Hydropedology: Bridging Soil and Water for Sustainable Land Management

Savita P Doni[1], Mounika M N[2], Salma[3] and Yallappa B Doni[4]

[1]Ph.D. Scholar, Department of Soil Science and Agricultural Chemistry, College of Agriculture, University of Agricultural Sciences, Dharwad - 580005, Karnataka, India.

[2]M.Sc. (Agri.), Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad 580005, Karnataka, India.

[3]Young Professional, ICAR-IIPR, Regional Research Station, Dharwad - 580005, Karnataka, India.

[4]M.Sc. (Agri.), Department of Agronomy, University of Agricultural and Horticultural Sciences, Shivamogga – 577204, Karnataka, India.

Corresponding Author: savitadoni0806@gmail.com

Introduction

Water and soil are inseparable components of terrestrial ecosystems. Their interaction governs crop productivity, groundwater recharge, nutrient cycling and environmental quality. Yet, conventional soil survey and land evaluation often treat soil morphology and hydrology as separate domains. Hydropedology integrates these perspectives, examining how soil properties control water movement and storage and how water, in turn, influences soil formation and function. This integrative approach is increasingly important for sustainable agriculture, climate resilience and informed land use planning.

Understanding Hydropedology

Hydropedology integrates pedology and hydrology to understand soil-water interactions from pore scale to watershed level. It views soil not as a static body, but as a dynamic regulator of infiltration, percolation, runoff, storage and preferential flow.

Soil properties such as texture, structure, organic matter, clay mineralogy and horizon development control hydraulic conductivity, water retention and drainage. In turn, hydrological processes like seasonal saturation, subsurface flow and water table fluctuations influence pedogenic processes including clay movement, carbonate accumulation and redox feature formation.

Because these interactions vary with scale, hydropedology examines pore geometry at the microscale, water availability at the field scale and groundwater recharge and streamflow at the watershed scale. This scale-based approach makes it highly relevant for agricultural landscape management.

Soil-Water Interactions and Crop Performance

Hydropedological properties strongly influence nutrient dynamics and crop productivity, particularly through soil water-nitrogen interactions. In a mid-Atlantic agricultural landscape study, Zhu *et al.*, 2009 showed that landform position, soil texture and subsurface flow pathways created significant within-field variation in nitrogen availability and corn yield. Fine-textured soils with lower saturated hydraulic conductivity retained more water and nitrogen, resulting in higher biomass and grain yield, whereas sloping areas with shallow lateral flow experienced greater nitrogen losses and reduced productivity.

These results demonstrate that soil water dynamics govern nutrient retention and loss pathways. Coarse, well-drained soils are more susceptible to nitrate leaching, while poorly drained or fine-textured soils may promote denitrification. Recognizing hydropedological variability therefore supports site-specific nutrient management and improved nitrogen use efficiency.

Table 1. Key Hydropedological Properties and Their Functional Significance

Property	Hydrological Role	Pedological Significance	Land Use Implication
Soil Texture (sand, silt, clay proportion)	Controls infiltration rate, water retention, drainage and leaching potential	Reflects parent material and degree of weathering; influences horizon differentiation	Determines irrigation frequency, fertilizer efficiency and crop suitability
Soil Structure (aggregation, pore arrangement)	Regulates permeability, preferential flow, aeration and runoff generation	Indicates pedogenic processes such as clay illuviation and organic matter stabilization	Guides tillage practices, erosion control measures and root development potential
Bulk Density	Influences infiltration capacity, porosity and root penetration	Indicates compaction, structural degradation or management impacts	Affects mechanization, irrigation efficiency and crop productivity

