Climate-Responsive Groundwater Vulnerability Assessment Model Integrating Hydrological Variability and Land-Use Change

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Abstract- Groundwater resources are increasingly threatened by the combined effects of climate variability and rapid land-use change, particularly in regions where monitoring infrastructure and long-term datasets remain limited. This study presents a Climate-Responsive Groundwater Vulnerability Assessment Model that integrates hydrological variability and land-use change dynamics to provide a robust, scalable, and policy-relevant framework for groundwater protection and sustainable water resource management. The model combines climate-sensitive hydrological indicators, including precipitation variability, evapotranspiration trends, recharge fluctuations, and groundwater level responses, with spatially explicit land-use metrics such as urban expansion, agricultural intensification, vegetation loss, and surface sealing. These variables are harmonized within a geospatial multi-criteria decision analysis environment to generate dynamic vulnerability indices that reflect both short-term climate anomalies and long-term anthropogenic pressures. Unlike conventional static vulnerability models, the proposed framework incorporates temporal weighting functions to capture seasonal and interannual climate variability, enabling the assessment of shifting vulnerability patterns under changing climatic regimes. Scenario-based simulations are employed to evaluate future groundwater vulnerability under alternative climate projections and land-use development pathways, thereby supporting proactive adaptation planning. The model is designed to operate effectively in data-scarce contexts by leveraging remotely sensed datasets, reanalysis climate products, and transferable hydrological parameters, reducing dependence on dense monitoring networks. Application of the framework demonstrates its capacity to identify vulnerability hotspots, reveal non-linear interactions between climate drivers and land-use transitions, and distinguish areas where groundwater systems are approaching critical stress thresholds. The results highlight the dominant influence of land-use change in amplifying climate-induced recharge variability, particularly in peri-urban and intensively cultivated zones. By integrating climate responsiveness with land-use dynamics, the model advances groundwater vulnerability assessment beyond static mapping toward a more adaptive and forward-looking decision-support tool. The proposed Climate-Responsive Groundwater Vulnerability Assessment Model offers practical value for water managers, planners, and policymakers seeking to align groundwater protection strategies with climate adaptation and sustainable land management objectives. Its flexible structure allows for regional customization, iterative updating, and integration into broader water security and environmental risk governance frameworks. Overall, the framework strengthens evidence-based groundwater governance by supporting integrated planning, risk prioritization, and resilient resource management across diverse hydroclimatic and socio-environmental contexts globally applicable.

Keywords: Climate Variability; Groundwater Vulnerability; Hydrological Variability; Land-Use Change; Geospatial Modeling; Climate Adaptation; Water Resource Management

I. INTRODUCTION

Groundwater constitutes a critical component of global freshwater resources, sustaining domestic supply, agriculture, industry, and ecosystem functions, particularly in regions where surface water is unreliable or seasonally constrained. However, growing evidence indicates that groundwater systems are increasingly vulnerable to the combined pressures of climate change and rapid land-use transformation. Climate-induced alterations in precipitation regimes, evapotranspiration rates, and recharge processes are modifying groundwater availability and resilience, while expanding urbanization, agricultural intensification, deforestation, and land sealing are disrupting natural infiltration pathways and degrading subsurface water quality (Ike, et al., 2018). These interacting pressures are reshaping groundwater dynamics in ways that traditional assessment approaches struggle to adequately capture.

Conventional groundwater vulnerability assessment models have largely relied on static representations of hydrogeological conditions, often assuming stationarity in climate variables and land-use patterns. Such assumptions are increasingly untenable in the context of heightened climate variability, extreme weather events, and accelerated human-driven land-use change. Static indices and snapshot-based mapping approaches tend to overlook temporal fluctuations in recharge, delayed system responses, and feedback mechanisms between surface processes and subsurface hydrology. As a result, they may underestimate emerging risks or fail to identify areas where vulnerability is intensifying due to compounding climatic and anthropogenic drivers (Nwokediegwu, Bankole & Okiye, 2019, Oshoba, Hammed & Odejobi, 2019).

The central problem addressed in this study is the lack of integrative, dynamic frameworks capable of capturing how hydrological variability and land-use change jointly influence groundwater vulnerability over time and space. Existing models often treat climate and land-use factors in isolation or apply them as secondary modifiers, rather than as interacting determinants of vulnerability. This gap limits the effectiveness of groundwater management strategies, particularly in data-limited regions where decision-making must rely on transferable indicators, remote sensing, and adaptive modeling approaches (Faseemo, et al., 2009).

The primary objective of this research is to develop a Climate-Responsive Groundwater Vulnerability Assessment Model that explicitly integrates hydrological variability and land-use change into a unified analytical framework. The study seeks to incorporate climate-sensitive hydrological indicators alongside spatially explicit land-use metrics, enabling the assessment of both short-term variability and long-term trends. By embedding temporal responsiveness and scenario-based analysis, the model aims to reflect evolving vulnerability patterns under changing climatic and developmental conditions (Bello-Dambatta, 2010, Leeson, et al, 2013).

The significance of adopting a climate-responsive assessment approach lies in its potential to transform groundwater vulnerability analysis from a static diagnostic exercise into a forward-looking decision-support tool. Such an approach enhances the capacity of water managers and policymakers to anticipate emerging risks, prioritize interventions, and align groundwater protection strategies with climate adaptation and sustainable land management goals (Hammed, Oshoba & Ahmed, 2019, Sanusi, et al., 2019). Ultimately, integrating hydrological variability and land-use change provides a more realistic and resilient foundation for safeguarding groundwater resources in an era of accelerating environmental change.

2.1. Methodology

The methodology adopted for developing the Climate-Responsive Groundwater Vulnerability Assessment Model integrating hydrological variability and land-use change follows a hybrid, systems-oriented approach that combines geospatial analysis, data-driven modeling, and multi-criteria decision analysis. This approach is informed by established frameworks in climate–hydrology interaction studies, decision-support system design, machine learning–assisted environmental modeling, and vulnerability assessment, as reflected in the referenced literature. The methodological design emphasizes adaptability to data-limited environments, transparency in indicator processing, and robustness under climatic and land-use uncertainty.

The process begins with comprehensive data acquisition and preprocessing, integrating multi-source climatic, hydrological, land-use, and hydrogeological datasets. Climate data, including precipitation, temperature, and extreme event indices, are derived from ground observations, reanalysis products, and remotely sensed datasets, following approaches used in climate–hydrology studies and hydrologic hazard indexing. Hydrological datasets such as groundwater level records, recharge estimates, and aquifer characteristics are compiled from monitoring networks, published hydrogeological reports, and proxy indicators where direct measurements are unavailable. Land-use and land-cover information is extracted from satellite imagery and classified using established remote sensing techniques, allowing detection of urban expansion, agricultural intensification, vegetation loss, and surface sealing patterns.

