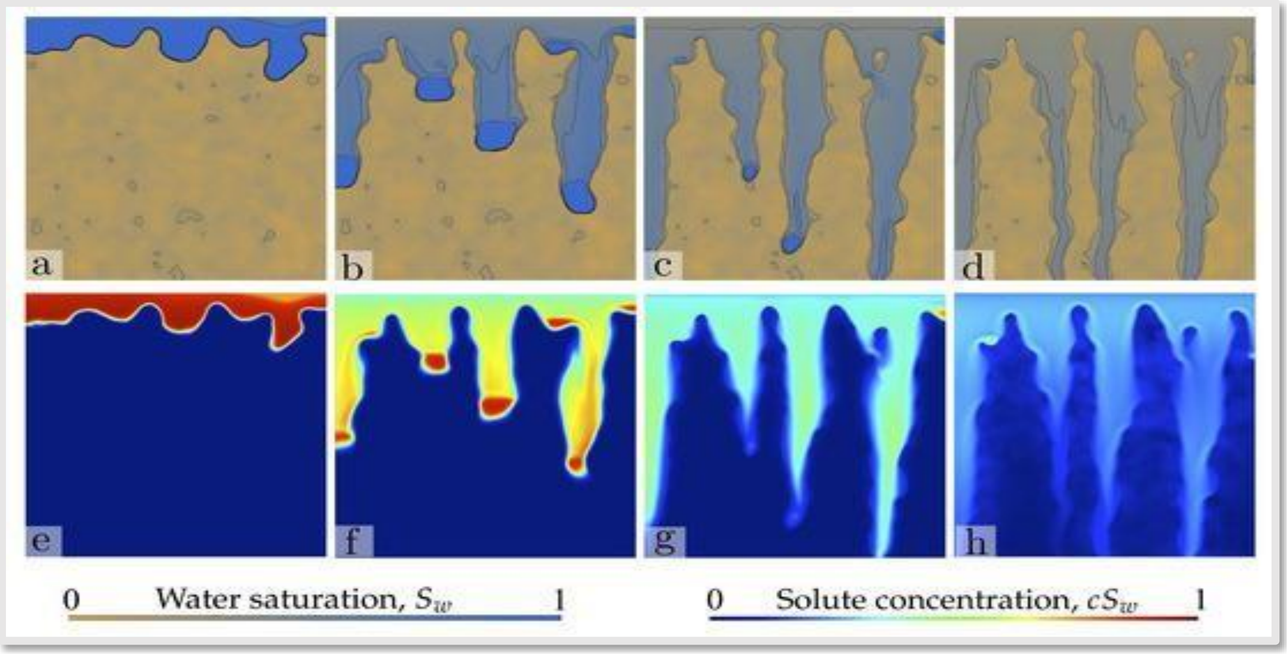

Figure3, Fingering: Source: Luis Cueto-Felgueroso et al., 2020

The concept of a macropore lacks a clear and consistent definition. Luxmoore et al. 1990 stated that: "**the term is either defined differently by different researchers nor is not defined at all**". Pores are usually classified based on their respective pore size. These pore sizes can be derived from the surface tension which depends on the radius of a cylindrical pore to the capillary capacity with which water is held in it (Yan &Cudmani, 2024). This relation is based on a capillary tube, thus significantly defining an equivalent rather than an actual pore radius. The height of a capillary rise perception was given by (Luo et al., 2024). The necessity for standard soil porosity terms was already articulated by Luxmoore in 1981.He mentioned that the use of three different soil porosity classes has corresponding three conditions of soil water behavior and they are associated with equivalent pore diameter ranges. The suggested classification distinguishes macro-pores as pores that retain water at field capacity (usually referred to as older water), with a corresponding diameter of less than 0.01 mm. Further, meso-pores are pores that are generally exhausted at field capacity, with an corresponding diameter of 0.01 to 1 mm. series of responses (Cao et al., 2024) are followed.

The macropore volume and structure represent a strong and dynamic balance between formation as well as degradation processes. Any changes in the terrestrial system and external conditions such as weather, will affect that balance (Cao et al., 2024). The vertical continuity of the macropores is dependent on Tillage and agricultural practices and break up the surface layer.(Cooper et al., 2021). It is found that within 4 years of no-till practice, the number of earthworm channels nearly doubled in the ploughed horizon of a loess soil when compared with a tilled practice(Seibutis et al., 2025).Quisenberry and Phillips (1978) evaluated the effect of tillage on displacement of initial soil water by simulated rainfall. Percent displacement increased as the depth of tillage increased(Amami et al., 2021).Tillage was found to result in disturbance of well-defined pores, indicating that less interaction between applied water and initial water occurred in non-disturbed soil, as compared to tilled or disturbed soil. The effect and its impact of tilling practices on the transport of pesticide (Summerton et al., 2023) was studied during a three-year field study in Maryland.

The pathogens in ground water migration are chiefly influenced by hydrogeological conditions, primarily the flow rate (Zhang et al., 2022). Lower flow rates, coupled with a higher hydraulic residence time, slow down pathogen movement and provide more time for their attenuation (Mustafa et al., 2025; Banasiak et al., 2023).Conversely, higher flow rates promote faster pathogen migration and facilitate rapid distribution within an aquifer(Curle et al., 2025). Due to their smaller size and higher resilience to extreme conditions, viruses tend to be transported farther in groundwater compared to bacteria and protozoa(Tork Zaban et al., 2019).

In fissured aquifers flow velocities are found to vary from less than 1m/day to 100m/day.in Karst aquifers velocities are seen exceeding 1000m/day (Betancourt et al., 2019). This phenomenon increases the vulnerability in karst aquifers to contamination because of the low filtration capacity(Knabe et al., 2023). Waterborne diseases are often to linked to karst aquifers as well as fractured rocks (Kalhor et al., 2019). The transport of viruses in subsurface state can well be explained by the structural heterogeneity of aquifer (Armanious et al., 2016). The attenuation and transport of viruses in aquifers is governed by flow mechanisms and porosity. The travel distances of viruses is also significantly affected by the type of aquifer viz. porous, fissured or karst with respect to ground water flow velocities(Ning et al., 2023). The viruses which reach the saturated zone have also an impact by the processes like advection, dispersion and diffusion (Jat Baloch et al., 2026).

Leaching phenomenon where water and dissolved pesticide infiltrating down through the soil profile move more rapidly through soil macropores or sand/gravel lengthen through the network-of-smaller-pores in-the bulk soil.

It is a fact that there are only limited number of studies which discuss about the effect of initial moisture content and rainfall intensities or irrigation on preferential flow. Analysis based on breakthrough curves developed from column studies using aggregates of different soils showed that prior breakthrough appeared at lower moisture content, due to incomplete mixing in nearly stagnant pores of the soil(Jiménez-Martínez et al., 2017). Increased infiltration was observed when water was applied to a silt loam soil with a water content close to field capacity which is less than the percolation (permeability) through the same soil at a slightly higher initial water content.

(Bouma, 1981)noted that the extent of bypass flow in the undisturbed soils depend on their structure, the hydraulic conductivity of the peds (natural soil lump), the rate of application, and the soil water content. Staining experiments in dry, cracked clay soil under sprinkler irrigation indicated that vertical movement of free water along the wall of the air-filled macropores occurred along a few small strips(Katuwal et al., 2021).

