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Review

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

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Abstract: The Earth's water resources, totalling 1.386 billion cubic kilometres, predominantly consist of saltwater in oceans. Groundwater plays a pivotal role, with 99% of usable freshwater supporting 1.5–3 billion people as a drinking water source and 60–70% for irrigation. Climate change, with temperature increases 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 the management of groundwater. Groundwater vulnerability assessments vary with the spatial and temporal considerations, as well as assumptions in modelling groundwater susceptibility. This 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 and groundwater contamination processes, gradual sea level rise scenarios, and realistic representations of the region of study. With 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 modelling.

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

1. Introduction to Groundwater Modelling

Of the total water of 1.386 trillion cubic meters on Earth, only 3% is freshwater. Furthermore, about 30% is groundwater, and the permanently frozen ice and snow is roughly 69%. Less than 1% of fresh water is stored in surface water systems. 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 50% of the world's current potable water, playing a vital role in supporting both human and natural systems [1–4].

Groundwater plays an essential part in the functioning of the climate system, as highlighted by Liesch and Wunsch [5]. However, the potential impacts of climate change on groundwater remain uncertain due to the intricate nature of the climate system, characterised by complex interactions and feedback [6]. As per the Intergovernmental Panel on Climate Change (IPCC), around 0.6 ± 0.2 °C increase in the global mean surface temperature has been recorded 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 surface water evaporation of and transpiration from the plant. These changes are expected to impact precipitation patterns, timing, and intensity, indirectly influencing the distribution and storage of water (IPCC, 5th Assessment Report).

Researchers have used certain hydrological models to evaluate how climate change could influence surface and groundwater resources. Research has been carried out on groundwater recharge, which is dependent on hydrological processes as well as the surface structure and soil. An early investigation in the Coastal Plain of Western Australia utilised a one-dimensional model of the unsaturated zone (based on Richard's equation) to analyse 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 utilisation of groundwater modelling 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 is worth noting that various groundwater modelling codes are available, each with distinct capabilities, operational characteristics, and limitations.

This paper aims to examine the interplay between climate change events and groundwater components, exploring the methods employed, their pros and cons, respectively, and the critical role of indicator selection in assessing groundwater vulnerability. A concise overview of prior literature is provided to offer a brief understanding of the diverse aspects considered in earlier research on climate change's impact on groundwater vulnerability. Unlike earlier studies, the recent methodologies, tools, techniques, and advancements in modelling approaches, along with spatial and temporal assumptions in groundwater vulnerability assessment, are deliberated in this study. Further, the importance of indicator choice for hybridisation of models is illustrated to highlight the research gap.

2. Climate Change and Groundwater Interactions

The large reduction in groundwater storage cannot be entirely attributed to the substantial increase in the world's population and the consequent rise in water demand. 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 demonstrated associations between climatic variations and groundwater levels. Future scenarios for the management of water resources and food security are anticipated to be significantly shaped by the increasing demand for groundwater, especially in rural and desert regions [13,14]. It serves as the primary means of meeting water needs in these regions. Certain impacts are 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, alterations in water requirements, changes in the spatial distribution of floral communities, and adjustments in the water consumption patterns of plants in response to variations in climate and carbon dioxide concentrations. Directly affecting the entire groundwater system [15], climate change affects various aspects, including groundwater–surface water interactions, groundwater flows, its recharge and storage [7], groundwater discharge, and groundwater quality. The availability of groundwater is under pressure from changes in land use brought on by climate change, including changes in types of vegetation and cultivation techniques, as well as possible increases in crop evapotranspiration water demand [16].

Discharge of groundwater takes place whenever water from underground sources is brought to the surface, either by way of an aquifer to a surface water body or by human consumption. 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]. The massive groundwater extraction required to fulfil the increasing need for cultivation and other agricultural uses is a significant secondary consequence of climate change. This extraction may significantly lower surface water elevations and, as a result, limit base flow inputs to stream flow. Studies, such as that by Solder et al. [20], provide proof of deteriorating groundwater attributed to climate variability, change, and increased water demand. Furthermore, the environmental conditions of groundwater discharges may be impacted by climate change. Simulations conducted by Kurylyk et al. [21] revealed an increase temperature of groundwater up to 3.6 °C in their study area in New Brunswick, Canada. Researchers argue that any future influence of climate change on discharge of groundwater 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 subsurface temperatures and surface air temperatures exhibiting a strong positive correlation, particularly in shallow aquifers [21]. This raise concerns the likelihood of exceeding crucial temperature thresholds in groundwater under the shared socioeconomic pathways.

For the systemic analysis of the literature, a total of 2380 articles were selected for the bibliometric analysis. Out of the 6447 keywords generated from the above articles, only 319 that met the set threshold (5 or more occurrences) were chosen for co-occurrence analysis. Some of the keywords were hydrologic process, groundwater recharge, precipitation, runoff, evapotranspiration, climate change, land use land cover pattern, global atmospheric general circulation models, downscaling, univariant model, multivariant model, MODFLOW, and shared socioeconomic pathways. The overall number of combination links among keywords for each of the 319 keywords was determined, and the words with the highest total connection strength were chosen. The literature clusters on the effects of climate change on the resources of groundwater and modelling are displayed in Figure 1. The relationship connecting the two bubbles in Figure 1 shows how different subcategories' texts are similar to one another. Higher text similarity in the category centre is indicated by a thicker line, and vice versa. A great deal of research has been carried out to fill many of the information gaps about the connection between groundwater and climate change (CC). The literature indicates that, in a broad sense, climate change will intensify the hydrologic cycle, causing colder areas to become even colder, and humid regions to become more humid (green). Based on the studies performed on groundwater, groundwater recharge stands out as the most comprehensively understood and studied variable (purple). Other aspects, including discharge, flow and storage, water quality, and surface water interactions related to groundwater, still lack in-depth understanding (blue). Regarding modelling, there exists a research gap concerning groundwater modelling, as evidenced by the scarcity of literature keywords, as shown in the current investigation (red). The practice of groundwater modelling is gaining popularity, encompassing disturbances below the surface and the definition of aquifer features, as highlighted in the record review results identifying the knowledge lackuna.

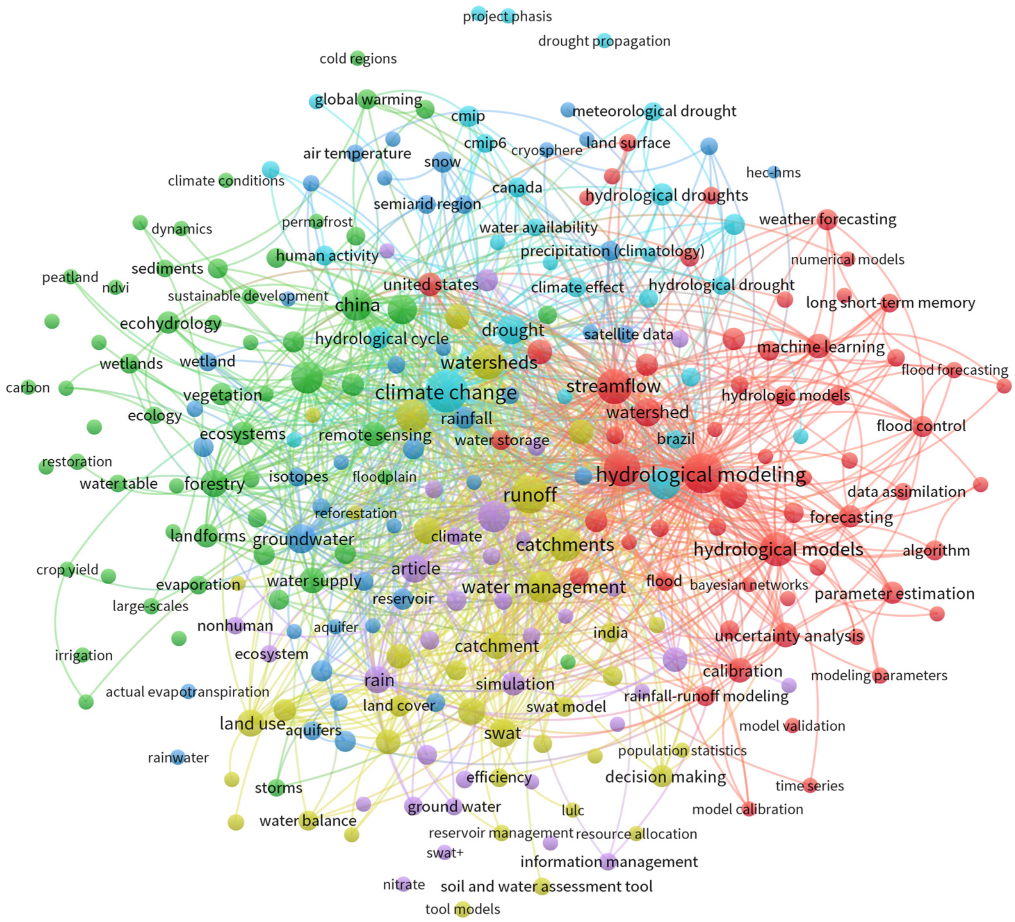


Figure 1. The bibliometric analysis of global research trends on climate vulnerability of hydrological resources.

Although groundwater plays a significant role in the climate system, the complex network of interactions and feedback that characterises the climate system means that many possible effects of climate change are still completely understood. The intricate relationship involving groundwater and elements of the climatic system is shown in Figure 2. The fundamental factor influencing the spatiotemporal fluctuations in groundwater recharge is climate, and precipitation is the component of climate that directly influences recharge the greatest, irrespective of the particular recharge pathway. The relevance of environmental variables in the broader picture of groundwater is emphasised by the widespread implementation of global climate models (GCMs) and information on precipitation to anticipate future groundwater conditions. A rise in overall precipitation at a particular location augments the quantity of water accessible for groundwater recharge, and under normal circumstances, it results in 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. Reduced recharge-to-precipitation ratios could occur from a snow-to-rain transition. Anticipating that, as the Earth warms, greater amounts of precipitation will fall as rain rather than snow, and regions characterised by cold climates may experience reduced recharge unless warmer winter temperatures diminish the ground frost depth, promoting increased infiltration and recharge. A warm winter might cause snowmelt to occur sooner and for a longer period, which would significantly increase winter recharge but decrease spring and summer recharge [24]. The rate at which precipitation falls also affects the recharge of groundwater. In tropical regions, rainfall intensity will be the primary determinant of groundwater recharging in the future. Additionally, evapotranspiration (ET) can obstruct infiltration beneath the root zone, reducing the ability of light rains to support groundwater recharging. Numerous studies showed significant variations in recharging as a result of modifications, such as the replacement of indigenous foliage with agricultural land or built-up surfaces [25]. For example, even with a minor decrease in rainfall, diminishing the leaf area through forest clearing for agriculture can improve groundwater recharge [26]. On the other hand, other research has shown that a higher foliage density, such as a transition from grassland to woodland, can result in declines in groundwater recharge [25], or rapid urbanisation and the replacement of natural surfaces with built-up areas. In general, whether it is a temporary change, such as alterations in vegetation, or a permanent change, such as urbanisation, land use/cover modifications can influence recharge by altering water balance processes, including evaporation, transpiration, infiltration, and surface runoff [27].