Following data harmonization, hydrological variability indicators are computed to characterize climate-driven dynamics affecting groundwater systems. These indicators capture precipitation variability, evapotranspiration trends, recharge anomalies, groundwater level fluctuations, and exposure to hydrological extremes. In parallel, land-use indicators are generated to represent anthropogenic modifications influencing infiltration, runoff, recharge efficiency, and contamination pathways. Indicator selection is guided by physical relevance, data availability, and transferability across regions, consistent with vulnerability assessment and decision-support literature.

All indicators are spatially standardized and normalized to a common vulnerability scale to enable integration. Normalization functions are selected to preserve the direction and intensity of influence of each indicator on groundwater vulnerability. Both linear and non-linear transformations are applied where threshold effects or non-proportional responses are expected, reflecting insights from subsurface process modeling and environmental risk assessment studies.

Indicator weighting is performed using a structured multi-criteria decision analysis framework. Weights are derived through a combination of expert-informed ranking, literature-based evidence, and sensitivity testing, ensuring methodological transparency and reproducibility. This step acknowledges that hydrological and land-use drivers do not contribute equally to groundwater vulnerability and that their relative influence may vary under different climatic or developmental contexts.

The weighted indicators are then integrated within a geographic information system environment using spatial overlay and aggregation techniques to produce a composite groundwater vulnerability index. This geospatial integration allows vulnerability to be mapped continuously across the study area, capturing spatial heterogeneity in climate exposure, land-use intensity, and hydrogeological sensitivity. Temporal dynamics are incorporated by repeating the analysis across historical baselines and future climate and land-use scenarios derived from downscaled climate projections and development pathways.

Scenario analysis is employed to evaluate evolving groundwater vulnerability under alternative climate and land-use futures. Climate projections are translated into adjusted hydrological indicators, while land-use scenarios simulate plausible trajectories of urban growth, agricultural expansion, and conservation-oriented development. Comparative analysis of scenario-based vulnerability maps enables identification of emerging hotspots, resilience zones, and critical thresholds.

Model validation and uncertainty assessment are conducted using available hydrogeological observations, including groundwater level trends, water quality records, and documented responses to historical climate extremes. Sensitivity analysis is applied to examine the influence of indicator selection and weighting on model outputs, while uncertainty ranges are explored through scenario ensembles and alternative parameter configurations. The methodology is designed as an iterative process, allowing refinement as new data and insights become available, thereby supporting adaptive groundwater governance and climate-resilient planning.

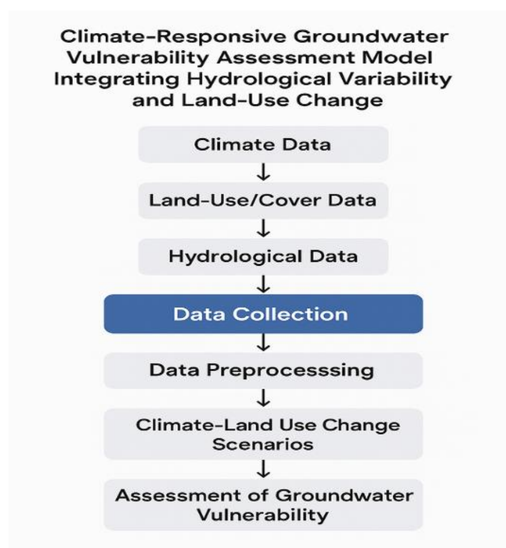

Figure 1: Flowchart of the study methodology

2.2. Conceptual Framework for Climate-Responsive Groundwater Vulnerability

The conceptual framework for a Climate-Responsive Groundwater Vulnerability Assessment Model is grounded in the recognition that groundwater systems function as dynamic components of the broader Earth system, continuously shaped by climatic forces, hydrological processes, and human-induced land-use transformations. Unlike surface water systems, groundwater responses are often delayed, cumulative, and spatially diffuse, making vulnerability difficult to detect until critical thresholds are crossed. A climate-responsive conceptualization therefore requires moving beyond static representations of aquifer properties to a systems-based understanding in which groundwater vulnerability emerges from the interaction of climate drivers, surface and subsurface hydrological processes, and land-use systems operating across multiple spatial and temporal scales (Fasasi, Adebowale & Nwokediegwu, 2019, Owulade, et al., 2019).

The theoretical foundation of this framework draws from integrated hydrology, hydrogeology, and socio-environmental systems theory. From a hydrological perspective, the framework aligns with the concept of the hydrological cycle as a coupled land–atmosphere–subsurface system, where precipitation, evapotranspiration, runoff, infiltration, and recharge are interdependent processes rather than isolated components. Climate science contributes the understanding that these processes are increasingly non-stationary under climate change, characterized by shifting rainfall patterns, rising temperatures, altered evapotranspiration demands, and increasing frequency of extreme events such as droughts and intense rainfall. Vulnerability theory further informs the framework by framing groundwater vulnerability as a function of exposure to stressors, system sensitivity, and adaptive or buffering capacity, rather than solely intrinsic aquifer characteristics (Awe, Akpan & Adekoya, 2017, Osabuohien, 2017).

Within this conceptual framework, climate drivers serve as primary external forcing mechanisms that regulate the magnitude, timing, and variability of hydrological inputs to groundwater systems. Changes in precipitation intensity, duration, and seasonality directly influence infiltration and recharge processes, while prolonged dry periods reduce effective recharge and increase reliance on groundwater abstraction. Rising temperatures amplify evapotranspiration, reducing soil moisture availability and further constraining recharge, particularly in semi-arid and arid regions. Extreme rainfall events, although capable of generating high recharge pulses, may also increase surface runoff and erosion, limiting infiltration where land surfaces are sealed or compacted (Akpan, Awe & Idowu, 2019, Ogundipe, et al., 2019). The framework therefore treats climate variability not as a uniform driver but as a set of interacting signals that can alternately enhance or suppress groundwater replenishment depending on local conditions. Figure 2 shows impact of climate change, land-use change, and environmental factors on groundwater presented by Huang, et al., 2017.

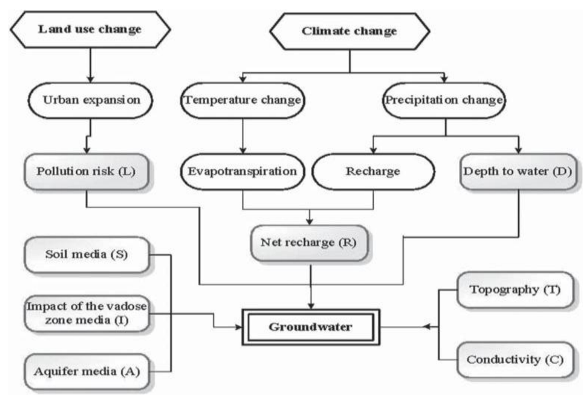

Figure 2: Impact of climate change, land-use change, and environmental factors on groundwater (Huang, et al., 2017).