Preferential flow pathway was more increased with increased irrigation intensities, whereas saturation resulted in full cracked areas. In spite of this, uneven flood irrigation helped considerable downward movement of water through preferential channels even when the soil remained unsaturated.(Katuwal et al., 2021). In one of the experiment the bromide movement in a well-structured Flanagan silt loam soil was conducted under low (2.5 cm/hr.) rainfall rates, however, no significant difference between mold board plough, chisel plough, disk plough and para-till were observed. Meanwhile, significantly greater bromide movement in the no-till treatments at a high simulated rainfall rate (10 cm/hr.) was noticed and it is attributed to preferential flow(Silburn et al., 2022). Transport of surface-applied chemicals was dominated by permeable volume rather than by rainfall intensity. The first storm following surface application of chemicals were found to reduce the potential for transport of reactive solutes in subsequent events, regardless of the first-storm characteristics. Previous moisture content within the pores allowed more of the smaller pores to contribute to penetration and water movement, thereby decreasing the overall contribution of preferential flow(Holbak et al., 2021).Recent research emphasizes the need for integrated management practices to mitigate solute losses. Practices like precision irrigation, controlled drainage, conservation tillage, and the use of buffer strips can reduce nutrient leaching and pesticide runoff (Bodrud-Doza et al., 2025) found that cover crops are effective in reducing nitrogen and phosphorus transport by improving soil structure and increasing uptake. Moreover, monitoring tools like lysimeters, tensiometers, and tracer studies are essential for field-scale validation of solute transport models (Araya et al., 2022).

From the above discussion it is evident there is a distinct gap in hydrological and hydro-geological properties on transport of microorganisms and ionic movement. Further, no major studies were reported on the transport processes with reference to anthropogenic disturbances and land use practices under varied climatic conditions. Therefore, it is quite significant to understand the health risks associated with the geochemical and microbiological processes and uncertainty involved in pathogen transportation.

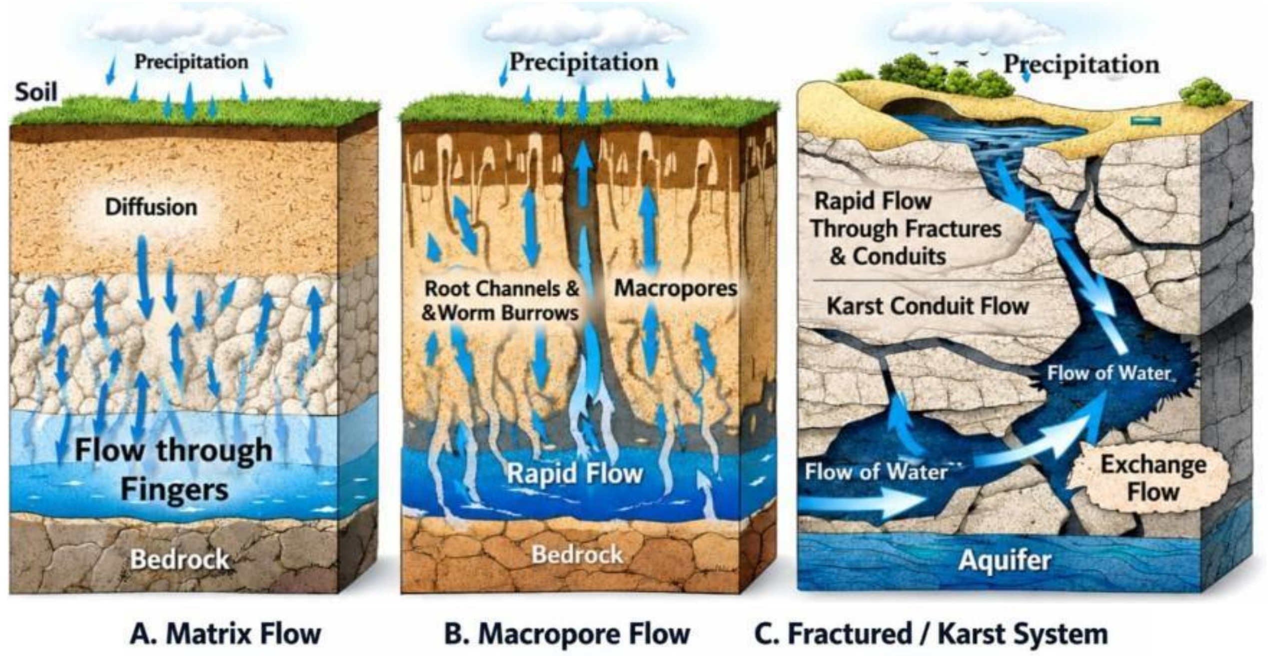

Figure 4: Conceptual representation of types of flows in vadose zone

3. GOVERNING PROCESSES CONTROLLING FATE AND TRANSPORT

Hydrological processes (unsaturated flow, advection, dispersion)

Generally, the vadose zone hydrological process will have a great impact on the fate of microorganisms, also the transport of these, their pathways of movement and interconnection of soil water films. So, it's evident that the understanding the processes and to assess the risk related to risk of micro-organisms in the vadose zone to ground water as well as public health of the society (Lebon et al., 2023).

Within the vadose zone water flows initially under the capillary forces and slowly leading to the complicated flow paths. This non-saturated flow definitely influences the microorganisms to transport as well as to distribute through such hydrological films (Jat Baloch et al., 2026). Such paths also create detached or remote water pockets and the microbes are retained in such pockets(Sepehrnia et al., 2024)

Soil moisture also plays the major role on the survival as well as movement of microbes. Lower moisture will affect the connectivity of microorganisms and increases the retention and adsorption to soil particles (Shawver et al., 2024). Microbial limit number (threshold) will exist reduction in numbers of microbes due to reduced dis-connectivity in path ways (Leue et al., 2019).pH and moisture content are the key aspects of adsorption. The adsorption can increase or diminish due to such changes.

Macropores and Preferential paths in vadose zone and to some extent fractures within the vadose zone can let go the soil adsorption characteristics as they allow rapid flow of water(De Carlo et al., 2021).Such fractures pose few challenges as the conventional models assume flow to be uniform. The challenge will be more in semi-arid and arid zones. Moisture alterations also change the depth of water films affecting the soil adsorption capacity (X. Li & Bourg, 2024) has used isothermal models for understanding the microbial activity.

Physical, Chemical and Biological interactions (Transport, filtration, straining, adsorption–desorption)

Heterogeneous soil structures create preferential pathways that enhance microbial mobility, as observed in studies of manure-applied agricultural lands. The type of solute being transported plays a significant role in its mobility and environmental impact. Nitrate, for instance, is highly mobile and poses a significant threat to groundwater quality due to its weak retention in soils. (Paswan & Sharma, 2025)highlighted how land use and irrigation practices influence nitrate leaching. In contrast, phosphorus binds strongly to soil particles and is mainly transported via erosion or in dissolved form under saturated conditions. Pesticide transport is more complex, depending on their physicochemical properties such as sorption coefficient and degradation rates.

Antonious, (2024)conducted a comprehensive groundwater survey in Long Island, USA, detecting 53 different pesticides in 54 monitoring wells, underscoring long-term contamination risks.

Solute transport in soils is a multi-faceted process affected by physical, chemical, and biological factors. Recent advances in modeling and imaging, along with field-based monitoring, have improved our understanding of how solutes move through the vadose zone into groundwater. This knowledge is vital for developing strategies to protect water quality, ensure sustainable agriculture, and address the challenges posed by climate change and increased chemical use (Zhou et al., 2023).