Porosity (macro and micropores)	Governs water storage, transmission and drainage pathways	Reflects aggregation status and biotic activity	Impacts drought resilience and waterlogging risk
Hydraulic Conductivity (Ks)	Determines rate of water movement through soil profile	Reflects structural continuity and clay mineralogy	Essential for drainage design, irrigation planning and flood mitigation
Soil Water Retention (field capacity, wilting point)	Defines plant-available water and drought buffering capacity	Influenced by texture, organic matter and mineral composition	Supports crop selection, irrigation scheduling and yield stability
Preferential Flow Pathways (macropores, cracks, root channels)	Facilitates rapid vertical and lateral water movement; enhances leaching risk	Associated with shrink-swell clays, bioturbation and structural development	Affects nutrient management, pesticide transport and groundwater protection
Soil Depth / Effective Rooting Depth	Controls total water storage capacity and subsurface flow behaviour	Reflects erosion-deposition history and landscape evolution	Determines crop choice, rooting potential and drought tolerance
Organic Matter Content	Enhances aggregation, infiltration and moisture retention	Indicator of biological activity and pedogenic stability	Promotes soil health, carbon sequestration and sustainable productivity
Clay Mineralogy (e.g., smectite dominance)	Influences shrink–swell behaviour, permeability and water holding	Determines pedogenic processes such as vertic properties and cracking patterns	Impacts infrastructure stability, irrigation response and land capability classification
Soil Salinity (EC)	Affects osmotic potential and water uptake by plants	Indicates accumulation processes under limited leaching	Guides drainage planning and crop salt tolerance management
Exchangeable Sodium Percentage (ESP)	Reduces infiltration and disperses clay particles	Reflects sodification and regressive pedogenesis	Requires reclamation measures (gypsum, drainage) for sustainable agriculture
Carbonate Accumulation ($CaCO_3$)	Modifies pore continuity and infiltration behaviour	Marker of semi-arid pedogenesis and leaching intensity	Influences nutrient availability and irrigation suitability
Topographic Position	Controls runoff convergence, recharge zones and soil moisture variability	Drives soil horizon differentiation and lateral translocation processes	Supports precision agriculture and variable-rate input management
Slope Gradient	Influences runoff velocity, erosion risk and infiltration opportunity time	Associated with soil thinning or deposition	Guides soil conservation practices and land capability assessment

Vertisols and Hydro-Pedological Complexity

Cracking clay soils (*Vertisols*) illustrate how hydropedological processes shape productivity in semi-arid tropical India. Derived from Deccan basalt, these soils exhibit swelling-shrinking behaviour and complex hydraulic characteristics. Zade *et al.*, 2017 showed that in the Marathwada region, pedogenic calcium carbonate formation and sodium enrichment significantly influence hydraulic conductivity and soil structure. Although Ca-zeolites in the parent material can initially improve aggregation by releasing calcium, under semi-arid conditions carbonate formation may outpace calcium release, increasing exchangeable sodium percentage, reducing saturated hydraulic conductivity and degrading structure.

Such regressive processes restrict water movement and root growth and irrigation may worsen sodicity and drainage issues. The findings highlight that soil modifiers operate within climatic limits and emphasize the importance of integrating pedogenic history with hydrological context in *Vertisol* management.

Hydropedology Across Landscapes

Landscape position strongly shapes hydropedological behaviour, as topography controls runoff, soil depth, erosion-deposition patterns and moisture distribution. As a result, soil properties and water dynamics vary considerably within a field.

Fu *et al.*, 2011 highlight that soil development and hydrological processes co-evolve, with horizon differentiation, clay illuviation and structural features reflecting long-term water flux patterns. Depressional areas tend to retain finer materials and moisture, while upper slopes are thinner and better drained. Likewise, Kavaklıgil and Ersahin, 2023 show that soil morphological features such as mottling, clay skins and structural changes serve as indicators of subsurface flow and saturation dynamics. By linking soil morphology with hydrology, hydropedology enhances traditional soil surveys and strengthens land capability assessment through functional interpretation of water behaviour.