Hydrological processes act as the mediating link between climate drivers and groundwater response. At the surface and near-surface level, soil properties, vegetation cover, and topography control how precipitation is partitioned between runoff, evapotranspiration, and infiltration. Subsurface processes, including percolation through the unsaturated zone, aquifer storage, transmissivity, and groundwater flow dynamics, determine how climatic signals are attenuated, delayed, or amplified before manifesting as changes in groundwater levels or quality (Awe & Akpan, 2017). The conceptual framework emphasizes that hydrological variability introduces temporal heterogeneity into groundwater systems, meaning that vulnerability cannot be adequately assessed through long-term averages alone. Seasonal recharge pulses, interannual climate oscillations, and multi-year drought cycles all shape groundwater resilience and stress trajectories.

Land-use systems are integrated into the framework as both direct and indirect modifiers of hydrological processes and groundwater vulnerability. Urban expansion, agricultural intensification, deforestation, and infrastructure development fundamentally alter land surface characteristics, influencing infiltration capacity, runoff generation, and pollutant transport. Impervious surfaces associated with urbanization reduce recharge while increasing flood peaks, whereas intensive agriculture can simultaneously enhance recharge through irrigation return flows and degrade groundwater quality through nutrient and agrochemical leaching. Vegetation removal alters evapotranspiration regimes and soil structure, affecting both the quantity and timing of recharge (Akpan, et al., 2017, Oni, et al., 2018). The framework conceptualizes land-use change not as a static layer but as a dynamic process that interacts with climate variability, often amplifying climate-induced stresses on groundwater systems.

A critical aspect of the conceptual framework is the recognition of feedback mechanisms between land-use systems, hydrological processes, and groundwater responses. For example, declining groundwater levels due to reduced recharge or over-abstraction may prompt land-use shifts toward less water-intensive activities, which in turn modify surface hydrology. Conversely, economic pressures and population growth may drive land-use changes that increase groundwater extraction, exacerbating vulnerability under adverse climatic conditions. These feedbacks highlight the need for an integrated framework capable of capturing both biophysical and anthropogenic dimensions of groundwater vulnerability (Liang, 2018, McGrath, Reid & Tran, 2017). Figure 3 shows conceptual model of climate change and variability impacts on the hydrologic cycle presented by Misra, 2013.

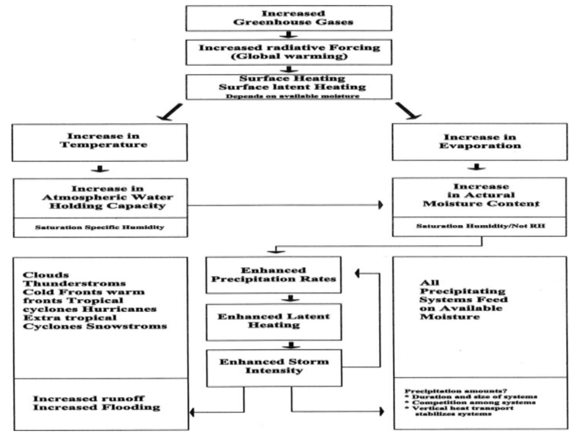

Figure 3: Conceptual model of climate change and variability impacts on the hydrologic cycle (Misra, 2013).

Groundwater response mechanisms constitute the outcome domain of the framework, encompassing changes in groundwater quantity, quality, and system resilience. Quantity-related responses include declining water tables, reduced baseflow contributions to surface water, and diminished aquifer storage, while quality-related responses involve increased contaminant concentrations, salinization, and mobilization of naturally occurring geogenic pollutants under altered redox conditions. The framework acknowledges that groundwater responses are often nonlinear, with gradual changes potentially leading to abrupt regime shifts once thresholds are exceeded (Akomea-Agyin & Asante, 2019, Awe, 2017, Osabuohien, 2019). This understanding reinforces the importance of incorporating variability, lag effects, and cumulative impacts into vulnerability assessment models.

Central to the conceptual framework is the integration of temporal and spatial dimensions. Spatial heterogeneity in geology, soils, land use, and climate exposure means that groundwater vulnerability varies significantly within and across regions. Temporally, the framework accommodates short-term climate anomalies, seasonal cycles, and long-term trends, allowing vulnerability to be assessed as an evolving condition rather than a fixed state (Bello-Dambatta & Javadi, 2010, Felisa, et al., 2015). By conceptualizing vulnerability as dynamic, the framework supports the development of assessment models that can be updated iteratively as new data become available or as climate and land-use conditions change. Figure 4 shows conceptual diagram on impacts of climate change on groundwater dependent aquatic ecosystem presented by Morsy, Alenezi & AlRukaibi, 2017.

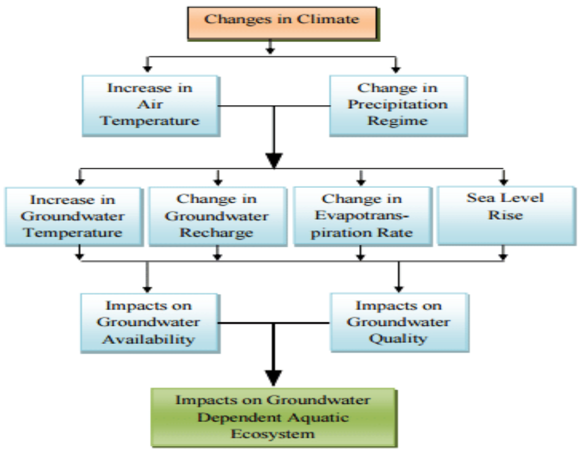

Figure 4: Conceptual diagram on impacts of climate change on groundwater dependent aquatic ecosystem (Morsy, Alenezi & AlRukaibi, 2017).

The climate-responsive framework also emphasizes adaptability and applicability in data-limited contexts. By grounding the conceptual model in transferable hydrological principles and observable land-use indicators, it supports the use of remote sensing, climate reanalysis products, and proxy datasets to characterize key processes. This theoretical openness enhances the relevance of the framework for regions where dense monitoring networks are unavailable but groundwater pressures are acute (Deschaine, 2014, Kresic & Mikszewski, 2012).

Overall, the conceptual framework for a Climate-Responsive Groundwater Vulnerability Assessment Model provides an integrated lens through which climate drivers, hydrological variability, land-use systems, and groundwater response mechanisms can be systematically linked. It shifts groundwater vulnerability assessment from a static, parameter-driven exercise toward a dynamic, systems-oriented approach that reflects real-world complexity. By embedding climate responsiveness and land-use dynamics at its core, the framework lays a robust theoretical foundation for developing assessment tools capable of informing sustainable groundwater management, climate adaptation planning, and long-term water security in an era of accelerating environmental change.

2.3. Hydrological Variability Characterization

Hydrological variability constitutes a central component of climate-responsive groundwater vulnerability assessment, as it governs the temporal and spatial behavior of water fluxes that ultimately sustain or stress groundwater systems. In the context of a Climate-Responsive Groundwater Vulnerability Assessment Model, characterizing hydrological variability requires a comprehensive understanding of how climate-driven factors interact to influence groundwater recharge, storage, and response dynamics. Unlike static hydrological representations, variability-focused characterization recognizes that groundwater systems are shaped by fluctuations in climate inputs and hydrological processes across seasonal, interannual, and longer-term timescales. This perspective is essential for capturing emerging vulnerability patterns under changing climatic conditions and evolving land-use regimes (Hipsey, et al., 2015, Scheidt, Li & Caers, 2018).