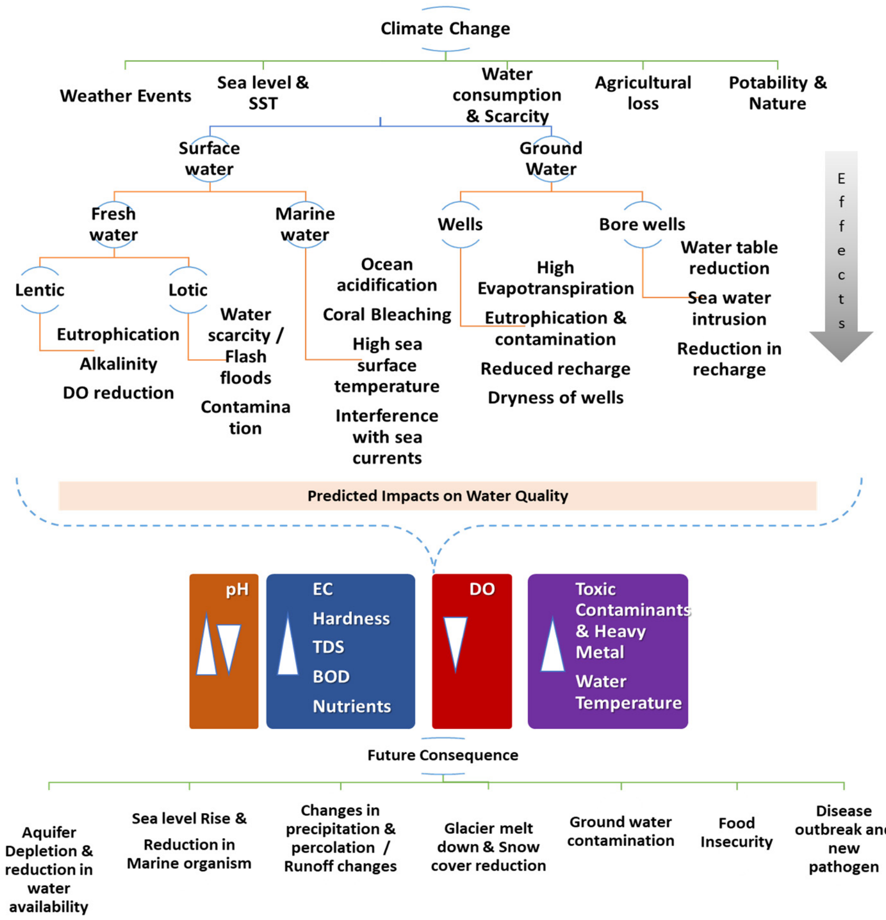


Figure 2. Groundwater systems' interactions and changes in the face of climate change.

The existing investigations on the impacts of climate change on groundwater are limited, and predictions are characterised by uncertainty. Nevertheless, two primary modes of impact are identified as: (1) the over-exploitation of coastal aquifers and (2) the introduction of chemical compounds into aquifers through flushing [24]. Irrigation return flows that seep into aquifers might bring dangerous substances that degrade the water's quality [28]. Future climate conditions, characterised by warmer winter temperatures and increased snowmelt in mid/high latitudes, may enhance solute leaching and pollutant capture in the unsaturated zone, thereby influencing groundwater quality. Furthermore, research suggests that climate change may exacerbate unsanitary conditions in underdeveloped areas, causing human excrement from pit latrines to seep into groundwater [29]. Numerous studies have assessed how climate change and land use change affect groundwater quality, specifically with regard to nitrate concentrations. These studies show that scenarios with high watering and recharge lead to an increase in concentrations of nitrates in groundwater [30]. Due to increased water demand and droughts brought on by climate change, saltwater intrusion (SWI) and the ensuing salt accumulation of freshwater from excessive consumption of wells are exacerbated by development, particularly in coastal areas [31,32]. Wells may dry up when groundwater abstraction rises, requiring deeper digging. This lowers groundwater quality, particularly in aquifers that are deeper in coastal regions that typically yield lower-quality water.

Significant data from the literature also point to a global reduction in groundwater levels in a variety of aquifers. Notable instances are significant aquifers in locations including the High Plains of the United States [33], as well as Northwest India [34], that have been undergoing rapid depletion of groundwater. Groundwater depletion is more serious than just a decrease in the amount of water available—it also poses risks to ecological sustainability and livelihoods, especially in dry spells [35]. The consequences of groundwater depletion are multifaceted. Firstly, it diminishes groundwater discharge into 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 diminution has been linked to land subsidence because of compaction of the aquifer system that previously held water, a phenomenon observed in locations such as Venice and Bologna in Italy [36], China [37], Iran [38], the central valley of California [39], and elsewhere. It is 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].

3. Key Modelling Approaches

The majority of the limited forecasts that are now available on how climate change would affect groundwater systems have made use of numerical models. These models are typically calibrated with historical data and then employed with weather data as input. Various approaches have been suggested for assessing the specific vulnerability to contamination. These approaches can be classified into overlay/index [40], 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. [41,42]. 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 [43]. Since model outputs greatly vary, analytical methodologies also add uncertainty into the process of projecting [44] and evaluating the affects and processes through impact models.

In a study conducted by Leterme and Mallants [45] in the Nete catchment in Germany, the Hydrus-1D model was employed to assess the relative impact of rainfall and land use change indicators. The study successfully determined that the impact on annual mean recharge under existing conditions is estimated to be 391 mm. In the case of a warmer environment, this value dropped by 7.7%, and in the case of a colder climate, it further dropped by 67.3%. Recharging in the existing and projected warm and cooler areas was reduced as a result of land use changes of all other kinds. In comparison to current (64%) and colder (48%) temperature scenarios, there was a greater decline in recharging in warmer condition scenarios (79%). Higher evapotranspiration (ET) is thought to be the cause of the decline in recharge in the warmer temperatures; however, it is less than in a colder environment because of the high water level (3 m).

In 2006, Scibek and Allen [46] formulated a method with a goal of connecting climate models with groundwater ones to explore the prospective effects on groundwater systems. The assessment examined an unconfined aquifer around Grand Forks in south-central British Columbia, Canada. Using Statistica modelling, climate change scenarios produced from model trials in the Canadian Global Coupled Model 1 (CGCM1) were adjusted to local conditions. Then, during one-year test runs (representing the periods 1961–1999, 2010–2039, 2040–2069, and 2070–2099), four climate scenarios were simulated using a three-dimensional transient groundwater flow model implemented in MODFLOW, and groundwater levels were compared with current conditions. The study discovered that, when compared to a visualisation of mean annual recharge, the spatial distribution of recharge had a bigger impact on groundwater levels than did temporal changes in recharge. The Grand Forks region's predicted future climate, as indicated by the downscaled CGCM1 model, calls for higher recharge to the unconfined aquifer from spring to summer. Nevertheless, the resulting consequence of this recharging on its water balance is negligible because of the major interactions among the river and aquifer, and the additional river water recharge.

A regional-scale numerical groundwater model was developed in 2009 by Toews and Allen [47] for the Oliver region in south Okanagan, British Columbia, Canada. Simulating the possible effects of predicted climate change on groundwater was the goal. The study's predictions showed that recharge will become more of a factor in the yearly water budget in the 2050s and 2080s. In comparison to the current situation, the estimated rise in the total budgets per year for the 2050s and 2080s was 1.2% and 1.4%, respectively. The changes in groundwater due to climate changes, as predicted by various models, are presented in Table 1.

Table 1. The predicted impacts of climate change on groundwater by various models.

S. No.	Country	Variables Used	Major Climate Change Event	Major Impact on Environment	Impact on Groundwater	Model Used	References
1	Shazand Plain, Iran	Hydraulic head, precipitation infiltration, surface water flow, and subsurface flow.	Rainfall in the region will decrease by 18–45% (2059). It is predicted that the average annual temperature will increase by 16%, from 13.7 to 15.9.	River discharge will decrease by 63–81% by the end of 2059.	Significant reduction of average groundwater level by 15.1 m in 2060.	Groundwater—Integrated hydrological model, MODFLOW-OWHM. Climate model—NorESM. River discharge—HEC-HMS model.	[48]
2	Punjab, India	Nitrogen fertiliser usage, land use change, population density, GW nitrate, precipitation, mean temperature, potential evapotranspiration (PET), and aridity index.	Precipitation is predicted to rise by 5% by 2040, while it would decline by 0.6% by 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).	[49]
3	Great Britain (Coltishall, Gatwick, and Paisley)	Precipitation, minimum and maximum temperature, vapour pressure, wind speed, sunshine duration, relative humidity, potential evapotranspiration, and soil moisture.	High greenhouse gas emissions (atmospheric CO_2 concentration increases to 525 ppm by the end of the present century) and rise in global temperature by 3.5 °C.	Up to 50% drier summers and 30% wetter winters by the 2080s.	A 40% decrease in the yearly projected groundwater recharge for Gatwick, a 20% decline for Coltishall, and a 7% reduction for Paisley.	Climate model—Global climate models (GCM; UKCIP02 scenario).	[50]
4	Palestine	Precipitation, potential evapotranspiration, and land use pattern.	10% reduction in annual rainfall and 3.0 °C increase in temperature.	-	14% to 24% reduction in groundwater recharge (636 to 516 mcm/year).	Climate model—GCM. Groundwater flow model—MODFLOW.	[51]
5	Oka River basin, European Russia	Surface air temperature, precipitation, air humidity deficit, and surface runoff.	Annual precipitation will 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.	-	Groundwater flow will decrease by 12–17% by 2050.	Climate models (GFDL-ESM2M, HadGEM2-ES, IPSLCM5A-LR, and MIROC5).	[52]

