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Review

A Critical Review of Climate Change Impacts on Groundwater Resources: A Focus on Current Status, Future Possibilities, and Role of Simulation Models

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Abstract: The Earth's water resources, totaling 1.386 billion cubic kilometers, predominantly consist of saltwater in oceans. Groundwater, plays a pivotal role, with 99% of usable freshwater supporting 1.5–3 billion people as drinking water source and 60–70% for irrigation. Climate change, with temperature increase and altered precipitation patterns, directly impacts groundwater systems, affecting recharge, discharge, and temperature. Hydrological models are crucial for assessing climate change effects on groundwater, aiding in management decisions. Advanced hydrological models, incorporating data assimilation and improved process representation, contribute to understanding complex systems. Recent studies, employ numerical models to assess climate change impacts on groundwater recharge that could help in management of Groundwater. Groundwater vulnerability assessments vary with the spatial and temporal considerations, as well as assumptions in modelling groundwater susceptibility. The review assesses the vulnerability of groundwater to climate change and stresses the importance of accurate assessments for sustainable water resource management. It highlights challenges in assumptions related to soil and aquifer properties, multiple stressors, adaptive capacity, topography, aquifer properties, and groundwater contamination processes and gradual sea level rise scenarios and realistic representations of the region of study. The advancements in hydrological modelling, including the integration of uncertainty quantification and remote sensing data, artificial intelligence, could assist in the efforts to improve models for assessing the impacts of climate change on hydrological.

Keywords: climate change; groundwater; hydrological models; model calibration

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1. Introduction to groundwater modeling

Earth has an estimated 1.386 billion cubic kilometers of water, with 97% being salt water in oceans and only 3% freshwater. The majority of freshwater, around 69%, exists as permanent ice and

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snow in Greenland and Antarctica, while 30% is groundwater. Surface water systems like rivers, lakes, streams, and swamps hold less than 1% of fresh water. Excluding the water in the cryosphere, only 1% is usable, and 99% of this is groundwater, making it a crucial source for various human uses and sustaining ecosystems. Approximately 1.5–3 billion people depend on groundwater as their primary drinking water source, and globally, 60–70% of groundwater withdrawals are used for irrigation. Groundwater constitutes a quarter of total water withdrawals and 50% of the world's current potable water, playing a vital role in supporting both human and natural systems [1–4].

Groundwater plays a crucial role in the climate system, as highlighted by Liesch and Wunsch (2019) [5]. However, many potential impacts of climate change on groundwater remain uncertain due to the intricate nature of the climate system, characterized by complex interactions and feedbacks [6]. According to the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature has increased by 0.6°C ± 0.2°C since 1861, and a further 2 to 4°C increase is anticipated in the next century. Temperature rises can significantly influence hydrological processes by increasing the evaporation of surface water and plant transpiration. These changes are expected to impact precipitation patterns, timing, and intensity, indirectly influencing the distribution and storage of water in surface and groundwater reservoirs, including lakes, soil moisture, and groundwater (IPCC, 5th Assessment Report).

To assess the impact of climate change on groundwater and surface resources, researchers employed specific hydrological models. Groundwater recharge, influenced not only by hydrological processes but also by soil and surface structure, has been a subject of study. An early investigation in the Coastal Plain of Western Australia utilized a one-dimensional unsaturated zone model (based on Richard's equation) to analyze the effects of changing rainfall on recharge. The findings indicated that recharge could be significantly altered by factors beyond just rainfall, with vegetation cover playing a crucial role.

The utilization of groundwater modeling has proven instrumental in supporting groundwater management planning and decision-making processes. These models provide a theoretical framework for comprehending the dynamics and controls of groundwater systems, including processes influenced by human intervention. Groundwater models have become increasingly essential in research related to water resources assessment, conservation, and restoration. They offer valuable and cost-effective insights for the development, assessment, and refinement of new groundwater strategies, legislation, and development designs. It's worth noting that various groundwater modeling codes are available, each with distinct capabilities, operational characteristics, and limitations.

Overall, this comprehensive review has illuminates the far-reaching consequences of climate change on the vulnerability and sustainability of groundwater reserves globally. The urgency of implementing adaptive and resilient strategies to manage groundwater resources has never been clearer. As we navigate the complex terrain beneath our feet, it is imperative that policymakers, researchers, and communities alike recognize the indispensable role of groundwater in sustaining ecosystems, agriculture, and human populations. This review not only serves as a call to action but also as a guide for informed decision-making to secure a more resilient future for our planet's vital groundwater resources.

2. Climate change and groundwater interactions

The considerable rise in the global population and the subsequent surge in water demand do not fully account for the significant depletion of groundwater storage. Numerous studies, including those by Asoka et al., de Graaf et al., Russo and Lall, Sivarajan et al., van der Knaap et al., and van Engelenburg et al. [7–12], have established correlations between climate perturbations and groundwater levels. The escalating demand for groundwater is expected to play a defining role in future scenarios for water resource management and food security, particularly in rural areas and arid regions [13,14]. It serves as the primary means of meeting water needs in these regions. Certain impacts of climate change are expected to be direct consequences of alterations in temperature, precipitation, and elevated concentrations of CO_2. However, other effects on groundwater systems will be indirect, stemming from shifts in land use, the accessibility of other water sources (surface water), alterations in human water requirements, changes in the spatial distribution of native and cultivated plant communities, and adjustments in the water consumption patterns of existing crops and native plants in response to variations in climate and carbon dioxide concentrations. Directly impacting the entire groundwater system [15], climate change affects various aspects, including groundwater-surface water interaction, groundwater flows, groundwater recharge and storage [7], groundwater discharge, and groundwater quality. The impact of climate change on groundwater systems can also be indirect, manifesting through changes in groundwater abstraction and alterations in land use/cover. Changes in land use due to climate-induced modifications, such as shifts in vegetation type and evolving agricultural practices, along with potential increases in crop evaporative water demand, collectively exert pressure on groundwater resources [16].

