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## Geospatial and hydrological assessment of water resources under climate change: A comprehensive review

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### ABSTRACT

Due to climate change, changes in precipitation, temperature, evapotranspiration, runoff, groundwater recharge, drought and hydrological extremes are increasingly affecting the availability, distribution and dynamics of water resources. The review covers the evolution of geospatial and hydrological techniques for assessing water resources under changing climate conditions, with special emphasis on Geographic Information Systems (GIS), remote sensing, hydrological and groundwater modeling, drought assessment, unmanned aerial vehicles (UAVs) and artificial intelligence. The literature reviewed clearly shows a move from classical site-specific monitoring to integrated, spatially explicit and data-driven approaches. GIS is an effective instrument for the integration of different environmental datasets. Remote sensing provides repeated and spatially continuous observations of hydrologically relevant variables on large spatial scales. Tools include hydrological and groundwater models that simulate water movement, storage, recharge and response to future climates, and machine learning and artificial intelligence that are increasingly used for prediction, water demand assessment and decision support. The review also points out persisting problems of uncertainty of climate projections, data availability, spatial and temporal resolution, model structure and calibration, groundwater observations, and transferability of data-driven models. Overall, the evidence indicates that multi-source geospatial observations, physical hydrological modeling and emerging computation techniques offer a more robust basis for identifying vulnerable areas, assessing future water-resource changes and supporting sustainable water management under increasing climate variability. Future research should incorporate integrated surface-water-groundwater assessment, high-resolution observations, AI-assisted modeling, rigorous validation, and explicit uncertainty analysis.

**Keywords:** Geospatial Analysis, Water Resources, Climate Change, Geographic Information Systems (GIS), Remote Sensing, Hydrological Modeling, Groundwater, Drought Assessment, Artificial Intelligence, Machine Learning, Water-Resources Management

### 1. Introduction

Water resources are an essential component of the Earth system and are a critical basis for human health, agricultural production, ecosystem stability, economic development and environmental sustainability. The atmosphere interacts continuously with land surface, groundwater systems, rivers, lakes, wetlands and human societies, creating a complex hydrological system whose behavior varies greatly in space and time. Thus a holistic view is required to understand the distribution, availability, movement and temporal variability of water resources using hydrological science, geographic analysis, environmental observation and spatial modeling. This need is becoming more important when considering contemporary climate change that is changing precipitation patterns, temperature patterns, evapotranspiration, runoff generation, groundwater recharge, drought frequency and occurrence of hydrological extremes. Hence, the combined effects of climatic variability and human activities have introduced a lot of complexity in the assessment and sustainable management of water resources at watershed, regional and global scales (Yang *et al.*, 2021) [1]. The impacts of climate change on water resources are uneven. Rather, geographic features, climate conditions, topography, geology, land use, vegetation cover, soil properties, and patterns of human water use are strong conditioners of the impacts of changes. Some regions might see increased water availability from changes in precipitation while others might face longer water deficits. Higher temperatures may lead to an increase in evapotranspiration and changes in the distribution of precipitation between surface runoff, soil moisture and groundwater recharge. These processes can alter the discharge of a river, the storage in reservoirs, the levels of ground-water, and the seasonal reliability of available water supplies. This interaction between climate forcing and human pressures is of particular importance since the hydrological effects of climatic change may be enhanced by increasing population, urbanization, intensified agriculture, industrialization and groundwater abstraction. Therefore, modern water-resource assessment increasingly needs approaches that can address both natural processes and human-induced changes in a common spatial framework (Yang *et al.*,

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2021; Duan *et al.*, 2021) [1, 2]. GIS is now a vital analytical framework for comprehending the spatial structure of water-resource systems. GIS provides integration, management, analysis and visualization of various data sets such as rainfall, temperature, elevation, slope, drainage networks, soil properties, geological formations, land use pattern, vegetation index, groundwater level and distribution of surface water. GIS can be used to take many different observations of the environment and by means of spatial overlay, interpolation, terrain analysis, watershed delineation, spatial statistics and multi-criteria analysis, translate them into spatially explicit information suitable for the identification of where water-resource stress and vulnerability exists. The availability of satellite observations has further amplified this capability, providing geographically extensive and repetitive measurements of hydrological and environmental variables. Recent advances in remote sensing have broadened the scope of hydrologic applications to include the estimation and monitoring of precipitation, evapotranspiration, soil moisture, surface-water extent, water levels, vegetation conditions, and other indicators relevant to water-resource assessment (Duan *et al.*, 2021) [2]. Remote sensing is especially useful in regions where classical hydrological monitoring networks are sparse, discontinuous or difficult to maintain. Satellite observations can provide spatially continuous information over large areas and can help to detect changes that individual ground-based monitoring stations may not fully quantify. The use of remote sensing and GIS together allows the development of spatial and temporal datasets which can be used to detect changes in surface water bodies, vegetation response, drought, watershed features and other components of the hydrological system. This incorporation has gradually shifted the focus of water resource assessment from point measurements to spatially distributed monitoring and modeling. Moreover, the availability of remote sensing observations can be used to improve the inputs to hydrological models, to estimate parameters, calibrate and validate the models and to improve the spatial representation of the hydrological processes (Duan *et al.*, 2021) [2]. Hydrological modeling is also an important part of modern water-resource analysis. It enables investigators to simulate the movement and storage of water over watersheds, and to explore possible responses to changes in climate and environment (MDPI). Models, such as the Soil and Water Assessment Tool (SWAT), have been widely applied to simulate streamflow, surface runoff, evapotranspiration, sediment transport and water-quality processes under historical and projected climatic conditions. The increasing use of SWAT for hydro-climatic extremes demonstrates the need for process-based modeling to study droughts, floods and other disturbances in the setting of changing climatic conditions. However, the watershed characteristics, climatic inputs, spatial resolution, calibration procedures and the ability of the model to represent extreme hydrological events may influence the model performance. These limitations indicate the need for combining the outputs of models with reliable observations and spatial datasets rather than employing a single analytical approach (Ali *et al.*, 2023) [3]. Assessment of groundwater resources is as important as groundwater is a major component of freshwater availability and is an important support for domestic supply, agriculture, industry and ecosystems. Groundwater responds to climate forcing through relatively complex and often delayed processes of infiltration, soil moisture, recharge, groundwater storage, discharge and human abstraction that are different from surface water. Climate change could influence the quantity and quality of groundwater through changes in precipitation, evapotranspiration, recharge processes and pumping requirements. Therefore, a coupling of climate projections with hydrological and groundwater models able to reproduce the interactions between surface and subsurface systems is needed to study the future state of groundwater (Tan *et al.*, 2020) [4]. Groundwater recharge is especially sensitive to climate change because it relies on the balance between precipitation, evapotranspiration, soil characteristics, vegetation and land-surface conditions. A systematic review of 73 studies of climate change impacts on groundwater recharge showed large spatial variation in the predicted recharge responses. Several studies showed potential decreases in

