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REVIEW

Hydrological Extremes under Climate Change: Advances in Predictive Modeling and Risk Assessment

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ABSTRACT

Hydrological extremes, such as floods, droughts, and compound events, are extremely dangerous to human societies, ecosystems, and infrastructures, whose frequency and severity are affected by climate change more and more. Effective disaster preparedness, water resource management, and climate adaptation have to do with accurate prediction and extensive risk assessment. This review sums up recent progress in predictive modeling and risk assessment systems in the framework of hydrological extremes in the changing climatic conditions. Statistical and empirical techniques, including extreme value theory and nonstationary frequency analysis, give probabilistic information using historic records, whereas process-based models give an understanding of physical hydrological processes at different climate and land-use conditions. New information-based and hybrid methods that use machine learning and high-resolution data take advantage of the complexity and nonlinearities and enhance the predictive power. Hazard, exposure, vulnerability, and adaptive capacity risk assessment models allow predictive output to be translated into actionable decision support, with socio-economic aspects and analysis of the scenario. Case studies of various regions across the globe show the use of these techniques to address floods, droughts,

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and compound events, with success and current problems. The review also addresses current trends such as compound hazard, multi-hazard integration, AI-enabled modelling, and cross-sectoral decision support, and outlines research priorities of improving predictive capability and resilience. This review will inform researchers, policymakers, and practitioners by offering a synthesis of all the effects of the hydrological extremes in climate change to formulate sound strategies for alleviating these effects.

Keywords: Hydrological Extremes; Climate Change; Predictive Modeling; Risk Assessment; Compound Events

1. Introduction

Hydrological extremes, which include floods, droughts, and compound events, are among the most devastating natural risks that affect human society and the ecological systems[1]. Their occurrence, severity, and location are closely associated with variability of climatic conditions, human-induced changes of land surfaces, and shifts in hydrological processes. Over the past few decades, the scientific community in the world has recorded the growing evidence that climate change not only changes the average conditions of hydrology but also plays a significant role in the occurrence and severity of extreme events. Such accumulating research demonstrates the necessity to improve predictive capacities and build effective risk evaluation systems on hydrological extremes with nonstationary climatic conditions[2–5].

The most prevalent types of hydrological extremes are floods and droughts that have a significant social, economic, and environmental impact. Floods may lead to loss of life, destruction of infrastructure, and agricultural inconvenience, and droughts affect the security of water, agricultural productivity, and increase energy supply problems. More complexities in prediction and management. Compound hydrological extremes, occurring when two or more hazard types happen together or in series (e.g., drought and flash floods), have further complexities. The rising number and intensity of such compound events in most parts of the world have aggravated the issue of climate resilience and disaster preparedness[6].

Climate change causes hydrological extremes, which are complex. Increased temperatures throughout the world impact the precipitation levels, the dynamics of the melting snow, and the rate of evapotranspiration, and hence affect the streamflow and the soil moisture levels. Moreover, climate phenomena on a large scale, including the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and monsoonal cyclones, adjust the regional hydrological extremes, which tend to have spatially heterogeneous effects. The anthropogenic actions, such as urbanization, construction of dams, deforestation, and land-use change, interact with the processes initiated by climate, further complicating the behavior of hydrological extremes. These interactions are important to understand to come up with predictive models that can capture both natural variability and anthropogenic influence[6–8].

Predictive modeling has become an essential part of hydrological science and the risk reduction of disasters. In the past, statistical and empirical models have been used to give information on the likelihood and frequency of extreme events, such as extreme value theory and nonstationary frequency analysis. The physically consistent simulation of hydrological reactions to different climate conditions, with consideration of land-surface hydrology and climate models, is possible with process-based models. In the more modern past, data-driven methods, especially machine learning and hybrid modeling architectures, have shown great potential in enhancing forecast accuracy and lead time. These innovations play an important role in early warning frameworks, water infrastructure planning, and water resource management in the context of the changing climate.

Although there is a lot of development, there are still a number of challenges. Areas of current development include the modeling of the extremes of compound, the incorporation of high-resolution remote sensing data, and the inclusion of the socio-economic aspects of the risks into the frameworks of risk assessment. In addition, a vast majority of areas, especially in developing nations, are not well-covered with data and modeling capabilities, which makes it impossible to use the sophisticated predictive and risk evaluation tools. To fill these gaps, interdisciplinary cooperation and further development of both computational and observational networks are needed[9]. Observed changes in the frequency, intensity, and spatial distribution of hydrological extremes have been reported across multiple regions worldwide (**Table 1**).

Table 1. Summary of observed trends in major hydrological extremes across different regions, highlighting dominant drivers and reported changes over recent decades.

Region	Type of Extreme	Observed Trend (Past Decades)	Key Drivers	References
North America	Flood	↑ frequency and magnitude	Intense rainfall, snowmelt, ENSO	Musselman et al. [10]
Sahel, Africa	Drought	↑ frequency and duration	Precipitation deficit, land degradation	Fensholt et al. [11]
South-East Asia	Flood & Drought	Seasonal shifts, compound events	Monsoon variability, urbanization	Loo et al. [12]
Western USA	Compound Events	↑ wildfire-flood sequences	Drought + heatwaves	Prestemon et al. [13]