The transfer of water from subsurface sources to the surface, whether through an aquifer to a surface-water body, or withdrawal for human purposes, constitutes groundwater discharge. Forecasts based on current climatic trends indicate a reduction in discharge from groundwater-fed springs in regions experiencing an increasingly arid climate, such as the southwestern United States [17], the Sikkim Himalaya [18], and Niangziguan Springs in Shanxi, China [19]. A significant indirect consequence of climate change is the extensive extraction of groundwater to meet the growing demand for irrigation and other human activities, which could substantially lower water table elevations and, consequently, reduce base flow contributions to stream flow. Studies, such as that by Solder et al. [20], provide evidence of declining groundwater discharge attributed to climate variability, change, and increased water demand. Additionally, climate change has the potential to influence the temperature of groundwater discharges. Simulations conducted by Kurylyk et al. [21] revealed an increase in groundwater discharge temperature of up to 3.6 °C in their study area in New Brunswick, Canada. Certain fish species heavily rely on cold groundwater discharges into streams and rivers to buffer them from temperature extremes and regulate their metabolism, especially during the summer months. Researchers argue that any future impact of climate change on groundwater discharge temperature could pose a threat to these already endangered species due to their critical dependence on thermal conditions [8,9,22]. The expected positive change in groundwater temperature is driven by projections of rising global air temperatures, with surface air temperatures and subsurface temperatures exhibiting a strong positive correlation, particularly in shallow aquifers with greater thermal sensitivities [21]. This raise concerns the likelihood of exceeding crucial temperature thresholds in groundwater-sourced thermal streams under the most extreme future climate scenarios.

The bibliometric analysis of the earlier studies on the climate vulnerability of water and features (Figure 1) shows the interconnectedness between them and the weightage given so far. The line between the two bubbles in Figure 1 indicates the text similarity between different sub-categories. The thicker the line, the greater the text similarity between the center of the category, and vice versa. Based on text similarity between sub-clusters, the 30 sub-clusters can be further converged into three clusters: 1) climate change facts and projections, 2) climate change impacts, and 3) climate change mitigation and adaptation. This is consistent with the framework of IPCC assessment reports. Nine sub-clusters, like climate change modelling, warming and extreme temperature, reconstruction of climate, and so on, are categorized into the cluster of climate change facts and projections (in purple). Fifteen sub-clusters, like human health, water resource, forest ecosystems, and so on, are categorized into climate change impacts (in green). Six sub-clusters, like GHGs emission, co-management of climate and environment, adaptation policy, and so on, are categorized into climate change mitigation and adaptation (in red).

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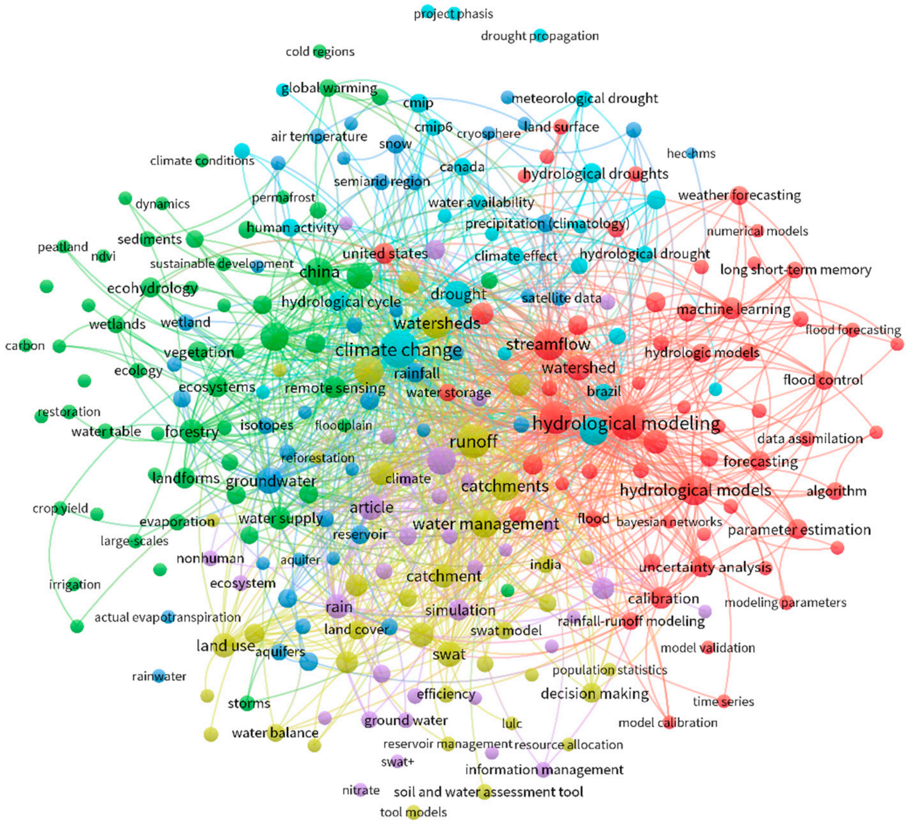

Figure 1. The bibliometric Analysis of Global research trends on Climate vulnerability of hydrological resources.

Climate stands as the primary driver of spatiotemporal variations in groundwater recharge, with precipitation emerging as the climate element exerting the most direct influence on recharge, regardless of the specific recharge pathway. The importance of climate in the context of groundwater is emphasized by the widespread use of Global Climate Models (GCMs) and precipitation data to predict future groundwater conditions. A rise in overall precipitation at a specific location augments the quantity of water accessible for groundwater recharge, and under normal circumstances, it is likely to lead to an increase in recharge. Conversely, reduced precipitation is anticipated to correspondingly decrease the amount of recharge [23]. Moreover, the type of precipitation event has an impact on recharge rates. A transition from snow to rain could result in lower recharge-to precipitation ratios. With the expectation of more precipitation falling as rain than snow on a warming Earth, regions characterized by cold climates may experience reduced recharge unless warmer winter temperatures diminish ground frost depth, promoting increased infiltration and recharge. A warmer winter might lead to earlier and prolonged snowmelt, resulting in substantial winter recharge but diminished spring and summer recharge [24]. The intensity of rainfall also plays a role in influencing groundwater recharge. The future of groundwater recharge will be primarily influenced by rainfall intensity in tropical regions. Evapotranspiration (ET) can also hinder infiltration below the root zone, making light rainfall less effective in contributing to groundwater recharge. Additionally, alterations in land use/land cover can modify the effects of precipitation and groundwater use on recharge. Various studies have demonstrated significant variations in recharge due to changes such as replacing natural vegetation with arable land or built-up surfaces [25]. For instance, reducing leaf area through clearing forests for agriculture can enhance groundwater recharge, even with a slight decrease in rainfall [26]. Conversely, other studies have indicated decreases in groundwater recharge resulting from increased vegetation density, such as a shift from grassland to woodland [25], or rapid urbanization and the replacement of natural surfaces with built-up areas. In general, whether it is a temporary change, like alterations in vegetation, or a permanent change, like urbanization, land use/cover modifications can affect recharge by altering water balance processes, including evaporation, transpiration, infiltration, and surface runoff [27].