Chemical and Biological Factors

The interactions between microorganisms and soil components, including adsorption and desorption, influence microbial mobility. Environmental factors such as temperature, salinity, and nutrient availability dictate microbial survival and inactivation. Bio clogging, a phenomenon caused by microbial activity, can reduce soil permeability, leading to reduced infiltration efficiency(Ping et al., 2021)

Biological processes (inactivation, decay, predation, bio-films)

Some studies have focussed on the fate and transport of indicator bacteria from bio piles (static compost piles) of slaughterhouse residuals(Bradford et al., 2015). More than 90% of the indicator bacteria load followed large precipitation events (at a small fraction of <0.01%) of the original population in bio pile effluent, signifying a significant role for retention and inactivation in bio piles while significant external controls on water entering and leaving the bio pile are effective and important measures to reduce risk for environmental impacts(Rizwan et al., 2024). Loads decreased exponentially with time. Entero-Bacteriaceae indicators remained low in conditions of higher soil water content and lower bio pile temperatures, whereas the Enterococcusi indicator appeared to regrow in these conditions(Upadhyay et al., 2024).

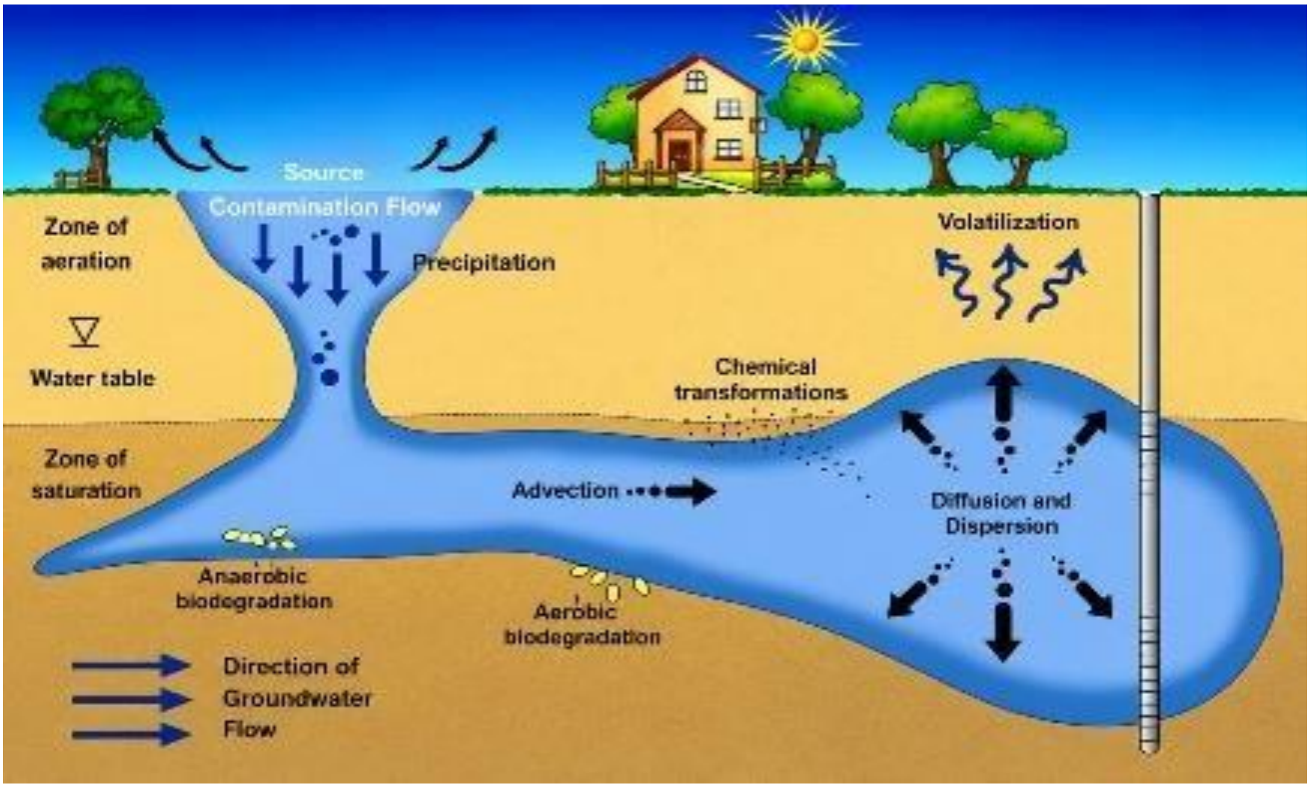

Figure 5: Key physical, chemical, and biological processes governing pathogen fate in the subsurface /Conceptual)

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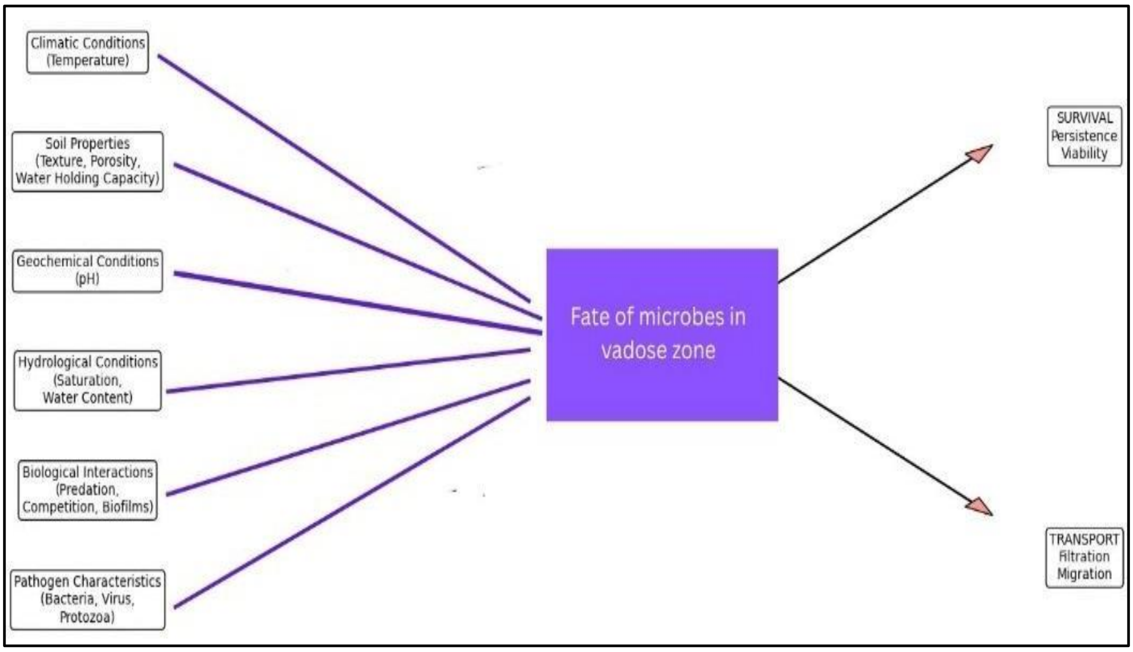

Figure 6: Created from two sources(Ning et al., 2023;W. Zhang et al., 2022)