Precipitation variability represents the primary climatic driver influencing hydrological processes linked to groundwater systems. Variations in precipitation amount, intensity, frequency, and seasonality directly control the availability of water for infiltration and recharge. Shifts toward more erratic rainfall patterns, characterized by fewer but more intense events, can reduce effective recharge despite stable or increasing annual rainfall totals. High-intensity storms often generate rapid surface runoff, particularly in landscapes affected by urbanization or soil compaction, limiting infiltration and promoting erosion. Conversely, prolonged low-intensity rainfall may enhance infiltration where soil and land-cover conditions permit. The assessment of precipitation variability within the model therefore extends beyond mean annual values to include temporal distribution, rainfall intermittency, and deviation from historical norms, all of which shape groundwater vulnerability trajectories.

Evapotranspiration trends form a critical counterbalance to precipitation inputs, mediating the proportion of water that ultimately contributes to recharge. Rising temperatures associated with climate change have increased atmospheric demand for moisture, intensifying both evaporation from soil and water bodies and transpiration from vegetation. In many regions, enhanced evapotranspiration has offset gains in precipitation, resulting in reduced net recharge even under wetter climatic scenarios. Seasonal shifts in evapotranspiration, driven by temperature extremes and changes in vegetation phenology, further complicate groundwater responses (Filippini, 2015, Mallants, et al., 2010). Characterizing evapotranspiration variability within a climate-responsive framework involves integrating temperature trends, land-cover characteristics, and vegetation dynamics to capture how atmospheric demand modifies soil moisture availability and infiltration potential over time.

Recharge dynamics represent the integrative outcome of precipitation and evapotranspiration interactions, filtered through soil properties, land use, and subsurface conditions. Recharge is inherently variable, both spatially and temporally, and often occurs episodically in response to favorable climatic and surface conditions. Climate change has altered recharge regimes by modifying the timing, magnitude, and frequency of recharge events, with important implications for groundwater sustainability. In humid regions, recharge may become more seasonal, while in arid and semi-arid settings, recharge may increasingly depend on infrequent extreme rainfall events. The assessment framework emphasizes the need to capture recharge variability rather than relying on long-term average estimates, recognizing that groundwater vulnerability increases when recharge becomes more uncertain, delayed, or concentrated into short periods that may not align with abstraction demands (Binley, et al., 2015, Francisca, et al., 2012).

Groundwater level fluctuations provide a direct indicator of aquifer response to hydrological variability and human pressures. Variations in groundwater levels reflect the balance between recharge inputs, natural discharge, and abstraction, modulated by aquifer storage and transmissivity. Climate-driven changes in recharge and evapotranspiration are often manifested as altered groundwater level trends, seasonal amplitudes, and recovery rates following stress events such as droughts. Increasing variability in groundwater levels, including deeper drawdowns and slower post-drought recovery, signals declining system resilience and heightened vulnerability. Within the climate-responsive assessment model, groundwater level fluctuations are interpreted not only as state variables but as dynamic indicators of system sensitivity to hydrological forcing (Yaron, Dror & Berkowitz, 2012, Zeidan, 2017).

Extreme hydrological events play a disproportionately influential role in shaping groundwater vulnerability under climate change. Prolonged droughts reduce recharge over extended periods, intensify groundwater abstraction, and can trigger irreversible declines in aquifer storage, land subsidence, and water quality degradation. Conversely, extreme rainfall and flooding events may generate short-lived recharge pulses but can also introduce contaminants into aquifers through rapid infiltration pathways, particularly in karst or fractured systems. The increasing frequency and intensity of such extremes challenge traditional vulnerability assessments that are based on average conditions. A climate-responsive characterization explicitly incorporates the role of extremes by examining their frequency, duration, and cumulative impacts on groundwater systems.

An important feature of hydrological variability characterization is the recognition of temporal lags and memory effects inherent in groundwater systems. Unlike surface water, groundwater responds slowly to climatic signals, with delays ranging from months to decades depending on aquifer depth, permeability, and unsaturated zone thickness. These lag effects can mask emerging vulnerability, as groundwater levels may continue to decline long after climatic conditions have improved. The assessment framework therefore accounts for lagged responses and cumulative deficits, enabling a more realistic appraisal of vulnerability evolution over time (Kuppusamy, et al., 2016, Majone, et al., 2015).

Hydrological variability is also spatially heterogeneous, influenced by local climate gradients, topography, soil characteristics, and land-use patterns. The framework integrates spatial analysis to identify zones where climate-driven hydrological variability exerts disproportionate influence on groundwater vulnerability. For example, recharge-sensitive areas such as alluvial plains, wetlands, and recharge zones in upland areas may experience heightened vulnerability under altered precipitation regimes or land-use encroachment. Recognizing these spatial patterns enhances the ability of the model to identify vulnerability hotspots and prioritize management interventions (Essaid, Bekins & Cozzarelli, 2015, Kobus, Barczewski & Koschitzky, 2012).

In data-limited contexts, characterizing hydrological variability relies on the strategic use of proxy indicators, remotely sensed data, and climate reanalysis products. Satellite-derived precipitation, evapotranspiration estimates, and groundwater storage anomalies provide valuable insights into variability patterns where in situ data are sparse. The climate-responsive framework accommodates such data sources, emphasizing consistency, trend detection, and variability metrics rather than absolute precision (Gober & Kirkwood, 2010, Mark, et al., 2010).

Overall, hydrological variability characterization within the Climate-Responsive Groundwater Vulnerability Assessment Model provides a dynamic foundation for understanding how climate-driven processes shape groundwater vulnerability. By integrating precipitation variability, evapotranspiration trends, recharge dynamics, groundwater level fluctuations, and extreme events, the framework captures the complex, non-stationary nature of groundwater systems under climate change. This approach enhances the capacity of vulnerability assessments to anticipate emerging risks, support adaptive groundwater management, and strengthen long-term water security in the face of increasing climatic uncertainty and land-use pressures.

2.4. Land-Use and Land-Cover Change Analysis

Land-use and land-cover change constitutes a critical determinant of groundwater vulnerability, as modifications to the land surface directly alter the pathways through which climatic inputs are transformed into hydrological processes that sustain or degrade groundwater systems. Within a Climate-Responsive Groundwater Vulnerability Assessment Model, land-use and land-cover change analysis provides the spatial and functional context through which hydrological variability is either buffered or amplified. Human-driven transformations such as urbanization, agricultural expansion, vegetation loss, and surface sealing fundamentally reshape infiltration dynamics, recharge regimes, and groundwater quality, often interacting with climate variability in ways that intensify vulnerability and reduce system resilience.