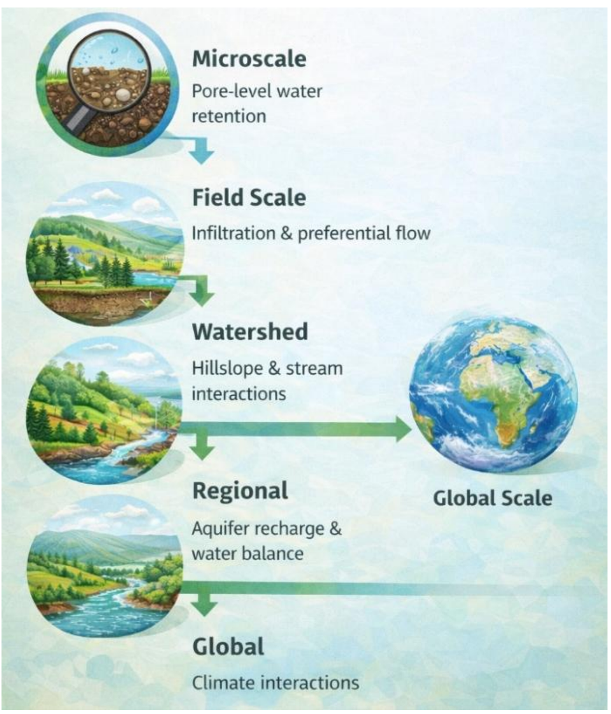

Fig. 1. Multi-scale hydropedology framework

Hydropedology operates across scales-from pore-level water retention to watershed hydrology and global climate interactions.

Implications for Precision Agriculture

Modern agriculture increasingly relies on spatially explicit data for decision-making. Precision farming technologies enable variable-rate fertilizer application, irrigation scheduling and site-specific soil management. However, these technologies must be grounded in process-based understanding.

Hydropedological insights support precision agriculture in several ways:

1. **Nitrogen Management:** By identifying zones prone to leaching or denitrification, fertilizer rates can be adjusted according to hydrological risk, improving nutrient use efficiency.
2. **Irrigation Planning:** Knowledge of soil water holding capacity and hydraulic conductivity informs irrigation scheduling, preventing both water stress and waterlogging.
3. **Drainage Design:** Understanding subsurface flow pathways assists in designing drainage systems tailored to soil structure and landscape position.
4. **Crop Selection:** Crops can be matched with soil water regimes, enhancing resilience under variable rainfall conditions.

The integration of soil survey data, hydrological modelling and remote sensing enhances the predictive capacity of hydropedological assessments. Rather than treating variability as a challenge, hydropedology transforms it into actionable management information.

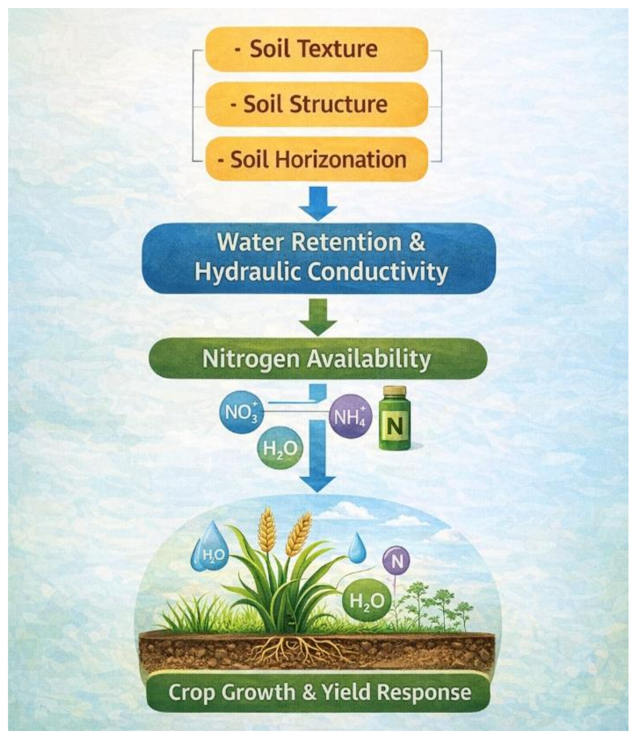

Fig. 2. Hydropedological Control on Crop Nitrogen and Water Dynamics

Hydropedological processes regulate nutrient availability and crop productivity through soil–water interactions.

Table 2. Hydropedological Controls Across Soil Horizons and Their Management Implications

Soil Horizon	Dominant Hydropedological Feature	Observed Spatial Pattern	Impact on Water Movement	Nutrient Dynamics	Practical Management Recommendation
A Horizon (Surface Layer)	High organic matter, strong micro-topographic influence, high nugget effect	Weak spatial continuity; high short-range variability	Rapid infiltration but variable retention	Active mineralization; prone to leaching and denitrification	Precision fertilizer application; residue retention; controlled traffic farming
B Horizon (Subsurface)	Strong spatial structuring; longer geostatistical range	Moderate to strong spatial dependency	Controls percolation and subsurface flow	Acts as nutrient buffering layer	Deep tillage only where compacted; subsoil amelioration if restrictive
C Horizon (Parent Material Zone)	Patchy variability; limited pedogenic development	Weak structuring similar to A horizon	Influences deep drainage and groundwater recharge	Limited nutrient storage	Avoid over-irrigation; monitor nitrate leaching
Fragipan / Restrictive Layer (where present)	Impeded permeability	Lateral subsurface flow zones	Water accumulation above layer	Potential nutrient accumulation above barrier	Drainage planning; contour farming; avoid heavy machinery
Sodic *Vertisol* Horizons (Bss)	Low saturated hydraulic conductivity; high ESP	Poor structural stability	Slow infiltration; surface runoff risk	Reduced N availability under water stress	Gypsum application; organic amendments; improved drainage