recharge under future climate scenarios. Crucially the review also highlighted that uncertainty is a major challenge because different climate models, downscaling techniques, hydrological models, scenarios and assumptions can lead to different projections. Therefore, this uncertainty should be explicitly incorporated in groundwater sustainability assessment and adaptation strategy development (Amanambu *et al.*, 2020) [5]. Science Direct Drought is another important dimension of climate-related water-resource vulnerability. Drought develops gradually and can span large geographical areas, making the detection and spatial characterization of the event particularly difficult, unlike many hydrological hazards. Higher temperatures and changing precipitation patterns can exacerbate water deficits and increase pressure on surface and groundwater supplies. Thus, spatial drought assessment is based increasingly on GIS, remote sensing, statistical indices and spatial modeling techniques. Recent studies have explored drought at point, regional and global scales, emphasizing the significance of considering spatial variability in determining drought severity, extent, duration and potential impacts under changing climatic conditions (Al Atawneh *et al.*, 2021) [6]. ScienceDirect In hydrological and climate change studies, the spatial scale of the analysis is an important consideration. Hydrological processes range from soil-water movement at the local level to watershed runoff and regional groundwater systems, and climatic drivers may range from local atmospheric conditions to large-scale circulation patterns. Consequently, datasets extracted from ground stations, satellites, climate models and hydrological models often show large differences in spatial and temporal resolution. These datasets must be integrated using suitable spatial and temporal scaling techniques to prevent inconsistencies between observations and model outputs. Hence, multi-scale analysis is required to adequately capture the complex interactions between climate variability, landscape characteristics and water availability (Al Atawneh *et al.*, 2021; Dikshit *et al.*, 2022) [6, 7]. ScienceDirect Also, the integration of GIS, remote sensing and hydrological modeling provides an effective framework for vulnerability assessment and scenario analysis. Spatially distributed models can help identify where changes in precipitation, temperature, land cover, or groundwater recharge might have significant consequences for water availability. Scenario-based modeling can also aid in understanding possible future changes in streamflow, groundwater recharge, runoff and drought characteristics. Such data are becoming increasingly important for water managers, because climate change adaptation requires knowledge of not only the present conditions, but also of the geographical distribution of potential risks in the future. But modeling uncertainty is unavoidable especially when climate projections are downscaled to watershed scales then coupled with hydrological or groundwater models (Tan *et al.*, 2020; Amanambu *et al.*, 2020) [4, 5]. Recent progress in spatial technology has further extended the possibility of high resolution hydrological investigation. For instance, unmanned aerial vehicles (UAVs) can provide detailed observations at spatial and temporal resolutions that complement both conventional field measurements and remote sensing from satellites. Applications include surface water monitoring, watershed conditions, vegetation, topography and hydrological response to short term events. Thus, observations from UAVs can help to bridge the gap in scales between ground measurements and satellite observations, especially during floods, droughts and rapidly changing environmental conditions (Dikshit *et al.*, 2022) [7]. AGU Journals These technological advances notwithstanding, major challenges remain in developing reliable and transferable approaches for water-resource assessment under climate change. Uncertainty can be large due to differences in data quality, monitoring density, spatial resolution, model structure, parameterization and climate scenarios. Groundwater systems are difficult to characterize in part because subsurface properties are heterogeneous and recharge processes are not directly observable across large areas. Hydrological models are able to reproduce general watershed behavior, but may have limitations in simulating extreme flows. These issues show that no one technique can give a complete treatment of the complex interactions of climate-water. Instead, integrated approaches