4. MODELLING, EXPERIMENTAL EVIDENCE AND RISK IMPLICATIONS

Conceptual and numerical modelling approaches

Over the last few decades, the Progress and application of models scrutinize the behavior of natural systems for research as well as planning purposes, have increased strongly. As far as planning is concerned, models have been proven to be cost- and time-effective tools for assessment of different management situations(M. Li et al., 2021). Models can be used as valuable tools to assess risk of leaching and contamination of groundwater under different cultivation practices. However, detection of unexpected high concentrations of contaminants in groundwater will not only raise environmental concerns related to groundwater quality, but also raise questions regarding the validity of quality of current groundwater and solute transport theories and models. The models that are presently in use, do not define the flow through structured soils, where water can move swiftly through large pores, cracks, and channels. Because the appropriate characteristics of these non-uniform transport processes are difficult to measure(Saeibehrouzi et al., 2024).They are Designed to describe solute movement under natural conditions in field soils(Holbak et al., 2021;Paraskevas et al., 2023). Recently, a number of models have been developed which try to include preferential flow and transport in the soil. Deterministic models have generally placed on a two-domain or dual-porosity approach. These models use a schematization of macro-pores to describe water flow in a combined macro-pore/matrix system. Two groups of models can be distinguished; models that consider the geometry of the macro-pore and those that do not explicitly consider the structure of the soil. The first group of models generally assumes macro-pore flow to take place through a single, well-defined macro-pore, in which water moves under gravity alone (Holbak et al., 2021). A number of researchers have used the Hagen-Poiseuille equation to describe gravity-based flow through cylindrical channels. Chen and Wagenet(Krol et al., 2021)used the Hagen-Poiseuille and the Chezy-Manning equation to describe the presumed turbulent flow in the macro-pores. Water movement in the soil matrix is subject to capillarity, and is generally described by the Richards' equation. Solute transport in the soil matrix is traditionally described by the convection-dispersion equation (Toutlini et al., 2024). Flow from the macropore into the soil matrix has been explained by the Green and Ampt equation (Dahunsi et al., 2025) the Philip's infiltration equation (Mesele et al., 2024)), or as a function of the pressure head difference between the two domains(X. Li et al., 2022) used statistical distribution functions to relate the different pore sizes of the cylindrical macropores to the macro-porosity of the soil.

Modern approaches to understanding solute transport involve both experimental and modelling techniques. Numerical models like HYDRUS-1D/2D/3D and dual-permeability frameworks are commonly used to simulate water and solute flow under variably saturated conditions (Šimůnek et al., 2024**)** enhanced HYDRUS capabilities to include reactive solute transport under complex boundary conditions. The convection-dispersion equation (CDE) models are widely applied, though they are often limited in capturing non-equilibrium transport seen in structured soils. In recent days, dual-porosity and dual-permeability models have been increasingly applied, especially in predicting the fate of contaminants in heterogeneous soils, as discussed.

Laboratory and field evidence (vadose zone, MAR systems)

Microbial transport studies utilize soil sampling techniques such as core extraction (Banasiak et al., 2023). Soil analysis follows ASTM guidelines (Barba et al., 2019). (Banasiak et al., 2023) examined microbial movement in undisturbed heterogeneous alluvial gravel vadose zones using X-ray computed tomography (CT). Potassium bromide tracers were employed to track microbial transport, while Chick's Law was used to assess microbial inactivation. Microbial movement was analyzed in both saturated and unsaturated conditions through hydraulic conductivity tests, with results supporting mathematical modeling of transport dynamics.

Sidhu et al. (2015) analyzed microbial behavior in the four Managed Aquifer Recharge (MAR) settings: confined, unconfined, calcareous aquifers. (Arnaud et al., 2015)detected E. coli below a 12-meter-thick vadose zone where swine manure was applied, with the bacteria persisting in all 23 samples for five months, indicating deeper migration through preferential pathways. (Morales et al., 2015)used HYDRUS 2D/3D software to simulate microbial transport. Bradford applied first-, second-, and third-order decay coefficients to model microbial fate, while (Lai et al., 2016)used a watershed-scale model to evaluate bacterial sediment interactions.(Sepehrnia et al., 2024) introduced QMRA catch, an interactive computational tool for simulating target microorganism and virus concentrations.

Model limitations due to heterogeneity and preferential flow

The presence of a preferential flow component imposes a major problem for field monitoring. Since only a small portion of the soil volume takes part in the transport of chemicals, time and place of sampling is critical (J. Zhang et al., 2025).As the flow process is heterogeneous, a greater number of samples has to be collected. Disturbed soil structure and its layers and non-representative samples have previously caused measurement difficulties in non-homogeneous soils. Indirect evidence of preferential flow, such as measurements of drainage rates or tracer concentrations cannot be generalized to other locations or conditions (Fukumasu et al., 2024). Preferential flow cannot be represented by an average of parameters values on a large (field or watershed) scale, sufficient data must be collected and the probabilistic nature of the process has to be investigated. Holistic field measurements are needed for acceptable description of the transport properties of heterogeneous soils (Zhang et al., 2025). New procedures to collect data in the field in order to compute the scope and impact of preferential movement of solutes through the soil need to be developed. This process should be relatively simpler and efficient to satisfy the need for large amount of data to be collected for assessment of simulation models(Nimmo et al., 2025).

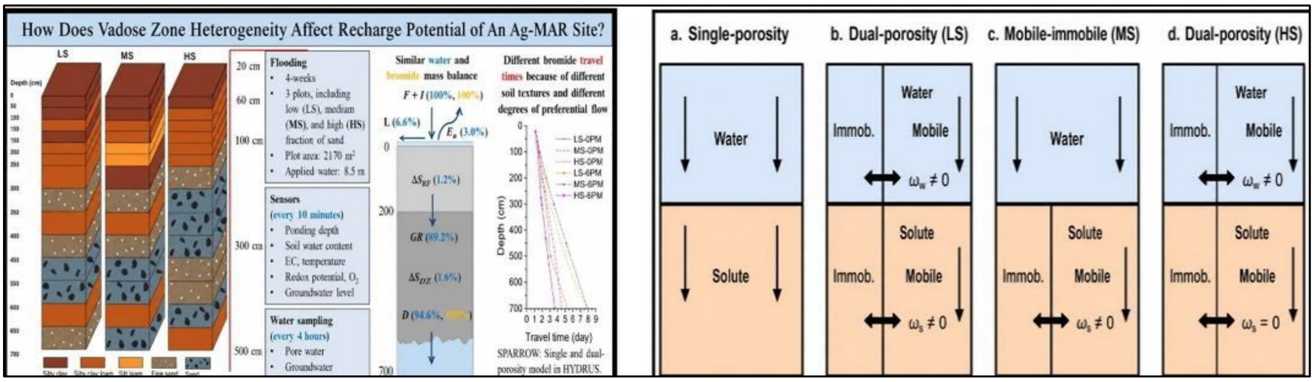

Figure 7: Source:(Zhou et al., 2023) An example of a literature study

However, the models presently used usually under predict measured solute concentrations, since they lack a preferential flow component (Holbak et al., 2021). The model water flow and solute transport in soils which show potential for preferential flow process need to be described. The preferential flow models, their applications presently developed have been limited. This is due to lack of understanding of the macro-porosity in actual field soils. Also the absence of appropriate parameter estimation techniques for computation of semi-empirical transfer coefficients between the two areas (Holbak et al., 2021). Furthermore, the existing preferential flow models are often limited to simulation of water flow, certain soil moisture or steady state flow conditions, or have considered flow and transport in one domain only. Thus, an efficient physically-based numerical model for predicting the movement of water and solutes through soils where preferential flow occurs is needed. Such a model should be enhanced with a stochastic framework to enable assessment of the uncertainty in model variables, and to allow statistical analysis of the model results (Caputo et al., 2024). The use of actual field data is essential for evaluation of such a model. To overcome the scarcity of field data available for testing flow and transport models, new field procedures need to be developed. The method should focus on the collection of data suitable for application of preferential flow models. (Z. Zhang et al., 2025). In the past the researchers assumed isotropic homogeneous stochastic models but in future there is a scope for heterogeneous multi domain scenarios models which high light the climatic and seasonal transient conditions.