In terms of climate change impacts on groundwater quality, existing research is limited, and predictions are characterized by uncertainty. Nevertheless, two primary modes of impact on groundwater quality in a changing climate are identified as: (1) the over-exploitation of coastal aquifers and (2) the introduction of chemical compounds into aquifers through flushing [24]. Infiltrating irrigation return flows can introduce certain chemical compounds into aquifers, impacting groundwater quality [28]. Future climate conditions, characterized by warmer winter temperatures and increased snowmelt in mid-/high-latitudes, may enhance pollutant capture and solute leaching in the unsaturated zone, thereby influencing groundwater quality. Additionally, studies suggest that climate change may worsen sanitary conditions in less developed regions, leading to the leaching of human waste from pit latrines into groundwater [29]. The impact of climate and land use change on groundwater quality, particularly related to nitrate concentrations, has been quantified in various locations, indicating an increase in nitrate concentrations in groundwater under scenarios of high irrigation and recharge [30]. Saltwater intrusion (SWI) and subsequent salinization of freshwater from excessive pumping or over-exploitation of wells, driven by increasing water demand and droughts associated with climate change and compounded by development, especially in coastal areas [31,32]. As groundwater abstraction increases, wells may run dry, necessitating deeper digging, which, in turn, contributes to a decline in groundwater quality, especially in deeper aquifers in coastal areas that tend to produce lower quality water.

The literature also provides substantial evidence indicating a global decline in groundwater levels across numerous aquifers. Notable examples include major aquifers in arid and semi-arid regions, such as the High Plains of the United States [33], and Northwest India, which are experiencing rapid depletion of groundwater. The significance of groundwater depletion extends beyond a mere reduction in water availability, posing threats to livelihoods and ecological sustainability, particularly during periods of drought [34]. The consequences of groundwater depletion are multifaceted. Firstly, it diminishes groundwater discharge to streams, springs, rivers, and other surface water bodies, impacting the well-being of Groundwater Dependent Ecosystems (GDEs). Secondly, it reduces the depth of the water table, thereby escalating the costs associated with extracting groundwater from deep boreholes and wells. Thirdly, groundwater depletion has been linked to land subsidence due to the compaction of soil and open pore spaces that previously held water, a phenomenon observed in locations such as Venice and Bologna, Italy [35], China [36], Iran [37], the central valley of California [38], and elsewhere. It's worth noting that groundwater storage exhibits varying sensitivities to seasonal or multi-year climatic fluctuations, with deeper aquifer systems reacting more slowly to direct changes in precipitation and recharge rates compared to smaller aquifers with shorter flow paths [22].

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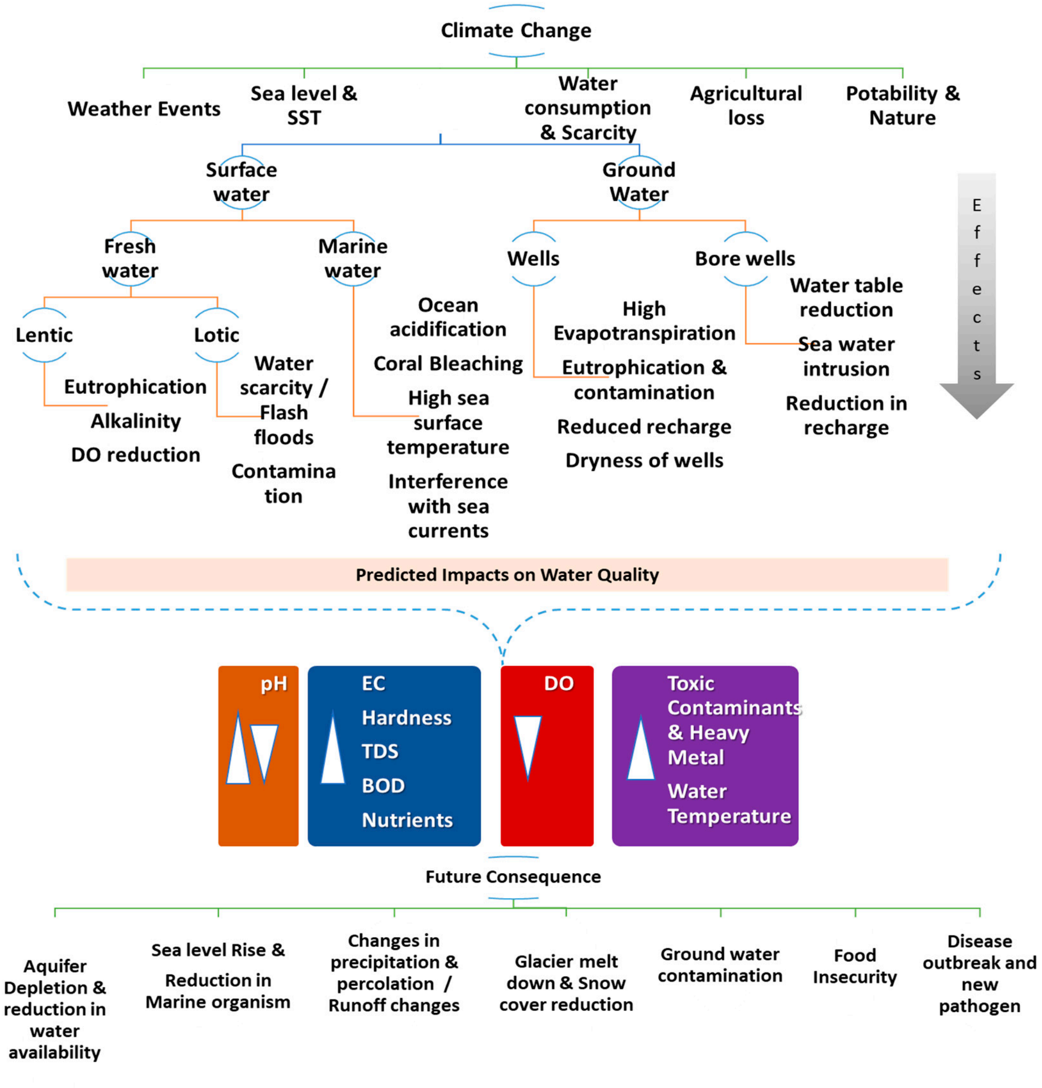


Figure 2. Groundwater systems interactions and changes in the face of climate change.