Urbanization represents one of the most significant land-use drivers of groundwater vulnerability. The expansion of built-up areas replaces permeable soil and vegetated surfaces with impervious materials such as asphalt, concrete, and rooftops, sharply reducing infiltration capacity. This surface sealing redirects precipitation toward rapid runoff, diminishing groundwater recharge even in regions experiencing increased rainfall. In addition to reducing recharge, urban runoff frequently carries contaminants, including hydrocarbons, heavy metals, and nutrients, which can infiltrate through preferential pathways such as fractures, drainage systems, or poorly designed infiltration structures (Langat, Kumar & Koech, 2017, Nashwan, et al., 2018). The concentration of abstraction wells in urban centers further exacerbates vulnerability by increasing localized drawdown, creating conditions where reduced recharge and elevated demand converge. Within the assessment model, urbanization is therefore conceptualized as both a quantitative stressor, through reduced recharge, and a qualitative stressor, through increased contamination risk.

Agricultural expansion and intensification exert complex and context-dependent influences on groundwater vulnerability. Conversion of natural land covers to cropland alters soil structure, vegetation cover, and hydrological connectivity, often increasing vulnerability through enhanced evapotranspiration and altered recharge patterns. In rainfed agricultural systems, vegetation clearance and soil disturbance may initially increase infiltration but can lead to soil compaction and erosion over time, reducing effective recharge. In irrigated systems, irrigation return flows can augment recharge, but this apparent benefit is frequently offset by groundwater over-abstraction and declining water quality (Hanson, et al., 2012, Wagesho, 2014). The leaching of fertilizers, pesticides, and salts poses significant risks to groundwater quality, particularly in shallow aquifers and regions with high irrigation intensity. The climate-responsive framework integrates agricultural land-use dynamics by assessing not only land-cover extent but also management practices that influence water fluxes and contaminant transport.

Vegetation loss, whether driven by deforestation, land clearing, or degradation of natural ecosystems, has profound implications for groundwater systems. Vegetation plays a key role in regulating evapotranspiration, stabilizing soils, and promoting infiltration through root systems and organic matter accumulation. The removal of vegetation alters the balance between evapotranspiration and infiltration, often leading to increased surface runoff and reduced soil moisture retention. In some contexts, reduced transpiration may increase potential recharge, but this effect is highly contingent on soil properties, rainfall intensity, and land management (Leibowitz, et al., 2014, Ribeiro Neto, et al., 2014). More commonly, vegetation loss reduces the capacity of the landscape to moderate climatic extremes, increasing the sensitivity of groundwater systems to precipitation variability and extreme events. The assessment model treats vegetation dynamics as a critical modifier of climate–hydrology interactions, influencing both recharge efficiency and vulnerability to contamination.

Surface sealing extends beyond urban centers and includes infrastructure development such as roads, parking areas, industrial zones, and compacted agricultural lands. Even partial sealing can significantly disrupt natural infiltration pathways, fragment recharge zones, and alter subsurface flow patterns. The cumulative effect of surface sealing is often underestimated, particularly in peri-urban and rapidly developing rural areas. By reducing diffuse recharge and concentrating flow into drainage networks, surface sealing increases the spatial heterogeneity of recharge and heightens vulnerability in areas dependent on local replenishment. The climate-responsive model incorporates surface sealing as a gradient rather than a binary condition, recognizing that varying degrees of imperviousness produce proportionate impacts on groundwater systems (Nelitz, Boardley & Smith, 2013, Perra, et al., 2018).

The combined impacts of land-use change on infiltration and recharge are central to groundwater vulnerability assessment. Infiltration capacity is influenced by soil texture, structure, and organic content, all of which are modified by land-use practices. Urban compaction, intensive tillage, and vegetation removal reduce soil permeability, while conservation practices and green infrastructure can partially restore infiltration potential. Recharge dynamics respond not only to infiltration capacity but also to the timing and distribution of precipitation, which are increasingly variable under climate change. Land-use change can therefore amplify or dampen climate-driven hydrological variability, making its integration essential to climate-responsive vulnerability analysis (Viviroli, et al., 2011, Watts, et al., 2015).

Groundwater quality is particularly sensitive to land-use and land-cover change, as surface activities determine the sources, pathways, and loads of contaminants reaching aquifers. Urban and industrial land uses introduce point and non-point pollution sources, while agricultural practices contribute diffuse nutrient and chemical loads. Vegetation loss reduces the natural filtering capacity of soils, increasing the likelihood of contaminant transport. Under climate change, intensified rainfall events can accelerate pollutant mobilization, while droughts can concentrate contaminants through reduced dilution. The assessment framework explicitly links land-use patterns to groundwater quality vulnerability, recognizing that quantity and quality dimensions of vulnerability are inseparable (Edwards, et al., 2012, Green, 2016).

Spatial analysis plays a pivotal role in evaluating land-use and land-cover change within the assessment model. Remote sensing and geospatial datasets enable the detection of land-use transitions, fragmentation patterns, and proximity to sensitive recharge zones. By integrating these spatial indicators with hydrological variability metrics, the model identifies areas where land-use change and climate stressors converge to create heightened vulnerability. This spatially explicit approach supports targeted management interventions, such as land-use zoning, protection of recharge areas, and the implementation of nature-based solutions (Field, 2012, McMillan, et al., 2016).

Overall, land-use and land-cover change analysis provides a critical bridge between human activities and climate-driven hydrological processes in the Climate-Responsive Groundwater Vulnerability Assessment Model. By evaluating urbanization, agricultural expansion, vegetation loss, and surface sealing in relation to infiltration, recharge, and groundwater quality, the framework captures the anthropogenic dimension of vulnerability. This integrated perspective enhances the relevance of groundwater vulnerability assessments for planning, policy, and adaptive management, supporting strategies that align land-use development with groundwater sustainability in an era of accelerating climate and environmental change.

2.5. Model Structure and Indicator Integration

The structure of a Climate-Responsive Groundwater Vulnerability Assessment Model is designed to translate complex interactions between climate-driven hydrological processes and land-use dynamics into an interpretable, spatially explicit representation of groundwater vulnerability. Central to this structure is the systematic selection, normalization, weighting, and integration of indicators that collectively capture the sensitivity of groundwater systems to both natural variability and anthropogenic pressures. The model is inherently modular, allowing diverse datasets to be combined within a geospatial and multi-criteria decision analysis framework while maintaining conceptual coherence and analytical transparency (Hubbard, et al., 2018, Singh, van Werkhoven & Wagener, 2014).

Indicator selection constitutes the foundational step in model structuring and reflects the theoretical premise that groundwater vulnerability emerges from the interaction of climate forcing, hydrological response, and land-use modification. Hydrological indicators are selected to represent climate-responsive processes such as precipitation variability, evapotranspiration trends, recharge potential, groundwater level dynamics, and exposure to extreme events. These indicators are chosen not only for their physical relevance but also for their measurability and transferability across regions. Land-use indicators are selected to reflect surface conditions and human activities that modify hydrological pathways, including urban extent, agricultural intensity, vegetation cover, surface sealing, and proximity to pollution sources (Furniss, 2011, Handmer, et al., 2012). The emphasis is on indicators that can be consistently derived from remote sensing, spatial databases, or secondary datasets, ensuring applicability in data-limited environments.