Implications for groundwater vulnerability and QMRA

Analysis of a forthright analytic solution, zero and also first-order time moments, and the setback distance for the problem of advective colloid transport with irreversible retention and Langmuir Ian blocking. The model described Escherichia coli breakthrough curves and their retention profiles in fine sand at four ionic strengths. The simulations demonstrated that blocking becomes more significant for smaller retention capacity (S_m) and for larger retention rate coefficient (k), input concentration (C_o), and pulse duration. The colloid arrival time at a specific location with respect to conservative tracer is delayed by the blocking of pores, in turn producing larger setback distances for smaller k and S_m/C_o

Bradford analyzed the impact of bacteria sediment interactions in a continuous, watershed-scale model that was calibrated with measurements of fecal indicator bacteria concentrations in the water column and stream bed sediment. The performance of the model was under a “sediment-attached” scenario was essentially equivalent to the simpler “free-phase” scenario for this site-specific scenario. It is not clear whether the additional model complexity associated with bacteria sediment interactions are justified and/or when these acquaintances need to be considered. Bradford also introduced the interactive computational tool QMRA catch to simulate concentrations of target microorganisms and viruses (TMVs) in catchment dominated water resources, to assess contamination risks from exposure, and to calculate the required treatment to meet health-based water quality targets. Sources of TMVs include wastewater discharge into a river and fecal deposits on a floodplain. Travel times for both the main river and a floodplain river actually were calculated using the Manning–Gauckler–Strickler formula, and concentrations of TMVs were subject to dilution and temperature dependent degradation. Applicability of QMRA catch is demonstrated by calibrating the tool for a study site at the River Danube near Vienna, Austria. Number of authors have considered the said method as a best and flexible tool for transmission of pathogens and also for public health policy formulation (Heida et al., 2024).

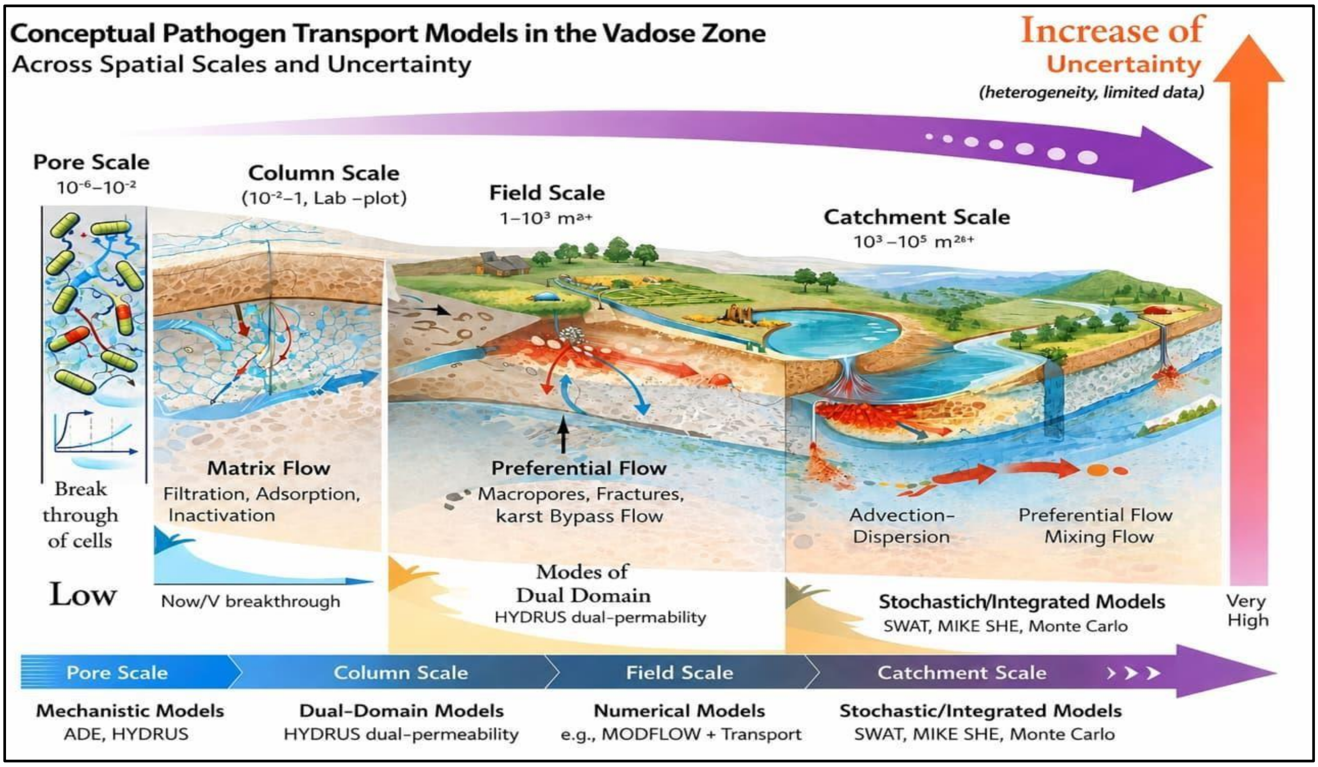

Figure 8: Comparison of pathogen transport modelling across spatial scales and uncertainty levels (Conceptual)

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Unlike past the future investigation shall be framing for public health considerations and risk factors which may include the simulations with real time monitoring and pathogen die-off rates

5. CONCLUSIONS AND FUTURE PERSPECTIVES

Pathogen transport in the vadose zone is a major issue due to its implications for quality of the water and public health, especially in the areas where untreated or partially treated wastewater is discharged or reused for irrigation. This review underlines the influence of soil heterogeneity, hydro-climatic conditions, chemical characteristics, pathogen decay, and transport mechanisms on survival and fate of pathogens. The combined findings in the field, at the laboratory, and modelling studies illustrates the complicated interactions governing pathogen movement in subsurface settings. Upcoming research should concentrate on exploring the double role played by the vadose zone as a temporary water storage medium and a potential secondary source of pollutants. Appropriate understanding will enhance the assessment of risk frameworks, strengthen ground water protection policies and uplift sustainable water resource management. In India there must be a shift of investigations, from pathogen indicator studies to fate and risk assessment of pathogens in transient hydrogeological and climatic variations.

Implications for groundwater protection and water reuse

Understanding vadose zone pathogen transport highlights the need to focus on groundwater protection policies. Preferential flow pathways aid rapid flow of contaminants through the vadose zone with limited curtailment. Protection measures vary from site to site, considering soil structure, groundwater depth, and flow conditions. For water reuse practices depending on soil as the only treatment barrier is not sufficient. A multi-barrier approach with prior treatment, skilful loading, and monitoring is essential. Risk assessments should include diverse pathogens to ensure safe and sustainable groundwater management. Limited studies on microbial assessment seasonally and effect of MAR in different seasons. Association of microbial risk and reuse of reclaimed waste water and guidelines for groundwater and Irrigation

Key research gaps (field data, scale effects, climate extremes)

In order to understand the process of subsurface pathogen transport yet the important gaps remain. There is no proper correlation of field data with natural and transient conditions, limiting validation of laboratory results and models. Many studies depend on controlled experiments that do not capture field-scale difficulty. Scale effects are poorly understood, as results from pore or column scales cannot be directly applied to field conditions.