Table 1. *Cont.*

S. No.	Country	Variables Used	Major Climate Change Event	Major Impact on Environment	Impact on Groundwater	Model Used	References
6	Vientiane basin, Laos	Infiltration, evaporation, runoff, rainfall patterns, temperatures, land cover, land use, soil type, and ground surface slope.	Annual rainfall higher than 1438 mm by about 230, 250, and 700 mm/year, respectively, from 2021 to 2050.	Freshwater areas (TDS < 500 mg/L) will typically see an increase in TDS, while water with TDS between 500 and 1500 mg/L would generally see a reduction.	Annual groundwater recharge would be increased by 22.7–47.5% (334 to 401 MCM/year).	Models for groundwater recharging (HELP3) and groundwater flow (MODFLOW), including salt transport (MT3D), are available.	[52,53]
7	Mosian plain, Iran	Rainfall, minimum and maximum temperatures, air temperature, radiation, GW recharge, hydraulic parameters, well initial heads, and stream flows.	Annual precipitation will decrease by 3% during 2015–2030.		Over the previous 24 years, the research area's groundwater level has declined at a rate of 0.48 m/year. In the next 16 years, the annual depletion of groundwater is expected to reach 0.75 metres.	Climate model—HadCM3. Groundwater flow model—MODFLOW.	[54]
8	India (Haryana, Utter Pradesh, Rajasthan, and Delhi)	Water flux, potential evapotranspiration, precipitation, temperature, wind speed, sunshine hours, relative humidity, and hydraulic conductivity.	Annual mean surface air temperature would rise by 1.7–2 °C in 2030.		Groundwater recharge would decrease by 2030 up to 0.09 m to 0.21 m compared to the reference year 2005.	HYDRUS and PMWIN models for vadose zone moisture movement and MODFLOW.	[55]
9	Arusha, Tanzania	Evapotranspiration, surface runoff, groundwater recharge, groundwater abstraction, and return flow	Yearly annual temperatures estimated to increase by between 0.8 °C and 1.8 °C by 2050. Annual precipitation will decrease by 10–11%.	Increased evapotranspiration.	Groundwater recharge may fall 30–44% by 2050, causing groundwater levels to drop by at most 75 m.	Parameter ESTimation (PEST) package of MODFLOW.	[56]
10	Benin, West Africa	The characteristics of an aquifer include its type, hydraulic conductivity, height above mean sea level, distances from the shore, impact of seawater intrusion, and thickness within a saturated aquifer.	Sea level rise and over-exploitation.	Seawater intrusion into aquifer.	Due to the drop in groundwater levels during that period, seawater intrusion is more likely to occur in February and less likely in July.	GALDIT	[57]
11	Birbhum District, West Bengal, India	Vadose zone impact, topography, depth to water level, net recharge, aquifer and soil medium, and hydraulic conductivity.	Industrialisation, urbanisation, intensive agriculture.	Groundwater contamination.	Fluoride (14.31), iron (5.8), sulphate (360.55), phosphate (1.86), and EC (2490).	DRASTIC	[58]
12	PT. X in Balangan, South Kalimantan, Borneo	The presence of groundwater, the kind of aquifer, its overall lithology, and its depth.	Mining activities.	Groundwater contamination.	Moderate (0.32–0.36) groundwater vulnerability.	GOD	[59]
13	Campania Region, Southern Italy	Hydraulic resistance of an aquifer, hydraulic conductivity.	Pyroclastic, alluvial, and marine deposits.	Groundwater vulnerability.	Very high (<-3.8) and high (-3.8 to -1) vulnerability index.	Modified AVI	[60]

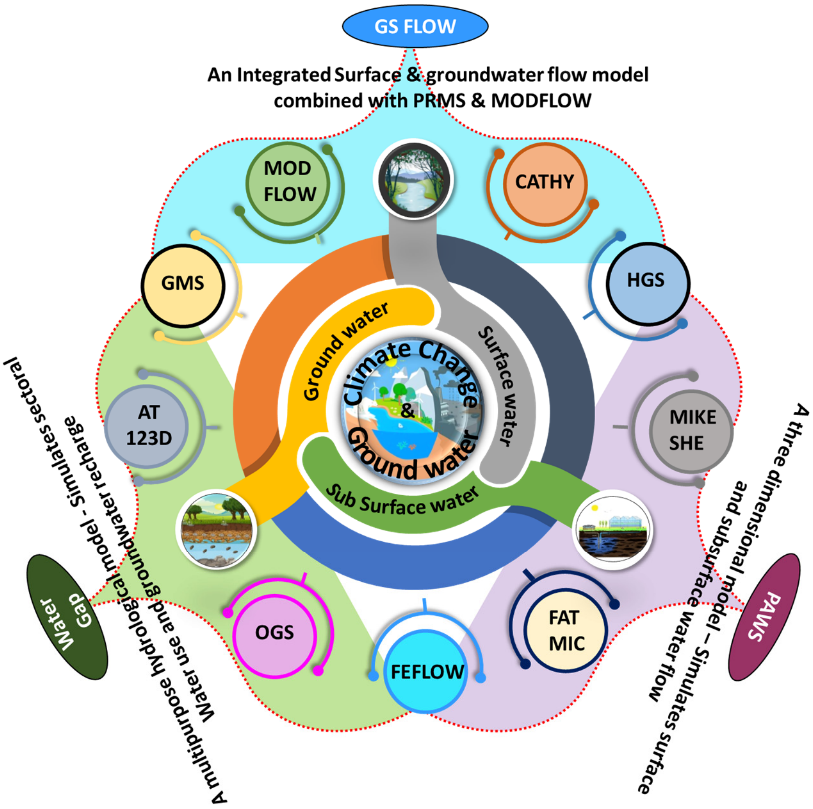
In 2014, Waikar and Somwanshi [61] conducted research on the impact of climate change on a dynamic groundwater system in a drought-prone area. The study focused on databases and their analysis, involving the generation of future rainfall and temperature data, estimation of recharge, and simulation of 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 measurement of the impacts of climate change on time-slice rates as well as groundwater recharge for the years 2004–2039 marked the study's conclusion.

Kumar et al. [62] concentrated on current research findings and techniques for assessing these effects utilising variables including soil moisture, groundwater recharge, and coastal aquifers. A succinct review of recent research is included in the report. Groundwater recharge was estimated with the use of WHI UnSat Suite and WetSpass. Weather station climate data were assessed, and general circulation models were employed to create datasets for future projected climate change. These datasets included elements such as sun radiation, precipitation, and temperature. In a groundwater study carried out in the United States' High Plains, sixteen global climate models (GCMs) as well as three global warming scenarios were used to evaluate how groundwater recharge rates will differ between a 1990 and a 2050 climate. The WAVES model (Soil–Plant Atmosphere Transfer) was employed to simulate groundwater recharge for a range of soil and plant types found in the High Plains. The Northern High Plains were predicted to grow by +8%, the Central High Plains to decline by −3%, and the Southern High Plains to decline by a more significant 10% in the median estimate for 2050. This strengthens the current north-to-south spatial trend in recharge. Future climatic scenarios with varying levels of precipitation showed predicted recharge variances that exceeded 50% of actual recharge. These differences included both increases and declines in recharge levels. Relatively speaking, areas with high current recharging rates are generally less sensitive to changes in rainfall, and vice versa, according to the susceptibility of recharge to rainfall changes [63].

Nyenje and Batelaan's study examined how baseflow and groundwater recharge in Uganda's upper Ssezibwa catchment are affected by climate change. Through the examination of historical data, the research was able to identify clear indicators of climate change in relation to observed discharge and temperature patterns. The statistical downscaling model (SDSM) was used to downscale data obtained from the UK climate model HadCM3 in order to evaluate possible climate change scenarios. The downscaled data on the climate served as inputs for the WetSpa hydrological model, a physically dispersed rainfall–runoff model used to predict subsequent changes in hydrology. During the rainy months (March–May and October–December), the downscaled climate forecasts suggested an upsurge in precipitation, which ranged from 30% in the 2020s to over 100% in the 2080s. The predicted increase in temperature was from 1 to 4 °C. The hydrological cycle was shown to be intensified by these alterations. It was estimated that between the 2020s and the 2080s, the mean annual daily base flow—which makes up 69% of discharge at 157 mm/year throughout the aforementioned period—would rise by 20–80%. In addition, compared to the existing 245 mm/year, the anticipated increase in recharging ranged from 20% to 100% [64].

4. Advancement in Hydrological Modelling Technologies

Hydrological modelling has been driven by improvements in data assimilation and 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 along with the water fluxes [65]. The behaviour of hydrological and meteorological phenomena under various climatic scenarios is also predicted by combining regional climate models with hydrological models based on land surface data. Decision-makers can use these climate scenarios as visible instruments to help characterise the future climate [66]. 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. The overlays of each model have a unique output with significance to hydrological processes and water gaps in the system (Figure 3). This may result in improved representation of land surface processes, and quantification of human impacts on water systems [67].



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.

Modifications to hydrological models are often carried out to evaluate the impacts of climate change on water resources, considering changes in temperature, precipitation patterns, and extreme events [68]. Incorporation of advanced uncertainty quantification techniques and data assimilation methods are essential to improve the model predictions and parameter estimation. Monte Carlo analysis, Bayesian statistics, multi-objective analysis, least-squares-based inverse modelling, response-surface-based approaches, and multi-modelling analysis are some of the frequently used techniques for uncertainty analysis [69,70]. Integrated hydrological models allow for a comprehensive understanding of the water cycle, incorporating surface water, groundwater, and atmospheric interactions [71,72]. Earth system models (ESM) simulate the connections between the atmosphere, oceans, land surface, and ice, enabling a more holistic representation of climate dynamics. The accuracy of estimates of land–atmosphere fluxes and biogeochemistry is significantly increased by improvements in the depiction of hydrologic processes in earth's system models [71,72]

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 modelling and prediction in diverse fields [73]. Larger and more intricate process-based models will be possible thanks to recent developments in computational platforms, including cloud along with quantum computing, as well as machine learning for certain process capture. Models predicting land use changes help assess the impacts of human activities on landscapes and ecosystems, facilitating sustainable land management [74]. Models that integrate human and natural systems help analyse feedback and interactions between social and environmental components. These references represent seminal works in their respective fields, providing a foundation for understanding the advancements in modelling technologies. Keep in mind that the field of modelling is dynamic, and ongoing research contributes to continuous improvement and innovation in modelling techniques.

5. Spatial and Temporal Consideration and Assumptions in Modelling Groundwater Susceptibility

Researchers from all around the world have evaluated groundwater's susceptibility to climate change in recent years at several temporal and spatial scales [55,75–77]. Finding any information gaps and recognising the parallels and differences across these studies can be difficult, though. Exposure, sensitivity, and adaptive ability all contribute to vulnerability, and there are considerable changes in the strategies used to quantify vulnerability because of scale and context dependence [78]. Different methodologies, which can be divided into overlay/index statistics and process/model-based methods, have been presented for measuring the intrinsic and specific vulnerability of groundwater [79–81]. Specific susceptibility to pollutants and sea level rise is quantified using process/model-based techniques, which also yield more complicated outputs, such as contamination concentrations and travel times.