3. Key modelling approaches

The few available predictions regarding the effects of climate change on groundwater systems have predominantly utilized numerical models. These models are typically calibrated with historical data and then employed with climate projections as input. Various approaches have been suggested for assessing the intrinsic and specific vulnerability of groundwater to contamination. These approaches can be classified into overlay/index [39], statistical, and process/model-based methods. Among these, the commonly employed international methods for evaluating intrinsic and specific vulnerability include DRASTIC, GOD, AVI, SINTACS, modified SINTACS, DART, GALDIT, etc. [40,41]. Additionally, hybrid methods such as PATRIOT combine these approaches. On the other hand, analytical methods simplify critical parameters by assuming constant hydraulic conductivity, transmissivity, and uniform aquifer thickness [42]. Analytical methods also introduce uncertainties when projecting climate change using climate models [43] and assessing the impacts of climate change on systems (e.g., groundwater) and processes (e.g., pollution transport to groundwater and recharge to groundwater) through impact models, owing to the considerable variability in model outputs.

In a study conducted by Leterme and Mallants [44] in the Nete catchment in Germany, the HYDRRS-1D model was employed to assess the relative impact of rainfall and land use change indicators. The study successfully determined the effects on mean annual recharge under existing climate and land use conditions, estimating it to be 391 mm. This value decreased to 361 mm (7.7%) in a warmer climate scenario and further to 128 mm (67.3%) in a colder climate scenario. Under projected future warmer and colder climates, recharge increased by 31% and 18%, respectively. Land use changes to all other types resulted in a decrease in recharge in both the current and projected warmer and colder climates. The reduction in recharge was more pronounced (79%) for the warmer climate compared to the current (64%) and colder (48%) climates. The decrease in recharge in the warmer climate is attributed to higher evapotranspiration (ET), although the reduction is less than in the colder climate due to a high water level (3 m).

In 2006, Scibek and Allen [45] developed a methodology aiming to connect climate models with groundwater models to explore the prospective effects of climate change on groundwater resources. The assessment involved an unconfined aquifer near Grand Forks in south-central British Columbia, Canada. Climate change scenarios derived from model runs in the Canadian Global Coupled Model 1 (CGCM1) were adapted to local conditions using the Statistical Downscaling Model (SDSM). A three-dimensional transient groundwater flow model, implemented in MODFLOW, was then utilized to simulate four climate scenarios during 1-year test runs (representing the periods 1961-1999, 2010-2039, 2040-2069, and 2070-2099) and to compare groundwater levels with present conditions. The study found that the spatial distribution of recharge significantly influences groundwater levels, with a greater impact than temporal variations in recharge compared to a representation of mean annual recharge. According to the downscaled CGCM1 model, the projected future climate for the Grand Forks region suggests increased recharge to the unconfined aquifer from spring to summer. However, due to the predominant interactions between the river and aquifer, as well as river water recharge, the overall impact of this recharge on the water balance is minimal.

In 2009, Toews and Allen [46] created a numerical groundwater model at a regional scale for the Oliver region in the south Okanagan, British Columbia, Canada. The objective was to simulate the potential impacts of anticipated climate change on groundwater. The study's projections indicated a heightened contribution of recharge to the annual water budget in future timeframes (specifically the 2050s and 2080s). The calculated increase was 1.2% for the 2050s and 1.4% for the 2080s of the total annual budget compared to the existing conditions.

In 2014, Waikar and Somwanshi [47] conducted research on the Impact of Climate Change on Dynamic Groundwater System in a Drought-Prone Area. The study focused on databases and their analysis, involving the generation of future rainfall and temperature data, estimation of recharge, and simulation of groundwater to enhance control and augmentation of groundwater in the basin. All thematic maps were generated using ILWIS3.2, and necessary data were collected. Future rainfall was produced for baseline, A1F1, and B1 scenarios for the 2004-2039 period based on the SRES GCM projections for the South Asia region. The researchers developed a site-specific database for soil, vegetation, and climate required for the Visual HELP model. Site-specific groundwater recharge was calculated at twelve basin locations. The groundwater simulation involved dividing the entire basin into twelve areas and employing the water balance method. The study concluded with the quantification of the effects of climate change on groundwater recharge and time-slice rates for the period 2004-2039.

Kumar et al. [48] conducted an assessment of the impact of climate change on groundwater resources in India, focusing on recent scientific studies and methods for evaluating this impact through parameters such as soil moisture, groundwater recharge, and coastal aquifers. The study includes a brief analysis of research conducted in recent years. The estimation of groundwater recharge was carried out using WHI UnSat Suite and WetSpass. Climate data from weather stations were evaluated, and General Circulation Models (GCM) were utilized to establish future predicted climate change datasets. These datasets encompassed variables such as temperature, precipitation, and solar radiation.

In a groundwater study conducted in the High Plains of the United States, 16 global climate models (GCMs) and three global warming scenarios were employed to assess changes in groundwater recharge rates for a 2050 climate compared to a 1990 climate. Groundwater recharge was modeled using the WAVES model (Soil Vegetation Atmosphere Transfer) for a variety of soil and vegetation types covering the High Plains. The median forecast for the year 2050 showed an increase of +8% in the Northern High Plains, a slight decrease of -3% in the Central High Plains, and a more substantial decrease in the Southern High Plains (-10%). This amplifies the existing spatial trend in recharge from north to south. Predicted recharge variations between dry and rainy future climate scenarios exhibited both increases and decreases in recharge levels, with the magnitude of this variation surpassing 50% of actual recharge. On a relative scale, the sensitivity of recharge to changes in rainfall indicated that regions with high current recharge rates were less sensitive to rainfall changes, and vice versa [49].

The study focused on investigating the impact of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda. The analysis involved examining historical data, revealing evident signs of climate change through observed temperature and discharge patterns. To assess potential climate change projections, the statistical downscaling model (SDSM) was employed to downscale data derived from the UK climate model HadCM3. The downscaled climate data served as input for the WetSpa hydrological model, a physically distributed rainfall-runoff model used to simulate resulting changes in hydrology. During the wet seasons (March-May; October-December), the downscaled climate projections indicated an increase in precipitation, ranging from 30% in the 2020s to over 100% in the 2080s. Correspondingly, the temperature was projected to rise from 1 to 4°C. These changes were found to intensify the hydrological cycle. The mean annual daily base flow, constituting 69% of discharge at 157 mm/year during the current period, was anticipated to increase by 20-80% from the 2020s to the 2080s. Concurrently, the expected increase in recharge ranged from 20 to 100%, relative to the current 245 mm/year [50].