Heterogeneity in soil structure, macropore connectivity, and hydraulic properties further reduces model reliability. Climate and seasonal factors such as intense rainfall, drought, and changing moisture in a region are not properly incorporated. Such conditions can alter flow paths, increase preferential transport, and disturb pathogen survival. Focusing on these gaps requires integrated, multi-scale field studies, improved monitoring, and models that account for dynamic, non-equilibrium processes. Application partially treated waste will not exhibit the correct factors which aid in survival of pathogens. Agricultural factors like use of fertilizers and its application and point and non-point sources also cannot clearly make the understanding of the fate of pathogens

6. CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

7. PLAGIARISM POLICY

All authors declare that any kind of violation of plagiarism, copyright and ethical matters will\ takecare by all authors. Journal and editors are not liable for aforesaid matters.

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REFERENCES:

[1] **1.**A, R. D., & Journal, Z. (2025). Correction to “A generalized analytical solution for preferential infiltration and wetting” (Vadose Zone Journal, 18, 1, (1-10), 10.2136/vzj2018.08.0148). *Vadose Zone Journal*, *24*(2), 2–3. https://doi.org/10.1002/vzj2.70018

[2] 2.Amami, R., Ibrahimi, K., Sher, F., Milham, P., Ghazouani, H., Chehaibi, S., Hussain, Z., & Iqbal, H. M. N. (2021). Impacts of different tillage practices on soil water infiltration for sustainable agriculture. *Sustainability (Switzerland)*, *13*(6). https://doi.org/10.3390/su13063155

[3] 3.Araya, S. N., Mitchell, J. P., Hopmans, J. W., & Ghezzehei, T. A. (2022). Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage. *Soil*, *8*(1), 177–198. https://doi.org/10.5194/soil-8-177-2022

[4] 4.Armanious, A., Aeppli, M., Jacak, R., Refardt, D., Sigstam, T., Kohn, T., & Sander, M. (2016). Viruses at Solid-Water Interfaces: A Systematic Assessment of Interactions Driving Adsorption. *Environmental Science and Technology*, *50*(2), 732–743. https://doi.org/10.1021/acs.est.5b04644

[5] 5.Banasiak, L. J., Weaver, L., Humphries, B., Dann, R., Blaurock, M., Gosses, M., Pang, L., & Close, M. (2023a). Microbial and solute transport through intact vadose zone cores of heterogeneous alluvial gravel under variably saturated conditions. *Vadose Zone Journal*, *22*(3). https://doi.org/10.1002/vzj2.20250

[6] 6.Barba, C., Folch, A., Gaju, N., Sanchez-Vila, X., Carrasquilla, M., Grau-Martínez, A., & Martínez-Alonso, M. (2019). Microbial community changes induced by Managed Aquifer Recharge activities: Linking hydrogeological and biological processes. *Hydrology and Earth System Sciences*, *23*(1), 139–154. https://doi.org/10.5194/hess-23-139-2019

[7] 7.Bekoe, E. M. O., Hayford, D., Quarcoo, G., & Yar, D. D. (2025). Groundwater microbial quality and risk evaluation in a rapidly transforming urbanized area of Northern Ghana. *BMC Environmental Science*, *2*(1). https://doi.org/10.1186/s44329-025-00022-w

[8] 8.Bouma, J. (1981a). Soil morphology and preferential flow along macropores. *Agricultural Water Management*, *3*(4), 235–250. https://doi.org/10.1016/0378-3774(81)90009-3

[9] 9.Bradford, S. A., Schijven, J., & Harter, T. (2015a). Microbial Transport and Fate in the Subsurface Environment: Introduction to the Special Section. *Journal of Environmental Quality*, *44*(5), 1333–1337. https://doi.org/10.2134/jeq2015.07.0375

[10] 10.Cao, Y., Zhang, K., Liu, S., & Wang, Y. (2024). A review of advancements in the theory and characterization of soil macropore structure. *PeerJ*, *12*(11). https://doi.org/10.7717/peerj.18442

[11] 11.Caputo, M. C., De Carlo, L., Masciale, R., Perkins, K., Turturro, A. C., & Nimmo, J. R. (2024). Detection and quantification of preferential flow using artificial rainfall with multiple experimental approaches. *Hydrogeology Journal*, *32*(2), 467–485. https://doi.org/10.1007/s10040-023-02733-3

[12] 12.Chen, X., Yu, Z., Yi, P., Hwang, H. T., Sudicky, E. A., Tang, T., & Aldahan, A. (2024). Effects of soil heterogeneity and preferential flow on the water flow and isotope transport in an experimental hillslope. *Science of The Total Environment*, *917*, 170548. https://doi.org/10.1016/J.SCITOTENV.2024.170548

[13] 13.Cook, P. G., Banks, E. W., Marshall, S. K., Harrington, G. A., Batlle-Aguilar, J., Dogramaci, S., & Turnadge, C. (2022). Inferring fault hydrology using groundwater age tracers. *Journal of Hydrology*, *610*, 127905. https://doi.org/10.1016/j.jhydrol.2022.127905

[14] 14.Cooper, H. V., Sjögersten, S., Lark, R. M., Girkin, N. T., Vane, C. H., Calonego, J. C., Rosolem, C., & Mooney, S. J. (2021). Long-term zero-tillage enhances the protection of soil carbon in tropical agriculture. *European Journal of Soil Science*, *72*(6), 2477–2492. https://doi.org/10.1111/ejss.13111

[15] 15.Cueto-Felgueroso, L., Suarez-Navarro, M. J., Fu, X., & Juanes, R. (2020). Numerical Simulation Of Unstable Preferential Flow During Water Infiltration Into Heterogeneous Dry Soil. *Water (Switzerland)*, *12*(3), 1–19. https://doi.org/10.3390/w12030909

[16] 16.Currle, F., Therrien, R., & Schilling, O. S. (2025). Explicit simulation of microbial transport with a dual-permeability, two-site kinetic deposition formulation using the integrated surface-subsurface hydrological model HydroGeoSphere. *Hydrology and Earth System Sciences*, *29*(20), 5383–5403. https://doi.org/10.5194/hess-29-5383-2025

[17] 17.Dahunsi, J., Pathirana, S., Cheema, M., Krishnapillai, M., & Galagedara, L. (2025). Estimating soil hydraulic conductivity from time-lapse ground-penetrating radar data in podzolic soils using the green-ampt model. *Journal of Hydrology*, *657*. https://doi.org/10.1016/j.jhydrol.2025.133059

[18] 18.De Carlo, L., Perkins, K., & Caputo, M. C. (2021). Evidence of preferential flow activation in the vadose zone via geophysical monitoring. *Sensors (Switzerland)*, *21*(4), 1–16. https://doi.org/10.3390/s21041358

[19] 19.Farmer-Diaz, K., Matthew-Bernard, M., Cheetham, S., Mitchell, K., Macpherson, C. N. L., & Ramos-Nino, M. E. (2025). Optimized Aluminum Hydroxide Adsorption–Precipitation for Improved Viral Detection in Wastewater. 20.*International Journal of Environmental Research and Public Health*, *22*(2). https://doi.org/10.3390/ijerph22020148

[20] 21.Fukumasu, J., Jarvis, N., Koestel, J., & Larsbo, M. (2024). Links between soil pore structure, water flow and solute transport in the topsoil of an arable field: Does soil organic carbon matter? *Geoderma*, *449*(May), 117001. https://doi.org/10.1016/j.geoderma.2024.117001

[21] 22.Heffron, J., Samsami, M., Juedemann, S., Lavin, J., Tavakoli Nick, S., Kieke, B. A., & Mayer, B. K. (2024). Mitigation of viruses of concern and bacteriophage surrogates via common unit processes for water reuse: A meta-analysis. *Water Research*, *252*(January), 121242. https://doi.org/10.1016/j.watres.2024.121242