The groundwater assessment susceptibility to climate change has been performed using both process/model-based and overlay/index methodologies, each having advantages and disadvantages [82]. Alternative interpretations of results may arise due to differences in opinion and perception, emphasising 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 [78,83]. In analytical methods, simplifying factors, such as constant hydraulic conductivity, transmissivity, and uniform aquifer thickness, also increase errors, especially in estimating climate change and its implications using models [84]. Most people agree that no single approach is better than another or that they should be used exclusively. The decision should be based on the goals of the study, the data and resources that are available, and the time frame [78].

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. Nevertheless, this simplification is limited to evaluating the effects of the most recent interglacial period when sea levels increased by four to six meters [85]. Assumptions that attempt to simulate the effects of future sea level rise with a single high value are invalid because this phenomenon is anticipated to occur gradually, increasing annually from 1.3 to 4.2 mm between 1901 and 2018 [86,87]. Furthermore, the way saltwater intrusion behaves in simulations differs based on whether instantaneous or gradual sea level rise is assumed, and the latter approach more accurately captures the intrusion process. Thus, modelling attempts must take into account the gradual rise in sea level in order to provide a more realistic evaluation of the effects of sea level rise on groundwater resources.

As long as the slope in topographically level areas stays constant or barely changes, it is acceptable to assume constant or average values for all parameters pertaining to the qualities of the soil or aquifer [75,88]. Nevertheless, these presumptions could result in assessment results that are undervalued, especially in rough topographies where these qualities are critical to aquifer recharge in climate scenarios. The validity of the uniform assumption is called into question by the existence of multiple geological strata that cover groundwater, each with unique hydraulic properties that can significantly affect aquifer recharging. The physical mechanisms causing groundwater pollution as a result of land use change and climate change are intricate and include absorption on soil particles, biological along with chemical degradation, and the transportation and dilution of contaminants [79,89,90]. The real pollution risk may be overestimated or underestimated if linearity with these physical events is assumed. Size has a significant impact on the outcomes since larger-scale research may simplify intricate methods. As a result, research carried out on a broader geographic scale might ignore or average site-specific processes, which could affect how groundwater quality is evaluated. The phenomenon of groundwater recharge is complex and depends on a number of variables, including rainfall, land use, aquifer content, groundwater table depth, topography, soil properties, and hydraulic conductivity [91]. For instance, a study by Zume and Tarhule [92] ignored other significant components and evaluated recharging just as an estimate of rainfall (i.e., 10% of yearly direct rainfall), which could result in an 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 [93–95]. Consequently, these stressors should be incorporated into exposure assessments, thereby influencing vulnerability evaluations. Climate change is a worldwide occurrence, which has an impact on systems at different scales, both directly, through changes in precipitation and temperatures, and indirectly, through population growth, groundwater abstraction, variations in land use and cover, altered evapotranspiration, and water demand, among other things [96–101]. To comprehensively characterise 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 Groundwater

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 [102]. Though climate change is a big factor, climatic variability is also big. Remarkably, all of the evaluated studies have only looked at climate change—none have included climate variability in their vulnerability evaluations. It is important to remember that variables and climate change both have an impact on climate vulnerability indicators [99]. For a more thorough examination of the real situation, variability—which stands for the range of climate changes at an average yearly time scale—must be included. The overall pattern of average environmental conditions, which represents change, might not accurately reflect the actual situation. One study that was looked at evaluated the vulnerability of the present [103], while others considered both current and future times. General circulation models under the Special Report on Emission Scenarios (SRES) A2, A1B, and B1 were used in these studies to project future climates. Acknowledging the uncertainties associated with scenarios and general circulation model projections, the scientific community has raised concerns. The likely coarser resolution of general circulation models at a scale of 1 to 2°, where one degree is equivalent to nearly 100 km, is the cause of these inaccuracies, making them less accurate in representing certain climate phenomena [104].

While considering both categories of indicators together poses a greater threat to the system than assessing them individually, interdependence exists among certain indicators, such as the link between land use/cover and climate through moisture exchange. Local climate circumstances have an impact on groundwater abstraction, which highlights the significance of indicator selection in assessments of climate change vulnerability. This integrated method improves how useful the outcomes are. On the other hand, a sensitivity study conducted in [43] successfully illustrated the influence of indicators on the resources of groundwater on Dauphin Island, USA. The authors evaluated the amount of groundwater available by taking into account several scenarios, both alone and collectively. Under Scenario 1 (continuous climate, land use/cover, and pumping), land use/cover modification (Scenario 2) resulted in a 3.9% drop in the volume of freshwater relative to the existing salinity level of 1.2%. In Scenario 3, a dry environment combined with alterations in land use and cover resulted in a 3.3% reduction in freshwater availability. However, when the wet climate with land use/cover was coupled (Scenario 4), more rainfall-triggered recharging caused the freshwater volume to revert to baseline levels. Combining a dry climate, changing land use/cover, and more pumping resulted in an 8.6% drop in freshwater availability (Scenario 5). The volume varied at 10% and 50% of the starting salinity stages, but the impact's direction stayed the same. This highlights the importance of indicator selection and the relative sensitiveness with groundwater amount as a function of condition under the effect of both climatic and non-climatic stressors.

Climate change interactions with biological and physical systems create complex feedback across sectors, complicating impact and adaptation strategies. The decision on the extent of including biophysical systems in modelling, amidst evolving socioeconomic and political changes, is essential to comprehend consequences of climate change on groundwater systems. Different modelling pathways, guided by the modeler's choice, yield varying impacts on biophysical systems and societies. Constant exploration of adaptive responses to climate change pathways supports informed decision-making for effective adaptation strategies. This can be assessed on its own or deduced from indicators of sensitivity and exposure. Generally speaking, adaptive ability indicators fall into three categories: governing institutions, available resources, and system assets [105–107]. These signs must be taken into account, particularly when evaluating adaptive capability separately from vulnerability assessments. It is advised to incorporate a range of indicators (health, income, and education, for example) chosen according to their functional links and systemic influence in order to increase the reliability of the assessed results [108]. Indicators that show functional links, such as governance and the rate of capacity creation, significantly influence the definition of a system's adaptive capability [109]. Therefore, it is likely that judgements will be less than ideal if any of these pertinent signs are ignored.

7. Hybrid Model for Vulnerability Assessment of Groundwater and Its Challenges

The study conducted by Aslam et al. [78] comprehensively considered all components and significant indicators of groundwater vulnerability. By assessing the possibility of integrating these indicators based on local conditions, data accessibility, and size, and identifying their functional relationships and dependencies on other indicators, a new frontier has been created [110]. This exploration can lead to new insights into the cumulative overall effects of these indicators. The IPCC framework recognises adaptive capacity as a key component for the vulnerability assessment process [86]. Modelling techniques for vulnerability assessment and index-based assessments have unique ways of quantifying vulnerability. The integration of index-based methodologies and impact modelling, incorporating adaptive capability, could yield improved output in future studies. This approach maximises the advantages of both methodologies while minimising some of their limitations.

Climatic variability is more influential than change, opening up additional extensive avenues for further studies [111–113]. Research on sea level increases and restored calculation has simplified the effects of significant factors [85,114]. However, more work is needed to address the heterogeneity of aquifer geology and hydraulic conductivity, accounting for real slopes, andscenarios of gradual sea level upsurge (e.g., lumped slope/hydraulic conductivity, instantaneous sea level rise, and homogeneous geology should be addressed to provide results that are convincing). Although model-driven results may contain uncertainties, these can be computed and assigned, enhancing the reliability of the assessment.

7.1. Advantages and Limitations of the Hybrid Study

7.1.1. Sea Level Rise and Its Attributes

By considering gradual sea level rise assumptions, the yearly rate of sea level increase is accounted to be 4 mm/year as projected by the IPCC [78]. Considering a single high value for the entire duration of projection questions the credibility of the projections on the vulnerability to saltwater intrusion and contamination. The satellite altimetry data indicate a global mean sea level escalation hastening at 0.084 ± 0.025 mm per year. If the trend continues, sea level rise by 2100 is estimated to exceed 65 cm due to hastened sea level upsurge, more than double the expected amount [115]. Moreover, several researchers have studied the contribution of land subsidence to sea level rise [116–119]. Land subsidence linked to the compaction of aquifer systems due to the extraction of groundwater has accounted for up to 85% of the 0.7 m of relative sea level rise. Projections indicate that in 2100, sea level rise will decrease by 30% to 10% in the predicted period due to land subsidence [120]. The findings emphasise the incorporation of the gradual sea level rise, the accelerating trend in sea level rise, and the relative sea level rise in hydrological and climate modelling.

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 [77,121,122]. A better option would be to change the variable from a lumped to its roughly accurate value by considering spatial variability and utilising data gathered from the digital elevation model (DEM). This provides a more precise representation of the topographical features and enhances the accuracy of the calculations.

7.1.3. Heterogenous Aquifer Properties

By utilising semi or fully distributed hydrological models, a further illustrative representation of the aquifer system is represented [94,108]. In particular, fully distributed 3D groundwater flow models, such as MODFLOW, are capable of incorporating heterogeneity in the aquifer and its properties [123]. 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 Optimisation

The usage of semi-distributed models, namely SWAT (Soil and Water Assessment Tool) and WetSpass, offer an advantageous middle ground as they do not demand as much data [85,106]. Additionally, they incorporate variability in multiple procedures, 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, which offers an optimal approach around the drawbacks of previous techniques.

8. Artificial Intelligence and Quantum Computing

Over the past twenty years, there has been a notable surge in the adoption of machine learning techniques and soft computing tools for analysing data-intensive hydrological modelling issues. These nonlinear methods are employed to extract features, patterns, or rules from datasets [124]. As such, methods such as bagging, stacking, and dagging have not been as frequently and successfully used in hydrological situations, compared to techniques such as boosting, AdaBoost, and high gradient boosting [125]. The most effective machine learning-derived, remote sensing-based precipitation predictions are probably PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) and its variations. Estimating evapotranspiration and soil moisture using in situ data and remote sensing has been performed using machine learning techniques [126]. There are new machine learning applications in groundwater hydrology. In order to train the model to map land subsidence caused by groundwater pumping, the authors of [127] employed evapotranspiration, land use, and sedimentation thickness of random forests. This produced accurate findings. Additionally, the sensitivity of the mapping accuracy depended on the quantity of the training dataset.