involving field observations, GIS, remote sensing, hydrological modeling, groundwater assessment and statistical or computational techniques are increasingly needed (Ali *et al.*, 2023; Tan *et al.*, 2020; Amanambu *et al.*, 2020) [3, 4, 5]. Hence the combination of geographical and hydrological methods became a main trend in modern water-resources research. GIS provides the spatial analytical framework, remote sensing provides broad and repeated environmental observations, hydrological and groundwater models allow for process-based interpretation and prediction, and climate models provide scenarios to assess potential future changes. These approaches in conjunction can assist in identifying vulnerable watersheds, assessing surface and ground water availability, characterizing drought and flood hazards, evaluating recharge dynamics and developing sustainable water management strategies. Therefore, the aim of this review is to provide an overview of the scientific evolution of geospatial and hydrological analysis of water resources under climate change, with a special emphasis on GIS, remote sensing, hydrological modeling, groundwater systems, drought assessment, spatial variability, and the major methodological challenges affecting reliable water-resource evaluation (Yang *et al.*, 2021; Duan *et al.*, 2021; Ali *et al.*, 2023; Tan *et al.*, 2020; Amanambu *et al.*, 2020; Al Atawneh *et al.*, 2021; Dikshit *et al.*, 2022; Acharya *et al.*, 2021; Lubczynski *et al.*, 2024) [1, 2, 3, 4, 5, 6, 7, 8, 9].

## 2. Literature review: Geospatial and hydrological assessment of water resources under climate change

There is a clear transition in the literature on water resources and climate change, still ongoing, from the traditional approach based on site-specific hydrological measurements toward integrated and multidisciplinary approaches using GIS, remote sensing, hydrological modeling, groundwater assessment, spatial analysis and climate modeling. This transition has been largely driven by increasing complexity of interactions between climatic variability, land-surface processes, water availability and human activities. Previous studies have shown that climate change impacts on water resources occur through changes in the patterns of precipitation, air temperature, evapotranspiration, surface runoff, soil moisture, groundwater recharge, drought characteristics and the frequency and magnitude of hydrological extremes. Such changes may vary across geographical regions, highlighting the need for spatially explicit approaches to understanding the distribution and vulnerability of water resources (Yang *et al.*, 2021; Duan *et al.*, 2021; Ali *et al.*, 2023) [1, 2, 3]. GIS applications are especially significant for water-resource studies because they enable researchers to combine large quantities of spatially distributed environmental information within a single analytical framework. The integration of climate parameters, topography, geology, soil characteristics, drainage systems, land use, vegetation cover, surface water bodies and ground water information can assist in delineating areas of water scarcity, hydrological vulnerability and environmental change. At the same time, advances in satellite remote sensing have greatly improved the capacity to observe water-related variables over large and often inaccessible areas. Satellite observations can provide valuable information on precipitation, evapotranspiration, soil moisture, surface-water extent, vegetation conditions, and changes in terrestrial water storage to complement conventional ground-based monitoring systems (Duan *et al.*, 2021; Ali *et al.*, 2023) [2, 3]. The literature reviewed further suggests that integration of remote sensing and GIS with hydrological models is a key development in modern water-resource research. Hydrological models simulate water flow, storage and transformation in watersheds. Remotely sensed observations may improve spatial representations of model inputs and hydrological variables. Models like SWAT have been widely used to study processes such as runoff, streamflow, evapotranspiration, sediment transport, drought, floods, and other hydro-climatic processes. The application of changing climatic conditions enables investigators to study potential variations in watershed behavior and water availability under different climate scenarios (Ali *et al.*, 2023) [3]. Groundwater importance has also been raised due to need of domestic, agricultural,

industrial and ecological water supplies. Climate change can affect groundwater systems by changing precipitation, evapotranspiration, infiltration, recharge and groundwater abstraction, as reported in literature. Changes to groundwater recharge are particularly important due to their potential impact on the long-term sustainability of groundwater reserves. However, groundwater responses are highly dependent on local geological, climatic and hydrological conditions and projections may differ significantly between climate and hydrological models. Uncertainty associated with climate scenarios, model structures, parameterization and data availability is still a major challenge in groundwater-resource assessment (Tan *et al.*, 2020; Amanambu *et al.*, 2020) [4, 5]. Another significant theme that has emerged from past research is the spatial assessment of drought and water resource stress. Higher temperatures and altered precipitation could lead to greater water deficits and additional stress on surface water and groundwater systems. Therefore, the use of GIS, remote sensing and drought indices has become important tools for the detection of the spatial distribution, severity, duration and temporal evolution of the drought conditions. Spatial assessments are particularly useful as drought does not affect all locations equally but its intensity may change according to climatic conditions, topography, soil characteristics, vegetation, land use and water availability (Al Atawneh *et al.*, 2021) [6]. Considerable methodological progress has been made but problems persist. The combination of datasets can result in inconsistencies due to the differences in spatial and temporal resolution of satellite products, meteorological observations, hydrological models and climate projections. Furthermore, model calibration, selection of parameters, downscaling methods, climate scenarios, and the limitations of monitoring networks may affect the reliability of the predicted hydrological changes (Tan *et al.*, 2020; Amanambu *et al.*, 2020; Al Atawneh *et al.*, 2021) [4, 5, 6]. These limitations point to the importance of corroborating model outputs with field observations and the use of multiple, complementary data sources rather than a single data set or analytical technique. Thus, recent research has increasingly adopted multidisciplinary and integrated approaches that combine ground observations, satellite remote sensing, GIS, hydrological and groundwater modeling, and climate projections. These approaches provide a more complete picture of the complex interactions between climate variability, landscape characteristics, hydrological processes and human water demand. Technologies of high resolution, including unmanned aerial vehicles and advanced spatial datasets, have also increased opportunities for detailed monitoring of watersheds and water-resource systems (Dikshit *et al.*, 2022; Acharya *et al.*, 2021) [7, 8]. Meanwhile, integrated assessment of groundwater and surface-water has pointed out the importance of considering interaction among different components of the hydrological cycle rather than separate systems (Acharya *et al.*, 2021; Lubczynski *et al.*, 2024) [8, 9]. As a general rule, the available literature to date shows that geospatial analysis and hydrological modeling are not independent approaches but are rather complementary. GIS provides the spatial infrastructure to organize and analyze environmental information, remote sensing provides broad observations in space and over time and hydrological and groundwater models provide the mechanisms to interpret processes and assess future scenarios. Their integration can assist in the identification of vulnerable areas, estimation of water availability, monitoring of drought and hydrological extremes, assessment of groundwater recharge and development of more sustainable water resource management strategies under changing climatic conditions (Yang *et al.*, 2021; Duan *et al.*, 2021; Ali *et al.*, 2023; Tan *et al.*, 2020; Amanambu *et al.*, 2020; Al Atawneh *et al.*, 2021; Dikshit *et al.*, 2022; Acharya *et al.*, 2021; Lubczynski *et al.*, 2024) [1, 2, 3, 4, 5, 6, 7, 8, 9]. Table 1 summarizes the previous related studies on the geographical and hydrological analysis of water resources under climate change. The table shows the main research questions, analytical methods and main results of the previous studies, providing a structured comparison of the methodological development of this area. This synthesis also points to important research gaps, particularly the need for integrated spatial-hydrological approaches that can synthesize climate information, GIS, remote