Normalization is a critical step that enables diverse indicators, expressed in different units and scales, to be combined within a unified analytical framework. Hydrological and land-use indicators often exhibit contrasting ranges and distributions, which can bias vulnerability outcomes if integrated directly. Normalization transforms each indicator into a standardized scale, typically ranging from low to high vulnerability, while preserving the relative differences across space. In the climate-responsive framework, normalization schemes are selected to reflect the directionality of influence, ensuring that increases in stressors such as precipitation variability or surface sealing correspond to higher vulnerability scores (Kato, 2010, Meerow & Newell, 2017). Where nonlinear relationships exist, transformation functions are applied to better represent threshold effects and diminishing or accelerating impacts.

Weighting reflects the relative importance assigned to individual indicators in shaping groundwater vulnerability. This step acknowledges that not all hydrological and land-use factors contribute equally to vulnerability, and that their influence may vary depending on hydrogeological context and climatic conditions. The model adopts a flexible weighting strategy that can incorporate expert judgment, empirical evidence, and sensitivity analysis. Multi-criteria decision analysis techniques, such as analytic hierarchy processes or entropy-based methods, are employed to derive weights in a transparent and reproducible manner (Jayasooriya, 2016, Sayles, 2017). Importantly, the climate-responsive framework allows weights to be adjusted to reflect temporal dynamics, recognizing that certain indicators may exert greater influence under specific climatic regimes or land-use trajectories.

The integration of indicators is achieved through a geospatial multi-criteria decision analysis approach that combines normalized and weighted indicators to produce composite vulnerability indices. Geographic information systems serve as the spatial backbone of the model, enabling the alignment, overlay, and aggregation of indicators across consistent spatial units. This spatial integration captures heterogeneity in climate exposure, land-use patterns, and hydrological conditions, allowing vulnerability to be mapped as a continuous surface rather than discrete categories. The integration process emphasizes transparency, with clear documentation of assumptions, weighting schemes, and aggregation methods to support interpretability and stakeholder engagement (Ferdinand & Yu, 2016, Koop & van Leeuwen, 2017).

A defining feature of the model structure is its capacity to incorporate temporal variability alongside spatial analysis. Hydrological indicators derived from time-series data are integrated in ways that capture seasonal fluctuations, interannual variability, and long-term trends. This temporal dimension is embedded through the use of moving averages, anomaly indices, or scenario-based adjustments, enabling vulnerability assessments to reflect evolving conditions rather than static snapshots. Land-use indicators are similarly treated as dynamic variables, with changes over time incorporated to represent development trajectories and policy-relevant scenarios (Boriana, 2017, Hou & Al-Tabbaa, 2014).

The multi-criteria decision analysis framework provides a structured methodology for managing uncertainty and subjectivity inherent in vulnerability assessment. By explicitly defining criteria, weights, and aggregation rules, the model allows alternative configurations to be tested and compared. Sensitivity analysis is integrated into the model structure to evaluate how changes in indicator selection or weighting influence vulnerability outcomes. This process enhances robustness by identifying indicators that disproportionately influence results and by revealing areas where vulnerability classifications are sensitive to methodological assumptions (Cheng, et al., 2011, Herat & Agamuthu, 2012).

Indicator integration within the model also accounts for interactions and synergies between hydrological and land-use factors. Rather than treating indicators as independent contributors, the framework allows for composite or conditional relationships where appropriate. For example, precipitation variability may be weighted more heavily in areas characterized by extensive surface sealing, reflecting reduced infiltration capacity. Such interaction-aware integration strengthens the model's ability to represent real-world processes where climate and land-use pressures are mutually reinforcing.

The geospatial structure of the model supports scalability and adaptability across spatial resolutions, from local catchments to regional aquifer systems. Indicators can be aggregated or disaggregated to align with management units, policy boundaries, or ecological zones, enhancing the model's practical relevance. This flexibility allows the framework to support diverse applications, including vulnerability hotspot identification, scenario analysis, and monitoring of vulnerability evolution over time (Mitchell, 2012, Sweeney & Kabouris, 2017).

Overall, the structure and indicator integration strategy of the Climate-Responsive Groundwater Vulnerability Assessment Model provide a coherent and adaptable foundation for translating complex environmental interactions into actionable insights. By systematically selecting, normalizing, weighting, and integrating hydrological and land-use indicators within a geospatial multi-criteria decision analysis framework, the model advances groundwater vulnerability assessment toward a dynamic, transparent, and decision-oriented approach. This structured integration enhances the capacity of groundwater managers and policymakers to understand vulnerability drivers, evaluate intervention options, and support sustainable groundwater governance under conditions of climatic uncertainty and land-use change.

2.6. Climate and Land-Use Scenario Development

Climate and land-use scenario development is a central component of a Climate-Responsive Groundwater Vulnerability Assessment Model because it enables the evaluation of how groundwater systems may respond to plausible future conditions rather than remaining anchored to historical or present-day states. Groundwater vulnerability is inherently forward-looking, as decisions related to land development, water allocation, and climate adaptation must account for changes that will unfold over decades. Incorporating future climate projections and land-use development scenarios allows the assessment model to capture evolving stress pathways, anticipate emerging risks, and support proactive groundwater management in the face of uncertainty (Cappuyns & Kessen, 2014, Williamson, et al., 2011).

Future climate projections provide the primary basis for representing potential changes in hydrological forcing. These projections are derived from climate models that simulate changes in temperature, precipitation, evapotranspiration, and the frequency and intensity of extreme events under different greenhouse gas emission pathways. Within the vulnerability assessment framework, climate projections are not treated as deterministic forecasts but as conditional scenarios that describe a range of plausible futures (Hardie & McKinley, 2014, Williamson, 2011). This approach recognizes uncertainty in climate modeling while still enabling structured analysis of how altered climatic conditions may influence groundwater recharge, storage, and resilience. Downscaled climate projections are particularly important, as groundwater processes respond to local-scale climate variability that may not be captured in coarse-resolution global models.

The integration of climate scenarios into the vulnerability model focuses on translating projected climatic changes into hydrologically meaningful indicators. Changes in precipitation regimes are assessed in terms of seasonal redistribution, intensity shifts, and interannual variability, all of which influence recharge dynamics. Temperature projections are used to estimate future evapotranspiration demand, which can significantly reduce effective recharge even where precipitation increases. Extreme event projections, including prolonged droughts and intense rainfall episodes, are incorporated to evaluate episodic stress and recovery patterns in groundwater systems. By embedding these climate-driven hydrological shifts into the model, vulnerability assessments reflect the non-stationary nature of future groundwater conditions (An, et al., 2016, Mgbeahuruike, 2018).