In addition to machine learning and artificial intelligence, quantum computing has been evolving as a substitute for traditional computing. Quantum computing can overcome the memory and speed limitations encountered by classical methods. Quantum linearsystem algorithms have several advantages over classical algorithms. Various methods, such as quantum gate arrays and quantum annealing, are being explored as avenues for quantum computing development [128]. Precisely forecasting crucial aspects of hydrological systems, such as subsurface flow, may necessitate solving extensive linear systems that surpass the capabilities of current and anticipated high-performance systems. Current quantum preconditioners do not demonstrate effectiveness in handling the surface and subsurface flow of fluids in hydrological systems. Using the inverse Laplacian preconditioner and presenting arguments against the scalability of traditional approaches can improve the scaling of the system and admits a quantum implementation [129]. However, quantum computing is in developing stages compared to classical computing, though it has been demonstrated to explain certain complicated subsurface flow problems. In the study conducted by Golden et al. [128], the D-Wave 2X quantum annealer was utilised to solve 1D and 2D hydrologic inverse problems that are considered as complicated and time-consuming problems for classical computers.

9. Implications for Sustainable Water Resource Management (Policy Considerations)

Water reserves are under more stress as a result of growing populations, urban sprawl, fast industrialisation, intensive farming, expanding tourism regions, and 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 resources is comprehensive, involving not only a wide range of objectives and possible activities, but also the improvement of the institutional framework and working practice. Some of the key implications for sustainable water resource management that must be tackled through policy interventions are discussed below.

Integrated water resource management (IWRM) is crucial for addressing the complexity of water systems, considering the interconnections between surface water, groundwater, and ecosystems. The fragmented and disorganised sector approach to managing water resources leads to ineffective management and heightened competition for limited supplies. Development and enforcement of policies that promote IWRM principles, emphasising stakeholder engagement, decentralised decision-making, and the integration of social, economic, and environmental considerations, should be given high priority [130]. Climate change poses challenges to water availability and quality, necessitating adaptive strategies to cope with changing precipitation 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 [131]. Over 70% of water is presently utilised in agriculture, a percentage expected to rise in the future. Ensuring sustainable water resource management becomes crucial, requiring optimal solutions for agricultural water use that balance the needs of the growing population without compromising the overall water availability [132].

To ensure fair distribution and minimise conflicts, equitable utilisation and oversight of water resources require efficient water policy structures and organisations. Sustainable resource use can be achieved by establishing and bolstering frameworks for water governance, emphasising accountability and openness, and actively including local communities in decision-making processes [133]. According to the Institutional Resources Regime (IRR), sustainability requires a sufficient level of regulation and cohesive policy combinations within and between policy sectors. This is especially true for the sustainable utilisation of natural resources, particularly water [134]. Encouraging efficient use and conservation of water resources can be achieved through pricing mechanisms that appropriately value them. The first objective should be to implement water pricing laws that accurately represent the cost of water, promote conservation, and provide funds for the development and upkeep of infrastructure [135].

As a result of economic growth, new industrial hubs are emerging, involving waste- and water-producing activities. Although the operation of these hubs is crucial for a region's economic growth, it is also advised that the region's water reserves be taken into account and that appropriate policies be created to protect them. Healthy ecosystems are vital for water quality and quantity, as degradation can lead to reduced water availability and increased treatment costs. For enacting and enforcing policies that protect and restore ecosystems, emphasising the importance of maintaining natural hydrological processes and biodiversity will be beneficial [136]. 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.

10. Summary and Future Perspectives

Hydrological modelling has greatly improved our capacity to study and comprehend intricate water systems. A more comprehensive depiction of the hydrological cycle has groundwater and land surface processes integrated 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. This study highlights the need to frame policies that address climate change and groundwater management, both of which must be implemented locally to assist sustainable growth since groundwater is crucial to achieving the sustainable development goals of the UN. Future studies ought to concentrate more on the development of policy directives for all the local bodies/governments/NGOs to collect and validate the ground truth data in a pattern or a format suitable for modelling studies. 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 in hydrological modelling has the potential to significantly improve model accuracy and efficiency. Hydrological models will be essential for evaluating and adapting to the implications of climate change as they become more evident. In the future, more advanced models that take into consideration the dynamic interconnections between water systems, land use, and climate could potentially be devised.

11. Conclusions

The future of hydrological modelling 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. A thorough study was carried out here to improve understanding. We analysed earlier research, critically evaluated approaches, and identified knowledge shortages based on fundamental presumptions. The review outlined the gaps and limits in the techniques and highlighted the importance of indicator choices in assessing the vulnerability of groundwater to climate change. This would help in developing an 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. In addition, cooperation among scholars, decision-makers, and practitioners will be necessary to guarantee that hydrological models are successfully applied in actual decision-making procedures. By advancing our understanding of water systems, these developments will help manage water resources sustainably in the face of changing environmental problems.

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References

1. Du Plessis, A. *Freshwater Challenges of South Africa and Its Upper Vaal River*; Springer: Berlin/Heidelberg, Germany, 2017; ISBN 3319495011.
2. López-Morales, C.A.; Mesa-Jurado, M.A. Valuation of Hidden Water Ecosystem Services: The Replacement Cost of the Aquifer System in Central Mexico. *Water* **2017**, *9*, 571. [CrossRef]
3. Misra, A.K. Climate Change and Challenges of Water and Food Security. *Int. J. Sustain. Built Environ.* **2014**, *3*, 153–165. [CrossRef]
4. Velis, M.; Conti, K.I.; Biermann, F. Groundwater and Human Development: Synergies and Trade-Offs within the Context of the Sustainable Development Goals. *Sustain. Sci.* **2017**, *12*, 1007–1017. [CrossRef] [PubMed]
5. Liesch, T.; Wunsch, A. Aquifer Responses to Long-Term Climatic Periodicities. *J. Hydrol.* **2019**, *572*, 226–242. [CrossRef]
6. Munday, P.L.; Donelson, J.M.; Domingos, J.A. Potential for Adaptation to Climate Change in a Coral Reef Fish. *Glob. Chang. Biol.* **2017**, *23*, 307–317. [CrossRef] [PubMed]
7. Asoka, A.; Gleeson, T.; Wada, Y.; Mishra, V. Relative Contribution of Monsoon Precipitation and Pumping to Changes in Groundwater Storage in India. *Nat. Geosci.* **2017**, *10*, 109–117. [CrossRef]
8. de Graaf, I.E.M.; van Beek, R.L.P.H.; Gleeson, T.; Moosdorf, N.; Schmitz, O.; Sutanudjaja, E.H.; Bierkens, M.F.P. A Global-Scale Two-Layer Transient Groundwater Model: Development and Application to Groundwater Depletion. *Adv. Water Resour.* **2017**, *102*, 53–67. [CrossRef]
9. Russo, T.A.; Lall, U. Depletion and Response of Deep Groundwater to Climate-Induced Pumping Variability. *Nat. Geosci.* **2017**, *10*, 105–108. [CrossRef]
10. Sivarajan, N.A.; Mishra, A.K.; Rafiq, M.; Nagraju, V.; Chandra, S. Examining Climate Change Impact on the Variability of Ground Water Level: A Case Study of Ahmednagar District, India. *J. Earth Syst. Sci.* **2019**, *128*, 122. [CrossRef]
11. van der Knaap, Y.A.M.; de Graaf, M.; van Ek, R.; Witte, J.-P.M.; Aerts, R.; Bierkens, M.F.P.; van Bodegom, P.M. Potential Impacts of Groundwater Conservation Measures on Catchment-Wide Vegetation Patterns in a Future Climate. *Landsc. Ecol.* **2015**, *30*, 855–869. [CrossRef]
12. van Engelenburg, J.; Hueting, R.; Rijpkema, S.; Teuling, A.J.; Uijlenhoet, R.; Ludwig, F. Impact of Changes in Groundwater Extractions and Climate Change on Groundwater-Dependent Ecosystems in a Complex Hydrogeological Setting. *Water Resour. Manag.* **2018**, *32*, 259–272. [CrossRef]
13. Gamvroudis, C.; Dokou, Z.; Nikolaidis, N.P.; Karatzas, G.P. Impacts of Surface and Groundwater Variability Response to Future Climate Change Scenarios in a Large Mediterranean Watershed. *Environ. Earth Sci.* **2017**, *76*, 385. [CrossRef]
14. Mustafa, I. Methylene Blue Removal from Water Using H2SO4 Crosslinked Magnetic Chitosan Nanocomposite Beads. *Microchem. J.* **2019**, *144*, 397–402.
15. da Costa, A.M.; de Salis, H.H.C.; Viana, J.H.M.; Leal Pacheco, F.A. Groundwater Recharge Potential for Sustainable Water Use in Urban Areas of the Jequitiba River Basin, Brazil. *Sustainability* **2019**, *11*, 2955. [CrossRef]
16. Alam, S.; Gebremichael, M.; Li, R.; Dozier, J.; Lettenmaier, D.P. Climate Change Impacts on Groundwater Storage in the Central Valley, California. *Clim. Chang.* **2019**, *157*, 387–406. [CrossRef]