Climate Change and Water Security

Climate change is increasing variability in rainfall intensity and distribution, particularly in semi-arid regions where prolonged dry spells are followed by intense storms. Such fluctuations amplify erosion, runoff and nutrient losses.

Hydropedology offers a framework to anticipate soil responses under altered hydrological regimes. High-intensity rainfall can exceed infiltration capacity in degraded or sodic soils, accelerating runoff and erosion, while extended droughts may intensify cracking in *Vertisols* and modify preferential flow during rewetting. By clarifying how soils store, transmit and filter water, hydropedology supports climate adaptation through improved groundwater recharge planning, erosion control and sustainable irrigation management.

Application in Land Use Planning

Effective land use planning requires assessing soil suitability, water availability and environmental risk. Hydropedology enhances this process by integrating water flow pathways and storage capacity into land evaluation.

Soil morphological indicators of saturation and low permeability help identify flood-prone zones, where agricultural or urban expansion may increase risk without proper drainage. Likewise, development on low-infiltration soils can intensify stormwater runoff and urban flooding. At the watershed scale, hydropedological mapping delineates recharge areas, subsurface flow paths and nutrient export zones, supporting drinking water protection and ecosystem sustainability.

Toward Regenerative Soil-Water Systems

Healthy soils act as sponges, filters and regulators in the hydrological cycle. Management practices such as organic matter addition, conservation tillage, residue retention and diversified cropping improve aggregation, infiltration and water retention. A hydropedological perspective clarifies how these practices modify soil–water dynamics over time. Increasing soil organic carbon enhances aggregate stability and hydraulic conductivity, reducing erosion and strengthening system resilience.

By integrating pedology and hydrology, hydropedology supports sustainable agriculture goals, including food security, water conservation and environmental protection.

Conclusion

Hydropedology offers a rigorous framework for understanding soil-water interactions across scales. Evidence from landscape nutrient studies, semi-arid *Vertisol* research and soil morphology-hydrology linkages shows that soil and water management are inseparable. Variations in texture, structure, mineralogy and topography directly influence water flow, nutrient dynamics and crop productivity.

For Indian agriculture, especially in semi-arid regions with cracking clay soils, hydropedological insights guide irrigation planning, nutrient management and climate-resilient land use. By integrating hydrological function into soil surveys, hydropedology converts static soil information into dynamic decision-support tools, strengthening sustainable and resilient land management.

References

Espinha M. J., Martins V., Santos P., Ribeiro J., Mansilha C., Melo A., Rocha F. and Flores D. (2021). Changes induced by self-burning in technosols from a coal mine waste pile: a hydropedological approach. Geosciences, 11(5), 195-214.

Fu Z., Li Z., Cai C., Shi Z., Xu Q. and Wang X. (2011). Soil thickness effect on hydrological and erosion characteristics under sloping lands: a hydropedological perspective. Geoderma, 167, 41-53.

Kavakhgil S. S. and Ersahin S. (2023). Spatial variability of some soil physical properties on semi-arid cultivated hillslopes in hydropedological perspective. Eurasian Soil Science, 56(6), 715-726.

Zade S. P., Chandran P. and Pal D. K. (2017). Ca-zeolites as transitory eco-system engineers: hydro-pedological evidence in cracking clay soils (*Vertisols*) of semi-arid Marathwada region, Maharashtra. Clay research, 36(2), 90-105.

Zhu Q., Schmidt J. P., Lin H. S. and Sripada R. P. (2009). Hydropedological processes and their implications for nitrogen availability to corn. Geoderma, 154(1-2), 111-122.

* * * * * * * * *