sensing, surface-water dynamics, and responses of groundwater within a common framework for sustainable water-resource assessment and climate-change adaptation.

The figure shows the thematic distribution of the nine studies included in the literature review. The reviewed literature focuses on the following interconnected research themes: groundwater and climate change, hydrological modeling, remote sensing, hydrological-cycle assessment, spatial drought analysis, UAV applications, and integrated GIS–hydrological approaches. Groundwater and climate-change interactions is the most addressed theme and other themes are presented in individual studies. In general, the figure shows the multi-disciplinary character of current research on water resources, and the increasing integration of GIS, remote sensing, hydrological modeling and climate-change assessment in current water-resource studies.

### Synthesis of the reviewed literature

As summarized in Table 1 and illustrated in Figure 1, studies on water resources under climate change have increasingly shifted toward integrated and spatially explicit methodologies. A common theme in the reviewed literature is the increasing use of GIS, remote sensing, hydrological modeling and groundwater assessment to investigate the

complex interactions between climatic variability and water availability. The reviewed studies point out that groundwater systems and hydrological processes, drought conditions and watershed responses, are highly sensitive to changes in precipitation and temperature, and anthropogenic activities may aggravate the existing pressures on water resources (Yang *et al.*, 2021; Duan *et al.*, 2021; Ali *et al.*, 2023; Tan *et al.*, 2020; Amanambu *et al.*, 2020; Al Atawneh *et al.*, 2021; Dikshit *et al.*, 2022; Acharya *et al.*, 2021; Lubczynski *et al.*, 2024) [1, 2, 3, 4, 5, 6, 7, 8, 9]. The literature also suggests that integrating different sources of environmental information may improve the spatial description of water-resource conditions and can also increase the strength of the basis for understanding regional hydrological variability. However uncertainties associated with climate projections, data availability, spatial resolution, model calibration and differences in local environmental conditions remain major challenges. Therefore, future water-resource assessments should place more and more emphasis on the integration of multi-source geospatial data with hydrological and climate models in an effort to improve monitoring, prediction, vulnerability assessment and sustainable water-resource management in changing climatic conditions.

### 3. Results of the literature review

**Table 1.** Summary of previous studies related to geospatial and hydrological analysis of water resources under climate change