17. Weissinger, R.; Philippi, T.E.; Thoma, D. Linking Climate to Changing Discharge at Springs in Arches National Park, Utah, USA. *Ecosphere* **2016**, *7*, e01491. [CrossRef]
18. Tambe, S.; Kharel, G.; Arrawatia, M.L.; Kulkarni, H.; Mahamuni, K.; Ganeriwala, A.K. Reviving Dying Springs: Climate Change Adaptation Experiments from the Sikkim Himalaya. *Mt. Res. Dev.* **2012**, *32*, 62–72. [CrossRef]
19. Zhong, Y.; Hao, Y.; Huo, X.; Zhang, M.; Duan, Q.; Fan, Y.; Liu, Y.; Liu, Y.; Yeh, T.J. A Statistical Model for Karst Spring Discharge Estimation under Extensive Groundwater Development and Extreme Climate Change. *Hydrol. Sci. J.* **2016**, *61*, 2011–2023. [CrossRef]
20. Solder, J.E.; Stolp, B.J.; Heilweil, V.M.; Susong, D.D. Characterization of Mean Transit Time at Large Springs in the Upper Colorado River Basin, USA: A Tool for Assessing Groundwater Discharge Vulnerability. *Hydrogeol. J.* **2016**, *24*, 2017. [CrossRef]
21. Kurylyk, B.L.; MacQuarrie, K.T.B.; Caissie, D.; McKenzie, J.M. Shallow Groundwater Thermal Sensitivity to Climate Change and Land Cover Disturbances: Derivation of Analytical Expressions and Implications for Stream Temperature Modeling. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2469–2489. [CrossRef]
22. Amanambu, A.C.; Obarein, O.A.; Mossa, J.; Li, L.; Ayeni, S.S.; Balogun, O.; Oyebamiji, A.; Ochege, F.U. Groundwater System and Climate Change: Present Status and Future Considerations. *J. Hydrol.* **2020**, *589*, 125163. [CrossRef]
23. Fu, G.; Crosbie, R.S.; Barron, O.; Charles, S.P.; Dawes, W.; Shi, X.; Van Niel, T.; Li, C. Attributing Variations of Temporal and Spatial Groundwater Recharge: A Statistical Analysis of Climatic and Non-Climatic Factors. *J. Hydrol.* **2019**, *568*, 816–834. [CrossRef]
24. Kløve, B.; Ala-Aho, P.; Bertrand, G.; Gurdak, J.J.; Kupfersberger, H.; Kværner, J.; Muotka, T.; Mykrä, H.; Preda, E.; Rossi, P. Climate Change Impacts on Groundwater and Dependent Ecosystems. *J. Hydrol.* **2014**, *518*, 250–266. [CrossRef]
25. Oliveira, P.T.S.; Leite, M.B.; Mattos, T.; Nearing, M.A.; Scott, R.L.; de Oliveira Xavier, R.; da Silva Matos, D.M.; Wendland, E. Groundwater Recharge Decrease with Increased Vegetation Density in the Brazilian Cerrado. *Ecohydrology* **2017**, *10*, e1759. [CrossRef]
26. Owuor, S.O.; Butterbach-Bahl, K.; Guzha, A.C.; Rufino, M.C.; Pelster, D.E.; Díaz-Pinés, E.; Breuer, L. Groundwater Recharge Rates and Surface Runoff Response to Land Use and Land Cover Changes in Semi-Arid Environments. *Ecol. Process.* **2016**, *5*, 16. [CrossRef]
27. Kundu, S.; Khare, D.; Mondal, A. Past, Present and Future Land Use Changes and Their Impact on Water Balance. *J. Environ. Manag.* **2017**, *197*, 582–596. [CrossRef]
28. Merz, C.; Lischeid, G. Multivariate Analysis to Assess the Impact of Irrigation on Groundwater Quality. *Environ. Earth Sci.* **2019**, *78*, 274. [CrossRef]
29. McGill, B.M.; Altchenko, Y.; Hamilton, S.K.; Kenabatho, P.K.; Sylvester, S.R.; Villholth, K.G. Complex Interactions between Climate Change, Sanitation, and Groundwater Quality: A Case Study from Ramotswa, Botswana. *Hydrogeol. J.* **2019**, *27*, 997–1015. [CrossRef]
30. Pulido-Velazquez, M.; Peña-Haro, S.; García-Prats, A.; Mocholi-Almudever, A.F.; Henríquez-Dole, L.; Macian-Sorribes, H.; Lopez-Nicolas, A. Integrated Assessment of the Impact of Climate and Land Use Changes on Groundwater Quantity and Quality in the Mancha Oriental System (Spain). *Hydrol. Earth Syst. Sci.* **2015**, *19*, 1677–1693. [CrossRef]
31. Romanazzi, A.; Gentile, F.; Polemio, M. Modeling and Management of a Mediterranean Karstic Coastal Aquifer under the Effects of Seawater Intrusion and Climate Change. *Environ. Earth Sci.* **2015**, *74*, 115–128. [CrossRef]
32. Knott, J.F.; Jacobs, J.M.; Daniel, J.S.; Kirshen, P. Modeling Groundwater Rise Caused by Sea-Level Rise in Coastal New Hampshire. *J. Coast. Res.* **2019**, *35*, 143–157.
33. Dong, Y.; Jiang, C.; Suri, M.R.; Pee, D.; Meng, L.; Goldstein, R.E.R. Groundwater Level Changes with a Focus on Agricultural Areas in the Mid-Atlantic Region of the United States, 2002–2016. *Environ. Res.* **2019**, *171*, 193–203. [CrossRef] [PubMed]
34. Kambale, J.B.; Singh, D.K.; Sarangi, A. Impact of Climate Change on Groundwater Recharge in a Semi-Arid Region of Northern India. *Appl. Ecol. Environ. Res.* **2017**, *15*, 335–362. [CrossRef]
35. Brauman, K.A.; Richter, B.D.; Postel, S.; Malsy, M.; Flörke, M. Water Depletion: An Improved Metric for Incorporating Seasonal and Dry-Year Water Scarcity into Water Risk Assessments. *Elementa* **2016**, *4*, 83. [CrossRef]
36. Tosi, L.; Strozzi, T.; Da Lio, C.; Teatini, P. Regional and Local Land Subsidence at the Venice Coastland by TerraSAR-X PSI. *Proc. Int. Assoc. Hydrol. Sci.* **2015**, *372*, 199–205. [CrossRef]
37. Zhu, L.; Gong, H.; Li, X.; Wang, R.; Chen, B.; Dai, Z.; Teatini, P. Land Subsidence Due to Groundwater Withdrawal in the Northern Beijing Plain, China. *Eng. Geol.* **2015**, *193*, 243–255. [CrossRef]
38. Ghazifard, A.; Moslehi, A.; Safaei, H.; Roostaei, M. Effects of Groundwater Withdrawal on Land Subsidence in Kashan Plain, Iran. *Bull. Eng. Geol. Environ.* **2016**, *75*, 1157–1168. [CrossRef]
39. Faunt, C.C.; Sneed, M.; Traum, J.; Brandt, J.T. Water Availability and Land Subsidence in the Central Valley, California, USA. *Hydrogeol. J.* **2016**, *24*, 675. [CrossRef]
40. Li, R.; Merchant, J.W. Modeling Vulnerability of Groundwater to Pollution under Future Scenarios of Climate Change and Biofuels-Related Land Use Change: A Case Study in North Dakota, USA. *Sci. Total Environ.* **2013**, *447*, 32–45. [CrossRef]
41. Luoma, S.; Okkonen, J.; Korkka-Niemi, K. Comparison of the AVI, Modified SINTACS and GALDIT Vulnerability Methods under Future Climate-Change Scenarios for a Shallow Low-Lying Coastal Aquifer in Southern Finland. *Hydrogeol. J.* **2017**, *25*, 203–222. [CrossRef]
42. Seeboonruang, U. Impact Assessment of Climate Change on Groundwater and Vulnerability to Drought of Areas in Eastern Thailand. *Environ. Earth Sci.* **2016**, *75*, 42. [CrossRef]

43. Chang, S.W.; Nemec, K.; Kalin, L.; Clement, T.P. Impacts of Climate Change and Urbanization on Groundwater Resources in a Barrier Island. *J. Environ. Eng.* **2016**, *142*, D4016001. [CrossRef]
44. De Sherbinin, A.; Bukvic, A.; Rohat, G.; Gall, M.; McCusker, B.; Preston, B.; Apotsos, A.; Fish, C.; Kienberger, S.; Muhonda, P. Climate Vulnerability Mapping: A Systematic Review and Future Prospects. *Wiley Interdiscip. Rev. Clim. Chang.* **2019**, *10*, e600. [CrossRef]
45. Leterme, B.; Mallants, D. Climate and Land Use Change Impacts on Groundwater Recharge. *Proc. Model CARE* **2011**, *355*, 313–319.
46. Scibek, J.; Allen, D.M. Modeled Impacts of Predicted Climate Change on Recharge and Groundwater Levels. *Water Resour. Res.* **2006**, *42*, 1–18. [CrossRef]
47. Toews, M.W.; Allen, D.M. Simulated Response of Groundwater to Predicted Recharge in a Semi-Arid Region Using a Scenario of Modelled Climate Change. *Environ. Res. Lett.* **2009**, *4*, 35003. [CrossRef]
48. Soltani, F.; Javadi, S.; Roozbahani, A.; Massah Bavani, A.R.; Golmohammadi, G.; Berndtsson, R.; Ghordoyee Milan, S.; Maghsoudi, R. Assessing Climate Change Impact on Water Balance Components Using Integrated Groundwater—Surface Water Models (Case Study: Shazand Plain, Iran). *Water* **2023**, *15*, 813. [CrossRef]
49. Sarkar, S.; Mukherjee, A.; Senapati, B.; Duttagupta, S. Predicting Potential Climate Change Impacts on Groundwater Nitrate Pollution and Risk in an Intensely Cultivated Area of South Asia. *ACS Environ. Au* **2022**, *2*, 556–576. [CrossRef]
50. Herrera-Pantoja, M.; Hiscock, K.M. The Effects of Climate Change on Potential Groundwater Recharge in Great Britain. *Hydrol. Process. Int. J.* **2008**, *22*, 73–86. [CrossRef]
51. Mizyed, N. Climate Change Challenges to Groundwater Resources: Palestine as a Case Study. *J. Water Resour. Prot.* **2018**, *10*, 215–229. [CrossRef]
52. Kalugin, A.S. The Impact of Climate Change on Surface, Subsurface, and Groundwater Flow: A Case Study of the Oka River (European Russia). *Water Resour.* **2019**, *46*, S31–S39. [CrossRef]
53. Soundala, P.; Saraphirom, P. Impact of Climate Change on Groundwater Recharge and Salinity Distribution in the Vientiane Basin, Lao PDR. *J. Water Clim. Chang.* **2022**, *13*, 3812–3829. [CrossRef]
54. Ghazavi, R.; Ebrahimi, H. Predicting the Impacts of Climate Change on Groundwater Recharge in an Arid Environment Using Modeling Approach. *Int. J. Clim. Chang. Strateg. Manag.* **2018**, *11*, 88–99. [CrossRef]
55. Joshi, N.; Rahaman, M.M.; Thakur, B.; Shrestha, A.; Kalra, A.; Gupta, R. Assessing the effects of climate variability on groundwater in Northern India. In Proceedings of the World Environmental and Water Resources Congress 2020, Henderson, Nevada, 17–21 May 2020; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 41–52.
56. Olarinoye, T.; Foppen, J.W.; Veerbeek, W.; Morienyane, T.; Komakech, H. Exploring the Future Impacts of Urbanization and Climate Change on Groundwater in Arusha, Tanzania. In *Groundwater*; Routledge: Abingdon, UK, 2023; pp. 79–93.
57. Yang, J.-S.; Jeong, Y.-W.; Agossou, A.; Sohn, J.-S.; Lee, J.-B. GALDIT Modification for Seasonal Seawater Intrusion Mapping Using Multi Criteria Decision Making Methods. *Water* **2022**, *14*, 2258. [CrossRef]
58. Ghosh, R.; Sutradhar, S.; Mondal, P.; Das, N. Application of DRASTIC Model for Assessing Groundwater Vulnerability: A Study on Birbhum District, West Bengal, India. *Model. Earth Syst. Environ.* **2021**, *7*, 1225–1239. [CrossRef]
59. Rukmana, B.T.S.; Bargawa, W.S.; Cahyadi, T.A. Assessment of Groundwater Vulnerability Using GOD Method. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *477*, 012020. [CrossRef]
60. Ducci, D.; Sellerino, M. A Modified AVI Model for Groundwater Vulnerability Mapping: Case Studies in Southern Italy. *Water* **2022**, *14*, 248. [CrossRef]
61. Waikar, M.L.; Somwanshi, M.A. Data Preparation For Assessing Impact Of Climate Change On Groundwater Recharge. *Int. J. Innov. Res. Adv. Eng.* **2014**, *1*, 15–21.
62. Manish, K.; Telwala, Y.; Nautiyal, D.C.; Pandit, M.K. Modeling the Impacts of Future Climate Change on Plant Communities in the Himalaya: A Case Study from Eastern Himalaya, India. *Model. Earth Syst. Environ.* **2016**, *2*, 92. [CrossRef]
63. Crosbie, R.S.; Scanlon, B.R.; Mpelasoka, F.S.; Reedy, R.C.; Gates, J.B.; Zhang, L. Potential Climate Change Effects on Groundwater Recharge in the High Plains Aquifer, USA. *Water Resour. Res.* **2013**, *49*, 3936–3951. [CrossRef]
64. Nyenje, P.M.; Batelaan, O. Estimating the Effects of Climate Change on Groundwater Recharge and Baseflow in the Upper Ssezibwa Catchment, Uganda. *Hydrol. Sci. J.* **2009**, *54*, 713–726. [CrossRef]
65. Niu, G.; Yang, Z.; Mitchell, K.E.; Chen, F.; Ek, M.B.; Barlage, M.; Kumar, A.; Manning, K.; Niyogi, D.; Rosero, E. The Community Noah Land Surface Model with Multiparameterization Options (Noah-MP): 1. Model Description and Evaluation with Local-scale Measurements. *J. Geophys. Res. Atmos.* **2011**, *116*, 1–19. [CrossRef]
66. Banda, V.D.; Dzwairo, R.B.; Singh, S.K.; Kanyerere, T. Hydrological Modeling and Climate Adaptation under Changing Climate: A Review with a Focus in Sub-Saharan Africa. *Water* **2022**, *14*, 4031. [CrossRef]
67. Hrachowitz, M.; Savenije, H.H.G.; Blöschl, G.; McDonnell, J.J.; Sivapalan, M.; Pomeroy, J.W.; Arheimer, B.; Blume, T.; Clark, M.P.; Ehret, U. A Decade of Predictions in Ungauged Basins (PUB)—A Review. *Hydrol. Sci. J.* **2013**, *58*, 1198–1255. [CrossRef]
68. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Stationarity Is Dead: Whither Water Management? *Science* **2008**, *319*, 573–574. [CrossRef] [PubMed]
69. Clark, M.P.; Fan, Y.; Lawrence, D.M.; Adam, J.C.; Bolster, D.; Gochis, D.J.; Hooper, R.P.; Kumar, M.; Leung, L.R.; Mackay, D.S. Improving the Representation of Hydrologic Processes in Earth System Models. *Water Resour. Res.* **2015**, *51*, 5929–5956. [CrossRef]
70. Moges, E.; Demissie, Y.; Larsen, L.; Yassin, F. Sources of Hydrological Model Uncertainties and Advances in Their Analysis. *Water* **2021**, *13*, 28. [CrossRef]