[22] 23.Holbak, M., Abrahamsen, P., Hansen, S., & Diamantopoulos, E. (2021a). A Physically Based Model for Preferential Water Flow and Solute Transport in Drained Agricultural Fields. *Water Resources Research*, *57*(3), 1–19. https://doi.org/10.1029/2020WR027954

[23] 24.Iqbal, S., Begum, F., Nguchu, B. A., Claver, U. P., & Shaw, P. (2025). The invisible architects: microbial communities and their transformative role in soil health and global climate changes. *Environmental Microbiome*, *20*(1). https://doi.org/10.1186/s40793-025-00694-6

[24] 25.Jat Baloch, M. Y., Baidya, P., Aryal, M., Moeen-ud-din, M., Yang, L., Iqbal, J., Ptak, M., llić, P., & Liu, C. (2026a). Fate and transport of viruses in the subsurface environment: A systematic review of pollution pathways in saturated and unsaturated porous media. *Environmental Research*, *288*(January), 1–8. https://doi.org/10.1016/j.envres.2025.123163

[25] 26.Jiménez-Martínez, J., Le Borgne, T., Tabuteau, H., & Méheust, Y. (2017). Impact of saturation on dispersion and mixing in porous media: Photobleaching pulse injection experiments and shear-enhanced mixing model. *Water Resources Research*, *53*(2), 1457–1472. https://doi.org/10.1002/2016WR019849

[26] 27.Kalhor, K., Ghasemizadeh, R., Rajic, L., & Alshawabkeh, A. (2019). Assessment of groundwater quality and remediation in karst aquifers: A review. *Groundwater for Sustainable Development*, *8*, 104–121. https://doi.org/10.1016/J.GSD.2018.10.004

[27] 28.Katuwal, S., Ashworth, A. J., & Owens, P. R. (2021a). Preferential flow under high-intensity short-duration irrigation events in soil columns from a karst and nonkarst landscape. *Vadose Zone Journal*, *20*(6), 1–13. https://doi.org/10.1002/vzj2.20160

[28] 29.Kidane, S. B. (n.d.). Groundwater-recharge estimation in Waja-Golesha Sub-basin, Northern Ethiopia: An approach using WetSpass Model. *J. Agri. Environ. Sci*, *8*(1), 2023. https://doi.org/10.20372/jaes.v8i1.10202

[29] 30.Knabe, D., Dwivedi, D., Wang, H., Griebler, C., & Engelhardt, I. (2023). Numerical investigations to identify environmental factors for field-scale reactive transport of pathogens at riverbank filtration sites. *Advances in Water Resources*, *173*, 104389. https://doi.org/10.1016/J.ADVWATRES.2023.104389

[30] 31.Krol, Q., Fouxon, I., Corso, P., & Holzner, M. (2021). Local Hydraulic Resistance in Heterogeneous Porous Media. *Geophysical Research Letters*, *48*(22), 1–10. https://doi.org/10.1029/2021GL094694

[31] 32.Lai, X., Liao, K., Feng, H., & Zhu, Q. (2016). Responses of soil water percolation to dynamic interactions among rainfall, antecedent moisture and season in a forest site. *Journal of Hydrology*, *540*, 565–573. https://doi.org/10.1016/J.JHYDROL.2016.06.038

[32] 33.Lebon, Y., François, C., Navel, S., Vallier, F., Guillard, L., Pinasseau, L., Oxarango, L., Volatier, L., & Mermillod-Blondin, F. (2023). Aquifer recharge by stormwater infiltration basins: Hydrological and vadose zone characteristics control the impacts of basins on groundwater chemistry and microbiology. *Science of The Total Environment*, *865*, 161115. https://doi.org/10.1016/J.SCITOTENV.2022.161115

[33] 34.Leue, M., Uteau-Puschmann, D., Peth, S., Nellesen, J., Kodešová, R., & Gerke, H. H. (2019). Separation of Soil Macropore Types in Three-Dimensional X-Ray Computed Tomography Images Based on Pore Geometry Characteristics. *Vadose Zone Journal*, *18*(1), 1–13. https://doi.org/10.2136/vzj2018.09.0170

[34] 35.Li, M., Yao, J., & Cheng, J. (2020). Study on the preferential flow characteristics under different precipitation amounts in simian mountain grassland of china. *Water (Switzerland)*, *12*(12), 1–12. https://doi.org/10.3390/w12123489

[35] 36.Li, M., Yao, J., Yan, R., & Cheng, J. (2021). Effects of infiltration amounts on preferential flow characteristics and solute transport in the protection forest soil of Southwestern China. *Water (Switzerland)*, *13*(9). https://doi.org/10.3390/w13091301

[36] 37.Li, X., & Bourg, I. C. (2024). Hygroscopic Growth of Adsorbed Water Films on Smectite Clay Particles. *Environmental Science and Technology*, *58*(2), 1109–1118. https://doi.org/10.1021/acs.est.3c08253

[37] 38.Li, X., Wen, Z., Zhan, H., Zhu, Q., & Jakada, H. (2022). On the Bimodal Radial Solute Transport in Dual-Permeability Porous Media. *Water Resources Research*, *58*(11). https://doi.org/10.1029/2022WR032580

[38] 39.Luo, S., Zhou, B., Likos, W. J., & Lu, N. (2024). Determining Capillary Pore–Size Distribution of Soil from Soil–Water Retention Curve. *Journal of Geotechnical and Geoenvironmental Engineering*, *150*(2), 1–14. https://doi.org/10.1061/jggefk.gteng-11647

[39] 40.Mattar, M. A. M., Eraqi, W. A., Zaki, M. B., Elkashlan, A. M., Abouzid, K. A. M., Aziz, R. K., Yassin, A. S., & Elbehery, A. H. A. (2025). What lies beneath: microbial quality of rural groundwater explored by shotgun metagenomics. *Annals of Microbiology*, *75*(1), 1–16. https://doi.org/10.1186/s13213-025-01801-1

[40] 41.Mesele, H., Grum, B., Aregay, G., & Berhe, G. T. (2024). Evaluation and comparison of infiltration models for estimating infiltration capacity of different textures of irrigated soils. *Environmental Systems Research*, *13*(1). https://doi.org/10.1186/s40068-024-00356-5

[41] 42.Morales, I., Amador, J. A., & Boving, T. (2015). Bacteria Transport in a Soil-Based Wastewater Treatment System under Simulated Operational and Climate Change Conditions. *Journal of Environmental Quality*, *44*(5), 1459–1472. https://doi.org/10.2134/jeq2014.12.0547

[42] 43.Mustafa, O., Thornton, S. F., Bau, D., & Mahmmud, R. (2025a). A review of the occurrence, fate, and transport of SARS-CoV-2 in the aqueous environment, with specific reference to groundwater. *Environmental Earth Sciences*, *84*(9), 1–16. https://doi.org/10.1007/s12665-025-12256-7

[43] 44.Nimmo, J. R., Wiekenkamp, I., Araki, R., Groh, J., Singh, N. K., Crompton, O., Wyatt, B. M., Ajami, H., Giménez, D., Hirmas, D. R., Sullivan, P. L., & Sprenger, M. (2025). Identifying preferential flow from soil moisture time series: Review of methodologies. *Vadose Zone Journal* , *24*(2), 1–25. https://doi.org/10.1002/vzj2.70017

[44] 45.Ning, Z., Wang, S., Guo, C., & Zhang, M. (2023a). The impact of environmental factors on the transport and survival of pathogens in agricultural soils from karst areas of Yunnan province, China: Laboratory column simulated leaching experiments. *Frontiers in Microbiology*, *14*(March), 1–11. https://doi.org/10.3389/fmicb.2023.1143900