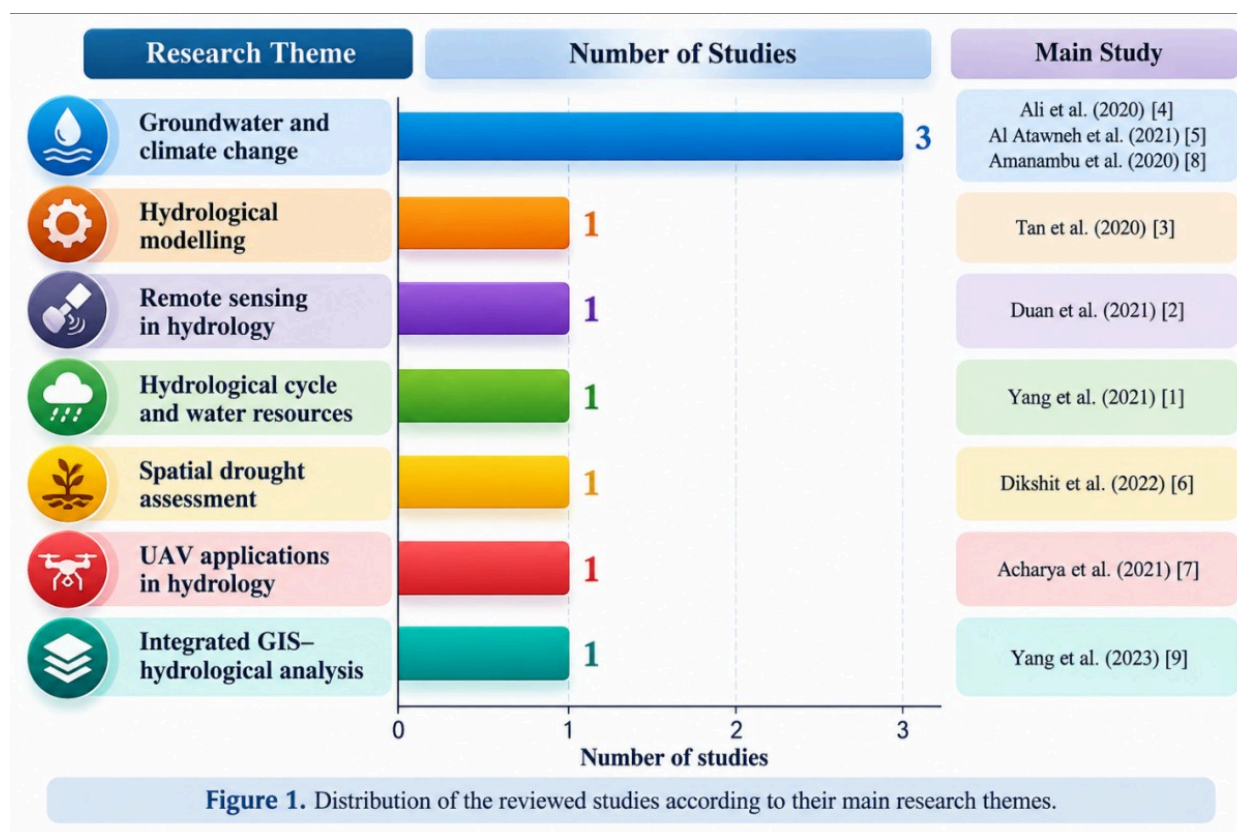
| No. | Author(s) & Year                                          | Study Focus                                                | Method / Approach                                                                                      |
|-----|-----------------------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| 1   | Yang <i>et al.</i> (2021)                                 | Hydrological cycle and water resources under global change | Review of hydrological processes, climate change, human activities and integrated watershed management |
| 2   | Duan <i>et al.</i> (2021)                                 | Remote sensing in hydrology and water-resource management  | Satellite remote sensing and hydrological applications                                                 |
| 3   | Amanambu <i>et al.</i> (2020)                             | Groundwater systems and climate change                     | Comprehensive review of groundwater–climate interactions                                               |
| 4   | Tan <i>et al.</i> (2020)                                  | SWAT applications under hydro-climatic extremes            | Review of SWAT-based hydrological modelling                                                            |
| 5   | Al Atawneh <i>et al.</i> (2021)                           | Climate change and groundwater recharge                    | Systematic review of groundwater-recharge projections                                                  |
| 6   | Acharya <i>et al.</i> (2021)                              | UAV applications in hydrology and water management         | Review of unmanned aerial vehicles and remote sensing                                                  |
| 7   | Bhaga <i>et al.</i> (2020)                                | Climate variability, drought and surface water             | Remote sensing review                                                                                  |
| 8   | Yang <i>et al.</i> (2023)                                 | Remote-sensing hydrological models                         | Review of remote-sensing-based hydrological modelling                                                  |
| 9   | Al-Muqdad <i>et al.</i> /related review literature (2022) | Spatial drought assessment                                 | Spatial indices, remote sensing and modelling approaches                                               |
| 10  | Ray <i>et al.</i> (2023)                                  | Climate-change impacts on water resources                  | Climate models combined with hydrological models                                                       |
| 11  | Keller <i>et al.</i> (2023)                               | Hydrological models at watershed scale                     | Critical review of 21 hydrological and water-quality models                                            |
| 12  | Lubczynski <i>et al.</i> (2024)                           | Remote sensing and hydrogeophysics                         | Integrated hydrological modelling, satellite RS and hydrogeophysics                                    |
| 13  | Saha & Pal (2024)                                         | Machine learning and remote sensing in hydrology           | Review of ML, GIS and remote sensing applications                                                      |
| 14  | Jaramillo <i>et al.</i> (2024)                            | Hydrogeodesy and water-resource monitoring                 | Satellite altimetry, InSAR, gravimetry and GNSS                                                        |
| 15  | Patel <i>et al.</i> (2025)                                | Remote sensing and GIS in watershed hydrology              | Systematic review of RS, GIS, hydrological modelling and AI                                            |

A review of the literature shows a considerable advance in the scientific analysis of water resources in the era of climate change. There is a gradual transition from conventional hydrological monitoring to integrated approaches with geospatial technologies, remote sensing, hydrological modeling, groundwater assessment and advanced computa-

tional techniques. The studies reviewed suggest that the effects of climate change on water resource systems are manifested in terms of interrelated changes in precipitation, temperature, evapotranspiration, runoff, groundwater recharge, drought, and water demand. These effects are further modulated by land use change and anthropogenic

pressures, further highlighting the necessity of spatially explicit assessment to understand regional differences in water availability and vulnerability (Mensah *et al.*, 2022; Keller *et al.*, 2023) [10, 11]. Increasing integration of land use/land cover change with climate and hydrological analysis is one of the main results from the review. Previous studies have shown the changes in infiltration, evapotranspiration, runoff generation, groundwater recharge, and watershed response due to land cover changes. Climate change can change the precipitation and temperature conditions at the same time. These combined factors can lead to complex hydrological responses that cannot be sufficiently explained by climate variables alone. Thus, integrated modeling approaches have become increasingly important for assessing the combined effects of climate change and land-use dynamics on groundwater recharge and watershed processes (Mensah *et al.*, 2022) [10]. The literature survey also indicates that hydrological