71. Flato, G.; Marotzke, J.; Abiodun, B.; Braconnot, P.; Chou, S.C.; Collins, W.; Cox, P.; Driouech, F.; Emori, S.; Eyring, V. Evaluation of Climate Models. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 741–866.
72. Swenson, S.C.; Lawrence, D.M. Assessing a Dry Surface Layer-based Soil Resistance Parameterization for the Community Land Model Using GRACE and FLUXNET-MTE Data. *J. Geophys. Res. Atmos.* **2014**, *119*, 10–299. [CrossRef]
73. LeCun, Y.; Bengio, Y.; Hinton, G. Deep Learning. *Nature* **2015**, *521*, 436–444. [CrossRef]
74. Verburg, P.H.; Erb, K.-H.; Mertz, O.; Espindola, G. Land System Science: Between Global Challenges and Local Realities. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 433–437. [CrossRef]
75. Dembélé, M.; Salvadore, E.; Zwart, S.; Ceperley, N.; Mariéthoz, G.; Schaefli, B. Water Accounting under Climate Change in the Transboundary Volta River Basin with a Spatially Calibrated Hydrological Model. *J. Hydrol.* **2023**, *626*, 130092. [CrossRef]
76. Swain, S.; Taloor, A.K.; Dhal, L.; Sahoo, S.; Al-Ansari, N. Impact of Climate Change on Groundwater Hydrology: A Comprehensive Review and Current Status of the Indian Hydrogeology. *Appl. Water Sci.* **2022**, *12*, 120. [CrossRef]
77. Crosbie, R.S.; McCallum, J.L.; Walker, G.R.; Chiew, F.H.S. Modeling Climate-Change Impacts on Groundwater Recharge in the Murray-Darling Basin, Australia. *Hydrogeol. J.* **2010**, *18*, 1639–1656. [CrossRef]
78. Aslam, R.A.; Shrestha, S.; Pandey, V.P. Groundwater Vulnerability to Climate Change: A Review of the Assessment Methodology. *Sci. Total Environ.* **2018**, *612*, 853–875. [CrossRef] [PubMed]
79. Jia, X.; Hou, D.; Wang, L.; O'Connor, D.; Luo, J. The development of groundwater research in the past 40 years: A burgeoning trend in groundwater depletion and sustainable management. *J. Hydrol.* **2020**, *587*, 125006. [CrossRef]
80. Forero-Ortiz, E.; Martínez-Gomariz, E.; Monjo, R. Climate Change Implications for Water Availability: A Case Study of Barcelona City. *Sustainability* **2020**, *12*, 1779. [CrossRef]
81. Bhunia, G.S.; Chatterjee, U. Chapter 15—Ground Water Depletion and Climate Change: Role of Geospatial Technology for a Mitigation Strategy. In *Climate Change, Community Response and Resilience*; Chatterjee, U., Shaw, R., Bhunia, G.S., Setiawati, M.D., Banerjee, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Volume 6, pp. 291–304. ISBN 978-0-443-18707-0.
82. Goderniaux, P.; Brouyére, S.; Blenkinsop, S.; Burton, A.; Fowler, H.J.; Orban, P.; Dassargues, A. Modeling Climate Change Impacts on Groundwater Resources Using Transient Stochastic Climatic Scenarios. *Water Resour. Res.* **2011**, *47*, 1–17. [CrossRef]
83. Tootoonchi, F.; Todorović, A.; Grabs, T.; Teutschbein, C. Uni- and Multivariate Bias Adjustment of Climate Model Simulations in Nordic Catchments: Effects on Hydrological Signatures Relevant for Water Resources Management in a Changing Climate. *J. Hydrol.* **2023**, *623*, 129807. [CrossRef]
84. Di Salvo, C. Groundwater Hydrological Model Simulation. *Water* **2023**, *15*, 822. [CrossRef]
85. Reinecke, R.; Müller Schmied, H.; Trautmann, T.; Seaby Andersen, L.; Burek, P.; Flörke, M.; Gosling, S.N.; Grillakis, M.; Hanasaki, N.; Koutroulis, A.; et al. Uncertainty of Simulated Groundwater Recharge at Different Global Warming Levels: A Global-Scale Multi-Model Ensemble Study. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 787–810. [CrossRef]
86. Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023.
87. Shukla, P.R.; Skea, J.; Slade, R.; Al Khourdajie, A.; van Diemen, R.; McCollum, D.; Pathak, M.; Some, S.; Vyas, P.; Fradera, R.; et al. (Eds.) IPCC Summary for Policymakers Sixth Assessment Report (WG3). In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; ISBN 9781107415416.
88. Benini, L.; Antonellini, M.; Laghi, M.; Mollema, P.N. Assessment of Water Resources Availability and Groundwater Salinization in Future Climate and Land Use Change Scenarios: A Case Study from a Coastal Drainage Basin in Italy. *Water Resour. Manag.* **2016**, *30*, 731–745. [CrossRef]
89. Giordano, M. Global Groundwater? Issues and Solutions. *Annu. Rev. Environ. Resour.* **2009**, *34*, 153–178. [CrossRef]
90. Mc, M. Climate Change Impacts on Groundwater: Literature Review. *Environ. Risk Assess. Remediat.* **2017**, *2*, 16. [CrossRef]
91. Lal, M.; Sau, B.L.; Patidar, J.; Patidar, A. Climate Change and Groundwater: Impact, Adaptation and Sustainable. *Int. J. Bio-Resour. Stress Manag.* **2018**, *9*, 408–415. [CrossRef]
92. Zume, J.T.; Tarhule, A.A. Modeling the Response of an Alluvial Aquifer to Anthropogenic and Recharge Stresses in the United States Southern Great Plains. *J. Earth Syst. Sci.* **2011**, *120*, 557–572. [CrossRef]
93. Shah, T.; Molden, D.; Sakthivadivel, R.; Seckler, D. *The Global Groundwater Situation: Overview of Opportunities and Challenges*; International Water Management Institute: Colombo, Sri Lanka, 2000.
94. Kenda, K.; Čerin, M.; Bogataj, M.; Senožetnik, M.; Klemen, K.; Pergar, P.; Laspidou, C.; Mladenić, D. Groundwater Modeling with Machine Learning Techniques: Ljubljana polje Aquifer. *Proceedings* **2018**, *2*, 697.
95. Riedel, T. Temperature-Associated Changes in Groundwater Quality. *J. Hydrol.* **2019**, *572*, 206–212. [CrossRef]
96. McNeill, V.F. Atmospheric Aerosols: Clouds, Chemistry, and Climate. *Annu. Rev. Chem. Biomol. Eng.* **2017**, *8*, 427–444. [CrossRef]
97. de Vries, F.W.T.P. Rice Production and Climate Change. In *Systems Approaches for Agricultural Development: Proceedings of the International Symposium on Systems Approaches for Agricultural Development, Bangkok, Thailand, 2–6 December 1991*; de Vries, F.P., Teng, P., Metselaar, K., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 1993; pp. 175–189. ISBN 978-94-011-2842-1.
98. Mitsch, W.J.; Bernal, B.; Nahlik, A.M.; Mander, Ü.; Zhang, L.; Anderson, C.J.; Jørgensen, S.E.; Brix, H. Wetlands, Carbon, and Climate Change. *Landsc. Ecol.* **2013**, *28*, 583–597. [CrossRef]