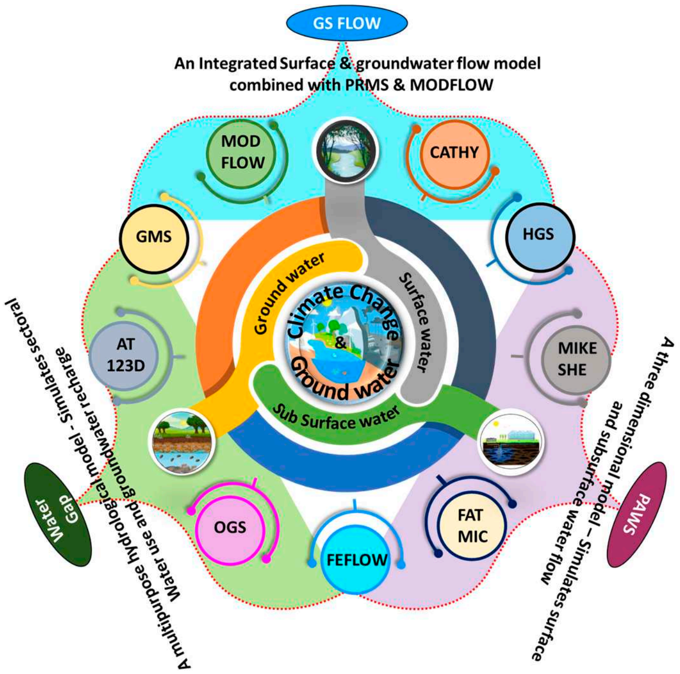
4. Advancement in hydrological modeling technologies

Hydrological modeling has been driven by improvements in data assimilation, computational capabilities, and a better understanding of hydrological processes has significantly contributed to our understanding and management of complex systems. Advanced hydrological models provide an improved representation of land-atmosphere interactions by coupling hydrological models with land surface models, enhancing the simulation of energy and water fluxes [51]. Hydrological models based on the land surface data coupled with regional climate models are also used for forecasting the behavior of hydrological and meteorological events under different climate scenarios. These climate scenarios are noticeable tools that are useful to decision-makers with respect to characterizing the future climate [52]. The use of distributed models that consider spatial variability in precipitation, land use, and soil properties can provide a more accurate representation of hydrological processes compared to conventional models. Integration of hydro informatics tools and remote sensing data can result in better model calibration, validation, and monitoring of hydrological processes. This may result in improved representation of land surface processes, and quantification of human impacts on water systems [53].

Modifications to hydrological models are often carried out to assess the impacts of climate change on water resources, considering changes in temperature, precipitation patterns, and extreme events [54]. Incorporation of advanced uncertainty quantification techniques and data assimilation methods are essential to improve the model predictions and parameter estimation. The commonly used methods for uncertainty analysis include Monte Carlo analysis, Bayesian statistics, multi-objective analysis, least-squares-based inverse modeling, response-surface-based techniques, and multi-modeling analysis [55,56]. Integrated hydrological models allows for a comprehensive understanding of the water cycle, incorporating surface water, groundwater, and atmospheric interactions [57,58]. Earth system models (ESM) simulate the interactions between the atmosphere, oceans, land surface, and ice, enabling a more holistic representation of climate dynamics. Advances in the representation of hydrologic processes in earth system models substantially improve the fidelity of simulations of land-atmosphere fluxes and biogeochemistry [57,58]

Integrated Assessment Models (IAMs) integrate multiple domains, such as climate, economy, and energy, to assess the interactions and trade-offs associated with different policy scenarios.

Machine learning techniques, including neural networks and ensemble methods, have been increasingly used for data-driven modeling and prediction in diverse fields [59]. Recent advances in computational platforms, like cloud and quantum computing, in addition to machine learning to capture some processes, will support the use of larger and more complex, process-based models. Models predicting land use changes help assess the impacts of human activities on landscapes and ecosystems, facilitating sustainable land management [60]. Models that integrate human and natural systems help analyze feedbacks and interactions between social and environmental components. These references represent seminal works in their respective fields, providing a foundation for understanding the advancements in modeling technologies. Keep in mind that the field of modeling is dynamic, and ongoing research contributes to continuous improvement and innovation in modeling techniques.



FATMIC	FAte and Transport of Microbes and Chemicals model for simulating contaminants transport in sub surface flow
FEFLOW	Finite Element sub surface FLOW system is an interactive graphic based model
OGS	Open Geo Sys - An object oriented numerical model for fluid flow in fractured – porous medium
GSFLOW	Groundwater and Surface water FLOW model
PAWS	Process based Adaptive Watershed Simulator model
WATER GAP	Water - a Global Assessment & Prognosis
AT123D	Analytical Transient one – two – three Dimensional model for long term pollutant movement in aquifer
GMS	Groundwater Modelling System for imagination to visualization and influence with other models
MODFLOW	MOdular three Dimensional finite difference groundwater FLOW model with enhanced capabilities to simulate water flow & transport
CATHY	CATchment HYdrology model integrates surface and ground water processes
HGS	HydroGeoSphere is an 3D finite element model to simulate terrestrial hydrological cycle
MIKESHE	MIKE System Hydrology European model for simulating surface water, recharge and evapotranspiration processes

Figure 3. Conceptual illustration of models and their integration for assessing hydrological vulnerability in the face of climate change.

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5. Spatial, Temporal Consideration and Assumptions in Modelling Ground Water Susceptibility

In recent years, researchers worldwide have assessed the vulnerability of groundwater to climate change at various spatial and temporal scales[61–64]. However, recognizing the similarities and differences among these studies and identifying potential knowledge gaps can be challenging. Vulnerability is a result of exposure, sensitivity, and adaptive capacity, and the methods to measure vulnerability vary significantly due to the context and scale dependence[65]. Different approaches have been proposed for quantifying the intrinsic and specific vulnerability of groundwater, categorized into overlay/index statistical and process/model-based methods[66–71]. Commonly used international methods include DRASTIC, GOD, AVI, SINTACS, modified SINTACS, DART, and GALDIT, often employed individually or in combination (hybrid methods) like PATRIOT[72–74]. Process/model-based methods are used to quantify specific vulnerability to pollutants and sea-level rise but provide more complex outputs, such as contaminant concentrations and time of travel.