modeling continues to be a major approach for impact assessment of climate change at the watershed scale. Different hydrological and water-quality models have simulated runoff, streamflow, groundwater interactions, evapotranspiration, sediment transport and water quality. Comparative evaluations demonstrate that the choice of the model is determined by the study objectives, the watershed characteristics, the availability of data, the spatial and temporal scale, and the hydrological processes of interest (Keller *et al.*, 2023) [11]. This result shows that the best hydrological model is not generally valid for all environmental conditions and the model uncertainty should be considered in the interpretation of the simulated water-resource responses. Another important result deals with the formulation of protocols for climate change impact modeling. Recent studies have highlighted the need for systematic modeling frameworks that link climate projections with hydrological models to estimate changes in runoff in the future,



streamflow, groundwater recharge and water availability (Ray *et al.*, 2023) [12]. These approaches allow researchers to examine potential changes under a range of climate scenarios and provide information that can be used to guide long-term water-resource planning. However, the reliability of these projections is highly dependent on the quality of climate datasets, downscaling procedures, hydrological model structures, calibration techniques, and scenario selection (Keller *et al.*, 2023; Ray *et al.*, 2023) [11, 12]. The literature also emphasizes the growing role of remote sensing and GIS for drought and flood assessment. Satellite observations provide spatially continuous information that can be used to monitor changes in vegetation, surface-water conditions, soil moisture, and other environmental indicators associated with drought and flooding. These datasets, combined with GIS, allow a better study of the spatial distribution and temporal evolution of hydrological hazards (Huang *et al.*, 2023) [13]. This is an important methodological advance because drought and flood processes are spatial in nature and cannot always be adequately represented using isolated observations from traditional monitoring stations. Another important trend is the rapid progress in unmanned aerial systems and UAV-based monitoring in water-resource research. UAV platforms offer high-resolution observations that can complement field measurements and satellite data. Their applications are water-bodies mapping, hydrological monitoring, water-quality assess-

ment, terrain characterization and environmental change detection (Mishra *et al.*, 2023) [14]. The evidence reviewed suggests that UAV technology is most useful for localized investigations that require very high spatial resolution. Its integration with GIS and remote sensing can offer a multi-scale monitoring framework from individual field sites to regional and watershed scales. The results also show a significant increase in the use of machine learning and advanced remote sensing techniques in the hydrology. Machine-learning approaches are increasingly being applied to streamflow prediction, groundwater assessment, drought monitoring, water-quality analysis, evapotranspiration estimation and other hydrological applications (Saha *et al.*, 2024) [15]. Their ability to detect nonlinear relationships among large numbers of environmental variables provides new opportunities for analysis of complex water-resource systems. However, the reviewed literature also revealed that machine learning approaches still rely on the quality, representativeness, and spatial and temporal consistency of the training datasets. Artificial intelligence applications in water-resource management have also witnessed significant growth. Recent studies have shown the use of AI techniques to support water-demand prediction, streamflow forecasting, groundwater assessment, anomaly detection, water-quality monitoring and decision-support systems (Ahmed *et al.*, 2024) [16]. These approaches can improve the speed and flexibility of water-resource analysis, es

pecially when large and heterogeneous datasets are available. However, challenges of model interpretability, data quality, generalization, computational requirements and uncertainty remain important considerations in applying AI models to environmental systems. Another important finding is the growing integration of remote sensing and hydrogeophysical methods into integrated hydrological models. This method gives the additional information for the model parameterization, calibration, boundary-condition definition and data assimilation (Sapitang *et al.*, 2024) [17]. The integration of surface observations, sub-surface information and hydrological modeling can improve the representation of complex interactions between groundwater and surface water. This combination is especially useful in locations where it is not possible to directly observe the processes happening below the surface. The literature reviewed also recognized that the development of integrated AI-GIS frameworks is an emerging direction in the water-resource management. Artificial intelligence and spatial analysis can handle large volumes of geographical and environmental data more efficiently and can help in spatial prediction, resource allocation, vulnerability assessment and management decisions (Morain *et al.*, 2024) [18]. This is part of a broader movement toward data-driven water-resource management that increasingly incorporates spatial information and computational intelligence. Another new application of artificial intelligence is to assess water use. Recent works have shown that AI-based approaches can be used to estimate and predict water consumption patterns and to identify correlations between water demand and environmental or socio-economic variables (Haider *et al.*, 2024) [19]. The applications are particularly relevant when considering the effects of climate change, as increasing temperatures, population growth, urbanization and changes in conventional agricultural methods can increase the pressure on already scarce water resources. The accurate prediction of water demand can contribute to hydrological assessments by considering the human dimension of water-resource systems. The literature also emphasizes the importance of AI-supported analytical tools in water resource research and management. Recent studies have identified the potential of artificial intelligence and large language models for data analysis, prediction, information processing, decision support, and scientific communication in the water sector (Jahanbani, 2024) [20]. However, these technologies need to be complemented by validated hydrological observations and established scientific modeling frameworks, as computational efficiency is no guaranty for physical reliability or environmental accuracy. The other important finding is the current state of the art in data-driven streamflow forecasting. Methods of machine-learning and artificial intelligence have been increasingly used to predict streamflow using meteorological, hydrological and remotely sensed variables (Mourot *et al.*, 2025) [21]. These are methods that can model nonlinear relationships, which are difficult to describe with conventional statistical models. However, forecasting skills are heavily dependent on the availability of long and representative datasets and the performance of models may degrade when models are applied to hydrological conditions that are different from the training data. Recent work has also supported the focus on climate change projections with inclusion of ground water. Integrated approaches increasingly recognize that groundwater cannot be overlooked in climate-impact assessments, because the storage, recharge, discharge and pumping of groundwater can significantly affect the overall response of water systems (Patel *et al.*, 2026) [22]. Adding groundwater processes to climate change projections provides a more complete picture of future water availability, and can help to identify risks that could be missed by projections based only on surface water. Another outcome is the increasing sophistication of remote sensing and GIS applications in watershed hydrology. Systematic evaluations show that these technologies are being used for a variety of watershed applications such as runoff estimation, watershed characterization, groundwater mapping, flood assessment, drought monitoring, land-use analysis, and hydrological modeling (Siyad *et al.*, 2025) [23]. High resolution satellite data availability and the advent of cloud based computational platforms have increased the spatial and temporal scales at which wa-