99. Lavell, A.; Oppenheimer, M.; Diop, C.; Hess, J.; Lempert, R.; Li, J.; Muir-Wood, R.; Myeong, S.; Moser, S.; Takeuchi, K. Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2012; pp. 25–64.
100. Earman, S.; Dettinger, M. Potential Impacts of Climate Change on Groundwater Resources—A Global Review. *J. Water Clim. Chang.* **2011**, *2*, 213–229. [CrossRef]
101. Gitz, V.; Meybeck, A.; Lipper, L.; De Young, C.; Braatz, S. Climate Change and Food Security: Risks and Responses. In *Food and Agriculture Organization of the United Nations (FAO) Report*; FAO: Rome, Italy, 2016; Volume 110.
102. Wallace, L.; Sundaram, B.; Ross, S.; Brodie, M.S.; Dawson, S.; Jaycock, J.; Stewart, G.; Furness, L. Vulnerability Assessment of Climate Change Impact on Groundwater Resources in Timor Leste. In *Australia Government Department of Climate Change and Energy Efficiency*; Geoscience Australia: Canberra, Australia, 2012; Volume 55.
103. Chattopadhyay, P.B.; Singh, V.S. Hydrochemical Evidences: Vulnerability of Atoll Aquifers in Western Indian Ocean to Climate Change. *Glob. Planet Chang.* **2013**, *106*, 123–140. [CrossRef]
104. Gosling, S.N.; Taylor, R.G.; Arnell, N.W.; Todd, M.C. A Comparative Analysis of Projected Impacts of Climate Change on River Runoff from Global and Catchment-Scale Hydrological Models. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 279–294. [CrossRef]
105. Patle, G.T.; Singh, D.K.; Sarangi, A.; Sahoo, R.N. Modeling of Groundwater Recharge Potential from Irrigated Paddy Field under Changing Climate. *Paddy Water Environ.* **2017**, *15*, 413–423. [CrossRef]
106. Sishodia, R.P.; Shukla, S.; Wani, S.P.; Graham, W.D.; Jones, J.W. Future Irrigation Expansion Outweigh Groundwater Recharge Gains from Climate Change in Semi-Arid India. *Sci. Total Environ.* **2018**, *635*, 725–740. [CrossRef]
107. Dangar, S.; Asoka, A.; Mishra, V. Causes and Implications of Groundwater Depletion in India: A Review. *J. Hydrol.* **2021**, *596*, 126103. [CrossRef]
108. Ferrant, S.; Caballero, Y.; Perrin, J.; Gascoin, S.; Dewandel, B.; Aulong, S.; Dazin, F.; Ahmed, S.; Maréchal, J.C. Projected Impacts of Climate Change on Farmers' Extraction of Groundwater from Crystalline Aquifers in South India. *Sci. Rep.* **2014**, *4*, 3697. [CrossRef]
109. Nayak, S.K.; Nandimandalam, J.R. Impacts of Climate Change and Coastal Salinization on the Environmental Risk of Heavy Metal Contamination along the Odisha Coast, India. *Environ. Res.* **2023**, *238*, 117175. [CrossRef]
110. Wojkowski, J.; Wałęga, A.; Młyński, D.; Radecki-Pawlik, A.; Lepeška, T.; Piniewski, M.; Kundzewicz, Z.W. Are We Losing Water Storage Capacity Mostly Due to Climate Change—Analysis of the Landscape Hydric Potential in Selected Catchments in East-Central Europe. *Ecol. Indic.* **2023**, *154*, 110913. [CrossRef]
111. Bennour, A.; Jia, L.; Menenti, M.; Zheng, C.; Zeng, Y.; Barnieh, B.A.; Jiang, M. Assessing Impacts of Climate Variability and Land Use/Land Cover Change on the Water Balance Components in the Sahel Using Earth Observations and Hydrological Modeling. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101370. [CrossRef]
112. Anurag, H.; Ng, G.H.C. Assessing future climate change impacts on groundwater recharge in Minnesota. *J. Hydrol.* **2022**, *612*, 128112. [CrossRef]
113. Adhikari, R.K.; Yilmaz, A.G.; Mainali, B.; Dyson, P.; Imteaz, M.A. Methods of Groundwater Recharge Estimation under Climate Change: A Review. *Sustainability* **2022**, *14*, 15619. [CrossRef]
114. Hughes, A.; Mansour, M.; Ward, R.; Kieboom, N.; Allen, S.; Seccombe, D.; Charlton, M.; Prudhomme, C. The Impact of Climate Change on Groundwater Recharge: National-Scale Assessment for the British Mainland. *J. Hydrol.* **2021**, *598*, 126336. [CrossRef]
115. Nerem, R.S.; Beckley, B.D.; Fasullo, J.T.; Hamlington, B.D.; Masters, D.; Mitchum, G.T. Climate-Change–Driven Accelerated Sea-Level Rise Detected in the Altimeter Era. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 2022–2025. [CrossRef]
116. Esteban, M.; Takagi, H.; Jamero, L.; Chadwick, C.; Avelino, J.E.; Mikami, T.; Fatma, D.; Yamamoto, L.; Thao, N.D.; Onuki, M. Adaptation to Sea Level Rise: Learning from Present Examples of Land Subsidence. *Ocean. Coast. Manag.* **2020**, *189*, 104852. [CrossRef]
117. Liu, Y.; Li, J.; Fasullo, J.; Galloway, D.L. Land Subsidence Contributions to Relative Sea Level Rise at Tide Gauge Galveston Pier 21, Texas. *Sci. Rep.* **2020**, *10*, 17905. [CrossRef]
118. Wang, G.; Zhou, X.; Wang, K.; Ke, X.; Zhang, Y.; Zhao, R.; Bao, Y. GOM20: A Stable Geodetic Reference Frame for Subsidence, Faulting, and Sea-Level Rise Studies along the Coast of the Gulf of Mexico. *Remote Sens.* **2020**, *12*, 350. [CrossRef]
119. Tay, C.; Lindsey, E.O.; Chin, S.T.; McCaughey, J.W.; Bekaert, D.; Nguyen, M.; Hua, H.; Manipon, G.; Karim, M.; Horton, B.P. Sea-Level Rise from Land Subsidence in Major Coastal Cities. *Nat. Sustain.* **2022**, *5*, 1049–1057. [CrossRef]
120. Liu, Y.; Rashvand, M.; Li, J. Preliminary Investigation of Land Subsidence Impacts on Sea Level Change in Baltimore Inner Harbor, Maryland. In Proceedings of the World Environmental and Water Resources Congress 2020, Henderson, Nevada, 17–21 May 2020; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 236–243.
121. Ng, G.H.C.; McLaughlin, D.; Entekhabi, D.; Scanlon, B.R. Probabilistic Analysis of the Effects of Climate Change on Groundwater Recharge. *Water Resour. Res.* **2010**, *46*, 1–18. [CrossRef]
122. Wood, W.W.; Imes, J.L. Dating of Holocene Ground-Water Recharge in Western Part of Abu Dhabi (United Arab Emirates): Constraints on Global Climate-Change Models. In *Developments in Water Science*; Alsharhan, A.S., Wood, W.W., Eds.; Elsevier: Amsterdam, The Netherlands, 2003; Volume 50, pp. 379–385. ISBN 0167-5648.
123. Wu, W.Y.; Lo, M.H.; Wada, Y.; Famiglietti, J.S.; Reager, J.T.; Yeh, P.J.F.; Ducharne, A.; Yang, Z.L. Divergent Effects of Climate Change on Future Groundwater Availability in Key Mid-Latitude Aquifers. *Nat. Commun.* **2020**, *11*, 3710. [CrossRef]

124. Rajaee, T.; Khani, S.; Ravansalar, M. Artificial Intelligence-Based Single and Hybrid Models for Prediction of Water Quality in Rivers: A Review. *Chemom. Intell. Lab. Syst.* **2020**, *200*, 103978. [CrossRef]
125. Zounemat-Kermani, M.; Batelaan, O.; Fadaee, M.; Hinkelmann, R. Ensemble Machine Learning Paradigms in Hydrology: A Review. *J. Hydrol.* **2021**, *598*, 126266. [CrossRef]
126. Aboutalebi, M.; Torres-Rua, A.F.; McKee, M.; Kustas, W.P.; Nieto, H.; Alsina, M.M.; White, A.; Prueger, J.H.; McKee, L.; Alfieri, J. Incorporation of Unmanned Aerial Vehicle (UAV) Point Cloud Products into Remote Sensing Evapotranspiration Models. *Remote Sens.* **2019**, *12*, 50. [CrossRef]
127. Majumdar, S.; Smith, R.; Butler, J.J., Jr.; Lakshmi, V. Groundwater Withdrawal Prediction Using Integrated Multitemporal Remote Sensing Data Sets and Machine Learning. *Water Resour. Res.* **2020**, *56*, e2020WR028059. [CrossRef]
128. Golden, J.; O'Malley, D.; Viswanathan, H. Quantum Computing and Preconditioners for Hydrological Linear Systems. *Sci. Rep.* **2022**, *12*, 22285. [CrossRef]
129. O'Malley, D. An Approach to Quantum-Computational Hydrologic Inverse Analysis. *Sci. Rep.* **2018**, *8*, 6919. [CrossRef]
130. Gleick, P.H. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. *Science* **2003**, *302*, 1524–1528. [CrossRef]
131. Bates, B.; Kundzewicz, Z.; Wu, S. *Climate Change and Water*; Intergovernmental Panel on Climate Change Secretariat: Geneva, Switzerland, 2008; ISBN 9291691232.
132. Boretti, A.; Rosa, L. Reassessing the Projections of the World Water Development Report. *NPJ Clean Water* **2019**, *2*, 15. [CrossRef]
133. Pahl-Wostl, C. A Conceptual Framework for Analysing Adaptive Capacity and Multi-Level Learning Processes in Resource Governance Regimes. *Glob. Environ. Chang.* **2009**, *19*, 354–365. [CrossRef]
134. Gerber, J.-D.; Knoepfel, P.; Nahrath, S.; Varone, F. Institutional Resource Regimes: Towards Sustainability through the Combination of Property-Rights Theory and Policy Analysis. *Ecol. Econ.* **2009**, *68*, 798–809. [CrossRef]
135. Tsur, Y. Economic Aspects of Irrigation Water Pricing. *Can. Water Resour. J.* **2005**, *30*, 31–46. [CrossRef]
136. Postel, S.; Richter, B. *Rivers for Life: Managing Water for People and Nature*; Island Press: Washington, DC, USA, 2012; ISBN 1597267805.