Both overlay/index and process/model-based methods have been utilized to assess groundwater vulnerability to climate change, each with its strengths and limitations [75]. Alternative interpretations of results may arise due to differences in opinion and perception, emphasizing the critical choice of an appropriate technique. Modified-DRASTIC-AHP is suggested as a convincing alternative, involving the assignment of weights based on experience to develop a hierarchy of indicators[65,76]. Analytical methods, simplifying parameters like constant hydraulic conductivity, transmissivity, and uniform aquifer thickness, also introduce uncertainties, especially in projecting climate change and its impacts using models[77]. There is a general consensus that no single method is superior or mutually exclusive, and the choice depends on the study's objectives, available resources and data, and the time frame[65].

The simplification introduced to modelling techniques may lead to a more rapid simulation of seawater intrusion, as opposed to the gradual rise in sea levels. However, this simplification is valid only for assessing the impact of the last interglacial period, during which the sea level rose by 4 to 6 meters[78]. It is not a valid assumption for simulating the impact of future sea level rise because the projected sea level rise is a slow phenomenon, expected to increase yearly from 0.2 to 4.0 meters from 1990 to 2100 [79,80]. Moreover, the simulated behavior of saltwater intrusion varies depending on assumptions of instantaneous and gradual sea level rise, with the latter representing the intrusion process in a more natural way. Therefore, for a more accurate assessment of the implications of sea level rise on groundwater resources, it is essential to consider the gradual rise in sea level in modelling efforts.

The assumption of constant or average values for parameters related to soil or aquifer properties is valid as long as the slope remains unchanged or undergoes negligible changes in topographically levelled regions[61,81]. However, such assumptions may lead to underestimated assessment results, particularly in rugged topographies where these properties play a vital role in aquifer recharge during climate scenarios. The presence of various geological layers overlying groundwater, each with differing hydraulic properties, can have a significant impact on aquifer recharge, challenging the validity of uniform assumption. The physical processes involved in groundwater contamination due to climate change and land use change are complex and encompass mechanisms like biological and chemical degradation, adsorption on soil particles, and the transport and dilution of pollutants[66,82,83]. Assuming linearity in these physical processes may result in overestimation or underestimation of the actual pollution risk. Scale is a critical factor influencing the results, as larger-scale studies may introduce simplifications to complex processes. Consequently, studies conducted over a larger spatial scale may overlook or average site-specific processes, impacting the assessment of groundwater quality. Groundwater recharge is a multifaceted phenomenon dependent on various factors such as rainfall, land use, aquifer media, depth to the groundwater table, topography, soil characteristics, and hydraulic conductivity[84]. For instance, a study by Zume and Tarhule [85] considers recharge solely as a function of rainfall (i.e., 10% of annual direct rainfall), omitting other influential factors, leading to potential overestimation or underestimation of groundwater recharge.

Multiple stressors are of paramount importance and have a significant impact on a system in terms of their effects [86–88]. Consequently, these stressors should be incorporated into exposure assessments, thereby influencing vulnerability evaluations. Climate change, a global phenomenon that affects systems at various scales through direct effects such as variations in temperature and precipitation, and indirect, involving changing evapotranspiration, increasing population, groundwater abstraction, land use and land cover changes, water demand, and more[89–94]. To comprehensively characterize these influences, an understanding of multiple stressors is essential, considering the involvement of diverse actors and varying time scales. The selection of stressors and the methods used for quantification introduce limitations that can lead to misinformed estimations of impacts. Therefore, a thorough consideration of the various stressors, along with their diverse actors and time scales, is crucial for accurate exposure and vulnerability assessments.

6. Selectivity and sensitivity indicators for climate vulnerability of Ground water

The vulnerability of groundwater resources is contingent upon the specific nature of climate change and the sensitivity of a given aquifer. Sensitivity, one of the three components of vulnerability, is connected to the inherent properties of the aquifer [95]. While climate change is a significant factor, climate variability is equally important. Surprisingly, none of the reviewed studies have incorporated climate variability into their vulnerability assessments, focusing solely on climate change. It's worth noting that indicators of climate vulnerability are influenced by both climate change and variability [93]. The inclusion of variability, which represents the range of changes in climate at a minimum yearly time scale, is crucial for a more robust analysis of the actual situation. Change, as represented by the trend of mean climate conditions, may not fully capture the real circumstances. Among the studies examined, one assessed current vulnerability [96]), while others considered both current and future times. These studies utilized General Circulation Models (GCMs) for future climate projections under the Special Report on Emission Scenarios (SRES) A2, A1B, and B1. Acknowledging the uncertainties associated with scenarios and GCM projections, the scientific community has raised concerns. These uncertainties stem from the coarser resolution of GCMs at a scale ranging from 1 to 2°, where one degree equals almost 100 km, making them less accurate in representing certain climate phenomena [97].

However, [98] effectively demonstrated the impact of indicators on groundwater resources on Dauphin Island, USA, through a sensitivity analysis. They assessed the quantity of groundwater resources by considering different scenarios, both individually and in combination. In comparison to the current salinity level of 1.2%, under Scenario-1 (constant climate, land use/cover, and pumping), land use/cover change (Scenario-2) led to a 3.9% reduction in the volume of freshwater. Under dry climate plus land use/cover change (Scenario-3), the quantity of freshwater decreased by 3.3%. However, under the combined consideration of wet climate and land use/cover (Scenario-4), the volume of freshwater returned to baseline levels due to an increase in rainfall-triggered recharge. When dry climate, land use/cover change, and increased pumping were combined (Scenario-5), the quantity of freshwater decreased by 8.6%. While the magnitude of volume was different at 10 and 50% of initial salinity levels, the direction of impact remained similar. This underscores the relative sensitivity of groundwater quantity as a function of quality under the influence of both climatic and non-climatic stressors, emphasizing the critical role of indicator choice.

The role of adaptive capacity in mitigating the vulnerability of a system to climate change is crucial. This capacity can be evaluated independently or inferred from exposure and sensitivity indicators. There are generally three categories of adaptive capacity indicators: assets in a system, available resources, and governing institutions[99–101]. These indicators should be considered, especially when assessing adaptive capacity independently within vulnerability evaluations. To enhance the reliability of assessed results, it is recommended to include a variety of indicators (such as health, wealth, and education) selected based on their functional relationships with each other and their magnitude of influence on the system[102]. Indicators like governance and the rate of capacity building, which demonstrate functional relationships, have a significant impact on defining the adaptive capacity of a system. Therefore, neglecting any of these relevant indicators is likely to result in sub-optimal assessments.