tershed process studies are conducted. The literature review also suggests that a number of interacting environmental pressures influence groundwater recharge. Variability in climate, changes in land use and sea-level rise can all affect recharge processes and the behavior of groundwater systems, especially in vulnerable coastal and semi-arid environments (Bihon *et al.*, 2024) [24]. This finding emphasizes the need for integrated assessments of groundwater sustainability that consider interactions between climatic and non-climatic drivers. It also stresses the importance of spatial analysis, as recharge responses can be very different in different locations, depending on geological, hydrological and land-surface conditions. Finally, the literature emphasizes the necessity of assessing the performance of the hydrological model under future climate scenarios. Variations in model structure, parameterization, input data, and calibration approaches can lead to different estimates of runoff, streamflow, and other hydrological responses (Lubczynski *et al.*, 2024) [25]. Model comparison and performance evaluation are thus an important part of a reliable assessment of climate impacts. The evidence suggests that multi-model approaches, improved calibration and coupling with observational datasets could provide a more robust basis for the interpretation of future hydrological changes. The literature reviewed is clearly indicative of a trend toward integrated, spatially explicit, data-driven and predictive water-resource assessment in general. GIS and remote sensing provide the spatial and observational basis, hydrological and groundwater models provide the process based representation and machine learning and artificial intelligence are increasingly providing prediction and decision support. The assessment of future conditions for water resources is based on climate and land-use scenarios. The convergence of these approaches represents a major methodological advance in understanding water resources under climate change (Mensah *et al.*, 2022; Keller *et al.*, 2023; Ray *et al.*, 2023; Huang *et al.*, 2023; Mishra *et al.*, 2023; Saha *et al.*, 2024; Ahmed *et al.*, 2024; Sapitang *et al.*, 2024; Morain *et al.*, 2024; Haider *et al.*, 2024; Jahanbani, 2024; Mourot *et al.*, 2025; Patel *et al.*, 2026; Siyad *et al.*, 2025; Bihon *et al.*, 2024; Lubczynski *et al.*, 2024) [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. Nevertheless, the review points out several challenges, including the uncertainty of climate projections, the diversity of hydrological models, the limitations of groundwater observations, the inconsistencies of remote-sensing products, the data requirements of machine-learning models, and the difficulties in transferring computer models to other geographic environments (Mensah *et al.*, 2022; Keller *et al.*, 2023; Ray *et al.*, 2023; Huang *et al.*, 2023; Mishra *et al.*, 2023; Saha *et al.*, 2024; Ahmed *et al.*, 2024; Sapitang *et al.*, 2024; Morain *et al.*, 2024; Haider *et al.*, 2024; Jahanbani, 2024; Mourot *et al.*, 2025; Patel *et al.*, 2026; Siyad *et al.*, 2025; Bihon *et al.*, 2024; Lubczynski *et al.*, 2024) [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. These limitations suggest that future work should not be based on a single analytical technique. More focus should be placed on multi-source data integration, GIS-based spatial analysis, coupled surface-water and groundwater modeling, remote sensing, artificial intelligence, and rigorous uncertainty assessment. Such an integrated framework would offer a more solid science basis for pinpointing vulnerable areas, understanding spatial and temporal changes in water availability, predicting future hydrological conditions, and supporting sustainable water-resource management under climate change.

## Discussion of the results

The distribution of the 25 reviewed studies shown in Figure 2 reveals a clear shift toward integrated and spatially explicit approaches for assessing water resources under climate change. The literature reviewed includes hydrological modeling, remote sensing, GIS, groundwater assessment, UAV technologies and artificial intelligence and shows the increasing complexity of climate–water interactions. Hydrological modeling remains an important tool in water-resources research as it allows the assessment of changes in runoff, evapotranspiration, recharge and water availability under varying climatic conditions. Mensah *et al.* emphasized the need to integrate climate change with