Land-use development scenarios complement climate projections by representing how human activities and policy choices may reshape the land surface and, consequently, groundwater vulnerability. These scenarios are constructed based on observed land-use trends, demographic projections, economic development pathways, and planning frameworks. Common land-use scenarios include continued urban expansion, agricultural intensification, conservation-oriented development, and mixed-use or managed growth pathways. Each scenario embodies distinct assumptions about land-cover change, infrastructure development, resource demand, and environmental protection, allowing the model to explore how alternative futures influence groundwater systems (Lemming, 2010, Wang, et al., 2017).

Incorporating land-use scenarios into the assessment framework involves translating qualitative development narratives into spatially explicit representations of land-cover change. Geographic information systems are used to simulate the expansion or contraction of urban areas, shifts in agricultural land use, changes in vegetation cover, and increases in surface sealing. These spatial transformations are then linked to hydrological processes such as infiltration, runoff generation, and contaminant transport. For example, scenarios emphasizing rapid urban growth typically show increased impervious surfaces and reduced recharge potential, while conservation-oriented scenarios may preserve recharge zones and enhance infiltration through green infrastructure. By explicitly modeling these land-use trajectories, the framework captures the anthropogenic dimension of future groundwater vulnerability (Ahmed, 2017, Karpatne, et al., 2018).

A key strength of scenario development lies in its ability to explore interactions between climate change and land-use dynamics. Climate and land-use drivers rarely operate independently; instead, their combined effects often amplify groundwater vulnerability. For instance, increased precipitation variability under climate change may have limited impact in landscapes with intact vegetation and permeable soils but may substantially reduce recharge in areas dominated by surface sealing and soil compaction. Conversely, land-use changes that reduce groundwater demand or enhance recharge may partially offset adverse climatic trends. Scenario-based analysis enables the identification of such synergistic or antagonistic interactions, providing a more nuanced understanding of vulnerability evolution (Liakos, et al., 2018, Singh, Gupta & Mohan, 2014).

The assessment of evolving groundwater vulnerability patterns under combined climate and land-use scenarios involves recalculating vulnerability indices for each scenario configuration. Hydrological and land-use indicators are adjusted to reflect projected conditions, and the integrated model generates spatial vulnerability maps corresponding to different future pathways. Comparing these maps reveals how vulnerability hotspots shift, intensify, or diminish over time. This comparative analysis highlights areas where groundwater systems are most sensitive to future change and where targeted interventions could yield the greatest resilience benefits.

Scenario development also supports temporal analysis by examining vulnerability trajectories over multiple time horizons, such as near-term, mid-century, and long-term futures. Groundwater systems often respond slowly to surface changes, and scenario-based modeling helps capture delayed or cumulative impacts that may not be evident in short-term assessments. For example, gradual increases in groundwater abstraction combined with declining recharge may lead to abrupt threshold crossings decades later (Naghibi, Pourghasemi & Dixon, 2016, Rodriguez-Galiano, et al., 2014). By evaluating vulnerability across time horizons, the framework supports long-term planning and avoids underestimating risks that emerge slowly.

Uncertainty is an inherent feature of both climate projections and land-use scenarios, and the assessment framework addresses this through the use of multiple scenarios rather than a single predicted outcome. Ensemble approaches, in which multiple climate models and land-use pathways are considered, allow vulnerability results to be expressed as ranges or probability-weighted outcomes. This approach enhances robustness by identifying patterns that are consistent across scenarios, thereby increasing confidence in priority areas for management action. It also supports adaptive decision-making by highlighting where uncertainty is greatest and where monitoring or flexible policy measures are most needed (Park, et al., 2016, Ransom, et al., 2017).

The practical significance of climate and land-use scenario development lies in its capacity to inform policy and management decisions. Scenario-based vulnerability assessments can be used to evaluate the groundwater implications of alternative development strategies, land-use regulations, and climate adaptation measures. For example, planners can assess how protecting recharge zones or promoting low-impact development influences future vulnerability under different climate conditions. Water managers can explore how demand management or artificial recharge initiatives perform across scenarios, supporting evidence-based investment and policy choices (Barzegar, et al., 2018, Karandish, Darzi-Naftchali & Asgari, 2017).

In data-limited regions, scenario development remains feasible by leveraging global climate datasets, remote sensing-derived land-use information, and transferable assumptions about development pathways. While uncertainties may be higher, scenario analysis still provides valuable insights into relative vulnerability patterns and the direction of change, which are often more important for decision-making than precise quantitative predictions.

Overall, the incorporation of future climate projections and land-use development scenarios transforms the Climate-Responsive Groundwater Vulnerability Assessment Model into a forward-looking analytical tool. By assessing evolving groundwater vulnerability patterns under multiple plausible futures, the framework moves beyond retrospective assessment toward anticipatory governance. This scenario-based approach strengthens the capacity of groundwater management systems to adapt to climate change, guide sustainable land-use planning, and safeguard groundwater resources in an uncertain and rapidly changing environmental context (Burritt, Schaltegger & Zvezdov, 2011, Gibassier & Schaltegger, 2015).

2.7. Model Application and Validation

Model application and validation represent critical stages in the development of a Climate-Responsive Groundwater Vulnerability Assessment Model, as they demonstrate the practical utility, robustness, and credibility of the framework under real-world conditions. Applying the model in representative case areas allows the conceptual and analytical structure to be translated into operational outputs, while validation and uncertainty analysis ensure that the resulting vulnerability assessments are scientifically defensible and decision-relevant (Ascui & Lovell, 2012, Steininger, et al., 2016). Given the complexity of groundwater systems and the inherent uncertainty associated with climate variability and land-use change, model application and validation are treated as iterative and integrative processes rather than one-time procedures.

Implementation of the model begins with its application to representative case areas that capture a range of hydrogeological, climatic, and land-use contexts. These case areas may include urbanizing catchments, intensively cultivated agricultural regions, semi-arid basins reliant on groundwater for water security, or mixed land-use settings experiencing rapid environmental change. Selecting diverse case areas allows the model to be tested across contrasting conditions, ensuring that its structure is sufficiently flexible and transferable (Ascui, 2014, Hartmann, Perego & Young, 2013). Spatial datasets describing climate variables, land-use patterns, topography, soils, and hydrogeological properties are compiled and harmonized within a geographic information system to support model execution.

Within each case area, hydrological and land-use indicators are derived according to the model's defined procedures and integrated to generate spatially explicit groundwater vulnerability maps. These outputs typically depict gradients of vulnerability rather than discrete classes, reflecting the continuous nature of groundwater response to stressors. The application phase emphasizes transparency and reproducibility, with all assumptions, parameter choices, and data sources documented to facilitate interpretation and comparison across locations. The resulting vulnerability patterns are analyzed in relation to known hydrogeological features, such as recharge zones, aquifer boundaries, and areas of intensive abstraction, to assess whether the model produces spatial distributions that are hydrologically plausible (Maas, Schaltegger & Crutzen, 2016, Tang & Luo, 2014).