Table 1. The Predicted Impacts of Climate Change on Groundwater by models.

S. No.	**Country**	**Major Climate Change Event**	**Major Impact on Environment**	**Impact on Groundwater**	**Model used**	**References**
1	Shazand Plain, Iran	Rainfall in the region will decrease by 18–45% (2059) Average annual temperature is projected to rise by 16 % (from 13.7 to 15.9).	River discharge will decrease by 63–81% by the end of 2059.	Average groundwater level in 2060 may decrease significantly by 15.1 m compared to 2010.	Groundwater - Integrated hydrological model MODFLOW-OWHM Climate model - NorESM, River discharge - HEC-HMS model.	[103]
2	Punjab, India	Precipitation is predicted to rise by 5% at 2040, while it would decline by 0.6% at 2030.		Groundwater nitrate pollution will increase to 49-50% in 2030 and 65-66% in 2040.	Groundwater contaminants prediction - RF model (Random Forest) Climate model - Global climate models (GCM).	[104]
3	Great Britain (Coltishall, Gatwick, and Paisley)	High greenhouse gas emission (atmospheric CO_2 concentration increases to 525 ppm by the end of the present century and rise global temperature by 3.5 °C.	Winters up to 30% wetter and summers up to 50% drier are probable scenarios for Coltishall and Paisley by the 2080s.	Decline of 40% in annual potential groundwater recharge for Gatwick and 20% for Coltishall, and for Paisley a 7% reduction in is likely.	Climate model - Global climate models (GCM) (UKCIP02 scenario).	[105]
4	Palestine	10% reduction in annual rainfall 3.0 ℃ increase in temperature.	-	14% to 24% reduction in groundwater recharge (636 to 516 mcm/year).	Climate model – GCM Groundwater flow model – MODFLOW.	[106]
5	Oka River basin, Euro	Annual precipitation will	-	Groundwater flow will decrease by 12–17% at the	Climate models (GFDL-ESM2M, HadGEM2-ES,	[107]

	pean Russia	increase by almost 10% Decrease in the annual runoff will amount to 25–30% by the middle of the century, and 18-22% at the end.		middle of the century and about 9% by its end.	IPSLCM5A-LR, MIROC5).	
6	Vientiane basin, Laos	Average annual rainfall was projected to be significantly higher than the baseline condition (2011-2020 - 1,438 mm) by about 230, 250, and 700 mm/year, respectively, from 2021 to 2050.	The water with the TDS between 500 and 1,500 mg/l will tend to decrease, while the freshwater (TDS < 500 mg/l) area will tend to increase.	Average annual groundwater recharge (272 MCM/year) can be increased by 22.7–47.5% (334 to 401 MCM/year).	Groundwater recharge model (HELP3), groundwater flow model (MODFLOW), and salt transport model (MT3D).	[107,108]
7	Mosian plain, Iran	Annual precipitation will decrease by 3% during 2015-2030.		Decline of groundwater level in the study area was 0.48 m/year during the past 24 years. Annual groundwater depletion should increase to 0.75 m in the coming 16 years.	Climate model - HadCM3 Groundwater flow model – MODFLOW.	[109]
8	India (Haryana, Utter Pradesh, Rajasthan and Delhi)	Annual mean surface air temperature would rise by 1.7-2℃ in 2030.		Groundwater recharge would decrease by 0.09 m to 0.21 m and 0.11 m, respectively, during 2030 and 2100 as compared to the reference year 2005.	HYDRUS and PMWIN model for vadose zone moisture movement and MODFLOW.	[63]
9	Arusha,	Mean annual temperatures	Increased	Groundwater recharge may fall	Parameter ESTimation	[110]

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	Tanzania	expected to increase by between 0.8 °C and 1.8 °C by 2050 Annual precipitation will decrease by 10-11%.	evapotranspiration	30–44% by 2050, causing groundwater levels to drop at most 75 m.	(PEST) package of MODFLOW	
10	Coastal plains of Odisha, India	Climate change-mediated rise in sea level.	Salt water intrusion into aquifers.	Concentrations of Fe (44%), Mn (44%), As (4%) and Al (4%) in post-monsoon and Fe (32%), Mn (32%), As (4%), B (8%) and Ni (16%) in pre-monsoon exceeded Bureau of Indian Standards (BIS) drinking water limits. High concentrations of heavy metals (Fe, Sr, Mn, B, Ba, Li, Ni and Co) and high EC (>3000 µS/cm).		[111]

7. Hybrid Model for Vulnerability assessment of Ground Water and its Challenges

The study conducted by Aslam et al. [65] comprehensively considered all components and significant indicators contributing to groundwater vulnerability. Exploring the possibility of integrating these indicators within a system, depending on local conditions, the scale of the study, and data availability, and identifying their functional relationships and dependencies on other indicators is an active area of research[112]. This exploration can lead to new insights into the combined effects of these indicators. The IPCC framework recognizes adaptive capacity as an integral part of the vulnerability assessment process[79]. Modelling techniques for vulnerability assessment and index-based assessments have unique ways of quantifying vulnerability. The integrated use of impact modelling and index-based methodologies, incorporating adaptive capacity, could yield better results in future research. This approach maximizes the advantages of both methodologies while minimizing some of their limitations.

Climatic phenomena, encompassing both variability and change, exert influence on the groundwater system. Some researchers even argue that variability is more influential than change, opening up another wide area for further research[113–115]. Studies focusing on sea level rise and recharge estimation have made simplifications for influential factors [78,116], but there is a need for further research on scenarios of gradual sea level rise, considering real slopes, and addressing the heterogeneity of aquifer geology and hydraulic conductivity. The use of climate and impact models to estimate two of the three components of vulnerability should address limitations associated with index-based methods (e.g., instantaneous sea level rise, lumped slope/hydraulic conductivity, and homogeneous geology), making the results more convincing. Although model-driven results may contain uncertainties, these can be quantified and assigned, enhancing the reliability of the assessment.

7.1. Advantages and limitations of the hybrid study

7.1.1. Gradually sea level rise

By considering gradual sea level rise assumption, sea level increase on yearly rate is accounted as projected by IPCC (0.2 to 4 m/year) [65]. This avoids considering a single high value for the entire duration of projection. This significantly improves the credibility of the projections on the vulnerability to salt water intrusion and contamination.