[45] 46.Paraskevas, C., Karpouzos, D., & Babajimopoulos, C. (2023). Application of Leak 2D to Describe Preferential Water Flow in a Soil Containing Artificial Macropores. *Mathematics*, *11*(13). https://doi.org/10.3390/math11132889

[46] 47.Paswan, A., & Sharma, P. K. (2025). The role of mobile-immobile sorbents on flow and colloid-facilitated contaminant transport through porous media: Two-dimensional modeling. *Journal of Hydrology*, *646*, 132307. https://doi.org/10.1016/J.JHYDROL.2024.132307

[47] 48.Ping, T., Zeshun, X., Penghui, M., & Yongchao, Z. (2021). Laboratory investigation on Bacillus subtilis addition to alleviate bio-clogging for constructed wetlands. *Environmental Research*, *194*, 110642. https://doi.org/10.1016/J.ENVRES.2020.110642

[48] 49.Richiardi, L., Pignata, C., Fea, E., Bonetta, S., & Carraro, E. (2023). Are Indicator Microorganisms Predictive of Pathogens in Water? In *Water (Switzerland)* (Vol. 15, Number 16). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/w15162964

[49] 50.Rizwan, H. M., Naveed, M., Sajid, M. S., Nazish, N., Younus, M., Raza, M., Maqbool, M., Khalil, M. H., Fouad, D., & Ataya, F. S. (2024). Enhancing agricultural sustainability through optimization of the slaughterhouse sludge compost for elimination of parasites and coliforms. *Scientific Reports*, *14*(1), 1–14. https://doi.org/10.1038/s41598-024-75606-8

[50] 51.Rusiñol, M. (2023a). Waterborne viruses in urban groundwater environments. In *PLOS Water* (Vol. 2, Number 8 August). Public Library of Science. https://doi.org/10.1371/journal.pwat.0000168

[51] 52.Saeibehrouzi, A., Abolfathi, S., Denissenko, P., & Holtzman, R. (2024a). Pore-scale modeling of solute transport in partially-saturated porous media. In *Earth-Science Reviews* (Vol. 256). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2024.104870

[52] 53.Sasidharan, S., & Bradford, S. A. (2025). Assessing drywell designs for managed aquifer recharge via canals and repurposed wells. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-024-84865-4

[53] 54.Seibutis, V., Tamošiūnas, K., Deveikytė, I., Kadžienė, G., & Semaškienė, R. (2025). Earthworm Population Response to Simplified Tillage and Shortened Crop Rotations in a Central Lithuanian Cambisol: A Five-Year Study. *Agriculture (Switzerland)*, *15*(4), 1–19. https://doi.org/10.3390/agriculture15040366

[54] 55.Sepehrnia, N., Teshnizi, F. A., Hallett, P., Coyne, M., Shokri, N., & Peth, S. (2024). Modeling bacterial transport and fate: Insight into the cascading consequences of soil water repellency and contrasting hydraulic conditions. *Science of the Total Environment*, *954*(May), 176196. https://doi.org/10.1016/j.scitotenv.2024.176196

[55] 56.Shawver, S., Ishii, S., Strickland, M. S., & Badgley, B. (2024). Soil type and moisture content alter soil microbial responses to manure from cattle administered antibiotics. *Environmental Science and Pollution Research*, *31*(18), 27259–27272. https://doi.org/10.1007/s11356-024-32903-z

[56] 57.Silburn, D. M., Tolmie, P. E., Biggs, A. J. W., & Crawford, M. H. (2022). Effects of farming systems, tillage, and traffic practices on deep drainage and soil salt loads in the Queensland Murray-Darling and Fitzroy Basins using soil chloride. *Soil Research*, *60*(3), 262–278. https://doi.org/10.1071/SR21084

[57] 58.Šimůnek, J., Brunetti, G., Jacques, D., van Genuchten, M. T., & Šejna, M. (2024). Developments and applications of the HYDRUS computer software packages since 2016. *Vadose Zone Journal* , *23*(4), 1–29. https://doi.org/10.1002/vzj2.20310

[58] 59.Summerton, L., Greener, M., Patterson, D., & Brown, C. D. (2023). Effects of soil redistribution by tillage on subsequent transport of pesticide to subsurface drains. *Pest Management Science*, *79*(2), 616–626. https://doi.org/10.1002/ps.7229

[59] 60.Torkzaban, S., Hocking, M., Bradford, S. A., Tazehkand, S. S., Sasidharan, S., & Šimůnek, J. (2019). Stochasting modeling of virus transport and removal during aquifer storage and recovery. *Journal of Hydrology*, *578*, 124082. https://doi.org/10.1016/j.jhydrol.2019.124082

[60] 61.Toutlini, N. E., Kamil, H., Soulaïmani, A., & Beljadid, A. (2024). Predictor-Corrector Second-Order Time-Stepping Schemes for Solving Water Flow and Solute Transport in Unsaturated Porous Media. *World Congress in Computational Mechanics and ECCOMAS Congress*, (July), 21–26. https://doi.org/10.23967/wccm.2024.050

[61] 62.Türk, H., Stumpp, C., Hrachowitz, M., Schulz, K., Strauss, P., Blöschl, G., & Stockinger, M. (2025). Soil moisture and precipitation intensity jointly control the transit time distribution of quick flow in a flashy headwater catchment. *Hydrology and Earth System Sciences*, *29*(16), 3935–3956. https://doi.org/10.5194/hess-29-3935-2025

[62] 63.Upadhyay, S. K., Singh, G., Rani, N., Rajput, V. D., Seth, C. S., Dwivedi, P., Minkina, T., Wong, M. H., Show, P. L., & Khoo, K. S. (2024). Transforming bio-waste into value-added products mediated microbes for enhancing soil health and crop production: Perspective views on circular economy. *Environmental Technology and Innovation*, *34*(February), 103573. https://doi.org/10.1016/j.eti.2024.103573

[63] 64.Wu, X., Shen, D., Hui, C., Yu, Q., & Long, Y. (2024). Evaluation of pathogen spread risk from excavated landfill. *Environmental Pollution*, *349*, 123993. https://doi.org/10.1016/J.ENVPOL.2024.123993

[64] 65.Yan, W., & Cudmani, R. (2024). A novel framework for deriving water retention behavior of multimodal unsaturated soils based on pore size distribution data. *Acta Geotechnica*, *19*(12), 8071–8088. https://doi.org/10.1007/s11440-024-02355-3

[65] 66.You, J., Wang, S., & Xu, D. (2022). Experimental Investigations on Influence of Fracture Networks on Overland Flow and Water Infiltration in Soil. *Water (Switzerland)*, *14*(21). https://doi.org/10.3390/w14213483

[66] 67.Zhang, W., Chai, J., Li, S., Wang, X., Wu, S., Liang, Z., Baloch, M. Y. J., Silva, L. F. O., & Zhang, D. (2022a). Physiological characteristics, geochemical properties and hydrological variables influencing pathogen migration in subsurface system: What we know or not? *Geoscience Frontiers*, *13*(6), 101346. https://doi.org/10.1016/J.GSF.2021.101346

[67] 68.Zhou, T., Levintal, E., Brunetti, G., Jordan, S., Harter, T., Kisekka, I., Šimůnek, J., & Dahlke, H. E. (2023). Estimating the impact of vadose zone heterogeneity on agricultural managed aquifer recharge: A combined experimental and modeling study. *Water Research*, *247*(April). https://doi.org/10.1016/j.watres.2023.120781