Sensitivity analysis forms a core component of model evaluation, as it examines how variations in indicator selection, weighting, and normalization influence vulnerability outcomes. Given that multi-criteria decision analysis involves subjective choices, sensitivity analysis helps identify which indicators exert the greatest influence on model results and which assumptions are most critical. This process typically involves systematically varying weights or excluding specific indicators and observing changes in vulnerability patterns. Indicators related to recharge variability, surface sealing, or groundwater level trends often emerge as dominant drivers, particularly in climate-sensitive regions (Bowen & Wittneben, 2011, Schaltegger & Csutora, 2012). Sensitivity analysis enhances model robustness by revealing potential biases and guiding refinement of indicator configurations.

Uncertainty assessment addresses the combined effects of data limitations, methodological assumptions, and variability in climate and land-use inputs. Groundwater vulnerability assessment is inherently uncertain due to sparse monitoring networks, limited long-term datasets, and the complex behavior of subsurface systems. The climate-responsive framework explicitly acknowledges these uncertainties by incorporating multiple data sources, scenario-based inputs, and probabilistic interpretations where feasible. Uncertainty assessment may involve comparing vulnerability outputs generated under alternative climate projections, land-use scenarios, or indicator weightings, thereby producing a range of plausible vulnerability outcomes rather than a single deterministic map (Hoek, Beelen & Brunekreef, 2011, Levy, 2013).

Validation of the model relies on the comparison of vulnerability outputs with independent hydrogeological data and observed system behavior. In many regions, comprehensive validation datasets are unavailable, necessitating the use of proxy indicators and partial validation approaches. Groundwater level records, where available, are commonly used to assess whether areas identified as highly vulnerable correspond to zones experiencing declining water tables, increased variability, or delayed recovery following droughts. Water quality data, such as nitrate concentrations or salinity trends, provide additional validation by indicating whether vulnerability hotspots align with observed contamination patterns (Derycke, et al., 2018, Kulawiak & Lubniewski, 2014).

Historical event analysis offers another avenue for validation, particularly in relation to climate extremes. Areas identified by the model as highly vulnerable should exhibit heightened sensitivity during past droughts or extreme rainfall events, such as pronounced groundwater declines or rapid quality deterioration. By comparing vulnerability maps with documented impacts of historical events, the model's capacity to capture real-world system responses can be evaluated. Although such validation is often qualitative, it provides valuable confidence in the model's explanatory power (Roghani, 2018, Wang, Unger & Parker, 2014).

In data-limited contexts, expert knowledge and stakeholder engagement play an important role in model validation. Local hydrogeologists, water managers, and land-use planners can provide insights into groundwater behavior that may not be fully captured in available datasets. Comparing model outputs with expert assessments of vulnerable areas helps identify discrepancies and areas for improvement. This participatory dimension enhances both the scientific and practical relevance of the model.

An important aspect of model application and validation is the recognition that groundwater vulnerability is dynamic and context-dependent. Validation is therefore not aimed at confirming absolute vulnerability values but at assessing whether relative vulnerability patterns are consistent with observed trends and known system characteristics. The model is designed to be iteratively updated as new data become available, allowing validation to be strengthened over time and enabling adaptive refinement of indicators and weights (McAlary, Provoost & Dawson, 2010, Provoost, et al., 2013).

The outcomes of model application and validation have significant implications for groundwater management and policy. Validated vulnerability maps can inform land-use planning, protection of recharge zones, prioritization of monitoring efforts, and design of climate adaptation strategies. Sensitivity and uncertainty analyses provide decision-makers with an understanding of confidence levels and risk ranges, supporting more informed and transparent decision-making. Importantly, the validation process builds trust in the model among stakeholders, increasing the likelihood that its outputs will be used in practice.

Overall, model application and validation demonstrate the operational viability of the Climate-Responsive Groundwater Vulnerability Assessment Model. Through implementation in representative case areas, systematic sensitivity analysis, explicit uncertainty assessment, and validation using available hydrogeological data, the framework establishes its capacity to capture complex interactions between climate variability, land-use change, and groundwater response (Andres, et al., 2018, Turczynowicz, Pisaniello & Williamson, 2012). This rigorous evaluation process ensures that the model functions not only as an academic construct but as a practical decision-support tool capable of guiding sustainable groundwater management under conditions of environmental change and uncertainty.

2.8. Conclusion

This study has presented a comprehensive Climate-Responsive Groundwater Vulnerability Assessment Model that integrates hydrological variability and land-use change to address the growing challenges facing groundwater systems under conditions of climatic uncertainty and intensified human activity. By moving beyond static representations of vulnerability, the framework demonstrates that groundwater risk is a dynamic outcome shaped by the interaction of climate-driven hydrological processes and evolving land-use systems. The integration of precipitation variability, evapotranspiration trends, recharge dynamics, groundwater level fluctuations, extreme events, and land-use transformations provides a more realistic and nuanced understanding of how vulnerability emerges, intensifies, or shifts across space and time.

The key findings underscore the central role of hydrological variability in governing groundwater resilience. Variations in climate inputs, particularly the timing and intensity of precipitation and the increasing influence of evapotranspiration, were shown to significantly affect recharge processes and groundwater storage. These effects are strongly mediated by land-use and land-cover conditions, with urbanization, agricultural expansion, vegetation loss, and surface sealing amplifying climate-induced stresses on groundwater systems. The model highlights that areas experiencing rapid land-use change are often disproportionately vulnerable, even where climatic conditions appear favorable, due to disrupted infiltration pathways and increased contamination risks.

The implications for groundwater management and climate adaptation are substantial. The climate-responsive framework offers water managers and policymakers a forward-looking decision-support tool capable of identifying vulnerability hotspots, evaluating alternative land-use and climate scenarios, and prioritizing targeted interventions. By explicitly incorporating future climate projections and land-use development pathways, the model supports proactive planning rather than reactive responses to groundwater decline or degradation. It provides a scientific basis for aligning groundwater protection strategies with climate adaptation policies, land-use regulation, and sustainable development goals, particularly in regions where groundwater constitutes the primary source of water security.

Despite its strengths, the model is subject to several limitations that warrant consideration. The availability and quality of hydrogeological and climate data remain a constraint in many regions, potentially affecting the precision of vulnerability estimates. The reliance on proxy indicators and remotely sensed data, while enhancing applicability in data-limited contexts, introduces uncertainty that must be carefully managed through sensitivity and uncertainty analyses. Additionally, the weighting and aggregation of indicators within a multi-criteria decision analysis framework involve subjective judgments that may influence outcomes, underscoring the importance of transparency and stakeholder engagement.

Future research should focus on refining the model through enhanced representation of subsurface processes, improved integration of groundwater abstraction dynamics, and incorporation of socio-economic drivers influencing water use. Expanding the use of long-term monitoring data and high-resolution climate projections would further strengthen validation and reduce uncertainty. There is also scope to integrate machine learning and data assimilation techniques to improve predictive capability and support real-time vulnerability assessment. Ultimately, continued development and application of climate-responsive groundwater vulnerability models will be essential for safeguarding groundwater resources and ensuring resilient water management in an era of accelerating environmental change.

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