7.1.2. Topography factors inclusion

The use of a single lumped slope value is a simplification that makes the process more manageable but can deviate from the actual conditions, resulting in a noticeable discrepancy between calculated and real-world outcomes[64,117,118]. To address this limitation, adjusting the parameter from a lumped to its nearly accurate value by considering spatial variability by incorporating data from the Digital Elevation Model (DEM) would be of better choice. This provides a more precise representation of the topographical features and enhancing the accuracy of the calculations.

7.1.3. Heterogenous aquifer properties

By utilizing semi or fully distributed hydrological models, a more realistic representation of the aquifer system is represented[87,102]. In particular, fully-distributed, 3D groundwater flow models like MODFLOW are capable of incorporating heterogeneity in the aquifer and its properties[119]. This capability allows for a more accurate and detailed simulation of the groundwater system, considering variations in geological features and hydraulic properties within the aquifer.

7.1.4. Groundwater contamination and rainfall recharge process optimization

The use of semi-distributed models, such as SWAT (Soil and Water Assessment Tool) and WetSpass, offer an advantageous middle ground as they do not demand as much data [78,100]. Additionally, they introduce heterogeneity in various processes, in contrast to lumped models, operating at the Hydrological Response Unit (HRU) or sub-basin levels. This characteristic allows for a more nuanced representation of hydrological processes, providing an optimal solution to the limitations encountered in previous methodologies.

8. Implications for sustainable water resource management (policy considerations)

There is increased pressure on water reserves due to population growth, urban sprawl, rapid industrialization, intensive farming, growing areas in tourism, climate change. Sustainable water resource management is a critical aspect of environmental stewardship, and policy considerations play a pivotal role in shaping effective strategies. Sustainable management of water resource is comprehensive involving not only a wide range of objectives and possible activities, but also the improvement of institutional framework and working practice. Some of the key implications for sustainable water resource management that has to be tackled through policy interventions are discussed.

Integrated Water Resource Management (IWRM) is crucial for addressing the complexity of water systems, considering the interconnections between surface water, groundwater, and ecosystems. The sector approach to water resource management is fragmented and uncoordinated resulting in inefficient management and increasing competition for scarce resources. Development and enforcement of policies that promote IWRM principles, emphasizing stakeholder engagement, decentralized decision-making, and the integration of social, economic, and environmental considerations should be given high priority [120]. Climate change poses challenges to water availability and quality, necessitating adaptive strategies to cope with changing precipitation

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patterns and increasing variability. Integration of climate change considerations into water management policies, including the development of adaptive strategies, infrastructure resilience, and promotion of water-use efficiency will be beneficial in the long run [121]. Currently more than 70% of the water is used in agriculture, and this quantity will increase in the future. Therefore, sustainable water resource management will need to find optimal solutions for managing water resources used in agriculture so as not to affect the water needs of the ever-increasing population [122].

Effective water governance structures and institutions are essential for the sustainable use and management of water resources, ensuring equitable distribution and minimizing conflicts. Establishing and strengthening water governance frameworks, emphasizing transparency, accountability, and the active involvement of local communities in decision-making processes will lead to sustainable resource use [123]. The Institutional Resources Regime (IRR) theorizes about the sustainable use of natural resources, particularly water, stating that a sufficient degree of regulation and policy mixtures that are coherent within and across policy sectors are required for sustainability [124]g. Proper valuation of water resources through pricing mechanisms can incentivize efficient use and conservation. Implementing water pricing policies that reflect the true cost of water, encourage conservation, and provide funding for infrastructure development and maintenance should be the top priority [125].

Emergence of new industrial hubs due to economic development involves activities that are water-consuming and waste-producing. While the functioning of these hubs is essential for the economic development of a region it is also recommended to consider the water reserves existing in that region and suitable policy should be framed for preserving them. Healthy ecosystems are vital for water quality and quantity; degradation can lead to reduced water availability and increased treatment costs. Enacting and enforcing policies that protect and restore ecosystems, emphasizing the importance of maintaining natural hydrological processes and biodiversity will be beneficial [126]. The policy considerations, informed by scientific research and practical experiences, can contribute to more sustainable water resource management practices. It is important for policymakers to adapt these principles to the specific contexts and challenges of their regions.

9. Summary and future prospective

The hydrological modeling has greatly improved our capacity to study and comprehend intricate water systems. A more comprehensive depiction of the hydrological cycle has been made possible by the integration of numerous elements, including surface water, groundwater, and land surface processes, into comprehensive models. In conjunction with advancements in computer power, data integration methodologies, and the incorporation of geographic variability, hydrological models have emerged as indispensable instruments for the management of water resources, evaluation of the consequences of climate change, and environmental strategy. The reliability of model predictions and parameter estimates has been further enhanced by the integration of uncertainty quantification approaches and data assimilation techniques. In order to address the inherent complexities and uncertainties related to hydrological processes, this has proved extremely important. The integration of hydro informatics tools and remote sensing data has opened new avenues for model calibration, validation, and monitoring, providing a more data-rich environment for hydrological studies.Furthermore, using machine learning and artificial intelligence approaches into hydrological modeling has the potential to significantly improve model accuracy and efficiency. As the effects of climate change become more apparent, hydrological models will be critical in assessing and adjusting to these changes. More sophisticated models that account for the dynamic interactions between climate, land use, and water systems may be developed in the future.

10. Conclusions

The future of hydrological modeling is bright, with ongoing attempts to improve existing models and develop new approaches. With the increased availability of high-resolution data, there is a greater emphasis on enhancing model spatial and temporal resolution to capture finer-scale phenomena. Evaluating the vulnerability of groundwater to potential stressors is crucial in translating these impacts into actionable measures. Recently, various initiatives have been undertaken globally at different scales to address this concern. To enhance understanding, a comprehensive review was conducted to analyses previous research, critically assess methodologies, and identify knowledge gaps based on underlying assumptions. The review emphasizes the significance of indicator selection in evaluating groundwater vulnerability to climate change, outlining limitations and gaps in the methodologies. This would help in developing approach that integrates the strengths of both impact modelling and index-based approaches, presenting a promising alternative for future research to overcome existing limitations and enhance the effectiveness of vulnerability assessments. Moreover, collaborative efforts between researchers, policymakers, and practitioners will be essential to ensure that hydrological models are effectively utilized in real-world decision-making processes. These advancements will contribute to a more comprehensive understanding of water systems, ultimately supporting sustainable water resource management in the face of evolving environmental challenges.

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