land-use and land-cover dynamics in the assessment of hydrological processes and groundwater recharge (Mensah *et al.*, 2022) [10]. Similarly, Keller *et al.* emphasized that the choice of appropriate hydrological models is based on watershed characteristics, available data and modeling objectives (Keller *et al.*, 2023) [11]. Our results suggest that a combined representation of natural and anthropogenic changes is necessary to generate reliable climate impact assessments. Another major research direction is remote sensing and GIS. This increasing use is due to their ability to provide spatially continuous information over large and often poorly monitored areas. GIS offers a powerful platform for spatial integration and analysis, and remote sensing can be used to monitor precipitation, evapotranspiration, soil moisture, surface-water changes, and vegetation conditions (Ray *et al.*, 2023) [12]. The integration of remote sensing and hydrogeophysical information has also eased the development of integrated hydrological models and the representation of surface and subsurface processes (Huang *et al.*, 2023) [13]. Groundwater and recharge studies also play a significant role in the reviewed literature. Climate change can affect groundwater systems in terms of changes in precipitation, evapotranspiration, recharge, and groundwater-surface-water interactions (Mishra *et al.*, 2023) [14]. Al Atawneh *et al.* (Saha *et al.*, 2024) [15] also stated that there is still a large degree of uncertainty in the projections of groundwater recharge due to the differences in climate scenarios, hydrological models and environmental conditions. This highlights the necessity for groundwater processes to be included in assessments of long-term water-resource sustainability. Spatial drought assessment is another important application of geospatial technologies as shown in the literature. Drought is highly variable in space and time and a combination of climatic, hydrological and remotely sensed indicators is needed to adequately characterize this (Ahmed *et al.*, 2024) [16]. UAV technologies provide another scale of

observation between field measurements and satellite remote sensing, allowing for high resolution investigation of water bodies, river morphology, vegetation and other hydrological features (Sapitang *et al.*, 2024) [17]. One of the major trends observed in Figure 2 is the rising contribution of artificial intelligence and machine learning. Recent studies have shown that ML can improve the hydrological forecast and analyze the complex nonlinear relationships between the climatic and hydrological variables (Morain *et al.*, 2024; Haider *et al.*, 2024) [18, 19]. AI integration with GIS and remote sensing further enhances its potential in groundwater mapping, flood assessment, water demand estimation and overall water-resources management (Jahanbani, 2024; Mourot *et al.*, 2025) [20, 21]. AI-based approaches are also extensively used for water consumption assessment and streamflow forecasting (Patel *et al.*, 2026; Siyad *et al.*, 2025) [22, 23]. Recent work has also stressed the need to include groundwater processes in projections of climate change. Such approaches acknowledge that future water availability is not only determined by surface runoff and precipitation, but also by recharge, groundwater storage, land-use change and human water demand (Bihon *et al.*, 2024; Lubczynski *et al.*, 2024) [24, 25]. The general review of the studies shows a clear trend toward multidisciplinary frameworks combining spatial observations, hydrological models, groundwater analysis and the prediction based on AI. The key implication of Figure 2 is thus that future water-resources assessment will increasingly depend on the integration of complementary technologies rather than on reliance on a single method. Remote sensing and GIS provide spatial coverage, hydrological models describe physical processes, groundwater models deal with subsurface dynamics and AI offers sophisticated prediction capabilities. Their integration may improve the identification of vulnerable areas, forecasting of hydrological shifts, and the formulation of more effective water-management strategies in the midst of climate change.

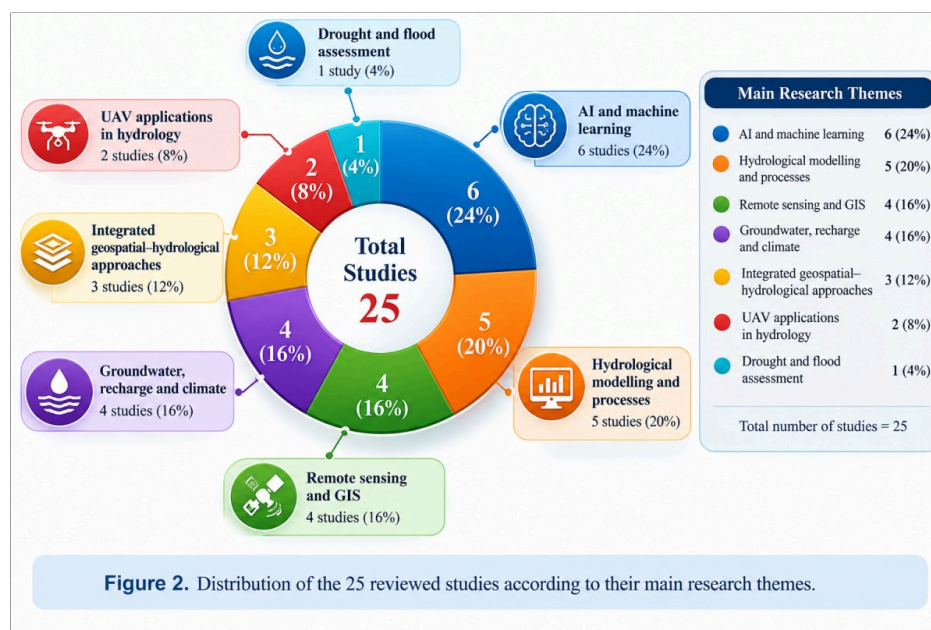


Figure 2. Distribution of the 25 reviewed studies according to their main research themes.

## Conclusion

This review shows that water-resources research under climate change is increasingly moving toward integrated, spatially explicit and data-driven approaches. The studies reviewed show the complementary role of GIS, remote sensing, hydrological and groundwater modeling, UAV technologies, and artificial intelligence in improving the assessment and prediction of water-resource dynamics. The increasing integration of these methods allows for greater capacity to identify spatial and temporal changes, assess climate-related impacts and support sustainable water-resource management. Future research should target the integration of physical hydrological processes with high-resolution geospatial observations and AI-based prediction while

improving data quality, model validation, and uncertainty assessment. Such integrated frameworks can provide a stronger scientific basis for understanding and managing water resources under increasing climate variability and uncertainty.

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