Although various reviews have studied hydrological extremes, predictive modelling methods, or the effects of climate change separately, a significant number of studies are still concerned with the summarization of current methods and do not offer a critical analysis of their comparative advantages and disadvantages in the context of emerging climate conditions [14]. More specifically, comparatively limited reviews assess the performance of various predictive modelling and risk assessment systems in the face of hydrological non-stationarity and compound extremes, which are becoming increasingly discussed as hallmarks of hydroclimatic systems in climate change. The proposed review would address this gap by conducting a comparative and integrative review of statistical, process-based, data-driven, and hybrid modeling models with a specific focus on their assumptions, uncertainty structures, and their applicability in terms of analyzing complex extreme events. Besides this, the review integrates progress in hydrological risk assessment systems and determines whether they can absorb the changing hazard probabilities, exposure dynamics, and vulnerability. Through combining the findings presented by predictive modelling, risk analysis, and representative case studies in various hydroclimatic zones, this research suggests a conceptual integration approach whereby climate driving factors, hydrological processes, modelling approaches, and risk assessment techniques are interconnected [15,16]. This framework demonstrates the way various methodological strategies can work with non-stationarity and compound hazard conditions, and what the central difficulties and opportunities are to enhance predictive ability and climate resilience. This synthesis makes the review more than a mere compilation of literature by offering critical perspectives on how the methodology of hydrological extreme analysis has evolved and where it will go in the future in a changing climate. The risk to human health is associated with the possibility of exposure to pathogens, heavy metals, and contaminants in wastewater irrigation, and thus, it is necessary to provide integrated risk assessment systems that can be used to measure and contain the vulnerability of human health to various environmental conditions [4,17].

2. Theoretical and Conceptual Framework for Hydrological Extremes

Complex interactions of climatic forcing, soil-based hydrology, and anthropogenic activities result in hydrological extremes, such as floods, droughts, and compound events. This is being redefined under climate change through changes in atmospheric circulation, an increase in temperatures, changes in precipitation regimes, and the increasing pace of land-use change. Such an effective theoretical and conceptual framework is therefore needed to comprehend the processes of the formation, migration, and spread of hydrological extremes in the natural and human system and the ways of their transformations in space and time. This kind of framework informs the activities of predictive modeling and forms the basis of risk assessment and adaptation planning [18,19].

2.1. Definition and Classification of Hydrological Extremes

Hydrological extremes are normally described as occurrences that are uncharacteristic of long-term hydrological averages, which usually happen at the ends of probability distributions of hydrological variables like precipitation, streamflow, soil moisture, and groundwater levels. Floods are typically linked to too much water in the short term, whereas droughts represent long-term precipitation and soil moisture deficits, which may be exacerbated by high evapotranspiration. In addition to these classical categories, more recent studies have focused on the extremes of compounds and cascades, where drivers or hazards interact both concurrently or in sequence, e.g., drought to flood changes or heatwaves and low-flow periods.

The duration, spatial extent, severity, and predominant drivers can be used to classify the hydrological extremes. Extremes in short durations are usually associated with extreme precipitation events, whereas long-duration extremes are associated with the long-term climatic anomalies and land-atmosphere interactions. Geographically, extremes can be confined to a given catchment, or they can be of large river basins and areas. The identification of these differences is important to choose the right modeling strategies and to understand the effects of climate change on various kinds of hydrological extremes [3,20].

2.2. Climatic Drivers and Atmospheric Processes

The changes in climate cause the rise in extreme atmospheric processes, which regulate precipitation and temperature, to affect the hydrological extremes. The increase in global temperatures increases the moisture-holding capacity of the atmosphere, which strengthens the hydrological cycle and the probability of the occurrence of heavy precipitation events. Meanwhile, increased temperatures also increase the rate of evapotranspiration, which worsens water shortages in the soil and aggravates the intensity of droughts in water-stressed areas [21].

Large-scale climate oscillations like the El Niño Southern Oscillation, the North Atlantic Oscillation, and monsoon systems are very important in regulating the frequency and amplitude of hydrological extremes. Climate change is modifying the occurrence, strength, and spatial distributions of these modes and hence affecting hydrological reactions in regions. Furthermore, variations in storm tracks, atmospheric blocking, and intermittency of precipitation increase the risk of flooding and extend dry periods, and climate-induced hydrological intensification is dual-fold [22].

2.3. Catchment Processes and Hydrological Response

Catchment scale processes mediate the climatic forcing to hydrological extremes, such as processes of infiltration, runoff generation, groundwater recharge, and storage processes. Precipitation distribution falls under soil properties, affects land cover, topography, and antecedent moisture conditions, and is how the true precipitation is categorized between surface and subsurface runoffs. Indicatively, dense soils and impermeable surfaces facilitate quick runoff and flooding, but deep soils and forested grounds would be able to absorb short-term changes in rainfall and are susceptible to long-term dryness [23,24].

Climate change may also change these processes indirectly by changing the patterns of vegetation, snow accumulation and melting, and soil moisture regime. Warming of snow-dominated basins causes a transition to rain rather than snow and earlier snowmelt, which increases the risk of winter-time floods and decreases summer water supply. Such scale-dependent and nonlinear hydrological reactions make it more difficult to attribute and predict extremes, and process-sensitive conceptual frameworks are critically important [25].

2.4. Anthropogenic Influences and Human–Water Interactions

Hydrological extremes are becoming more and more influenced by human activity and its effects. Due to urbanization, deforestation, agricultural development, and river control, the natural flow regimes change, and the hydrological behavior of the watersheds is altered. Urban surfaces are impervious, thereby increasing flood peaks, and irrigation withdrawals and reservoir operations may either enhance or alleviate the effects of droughts, depending on how the devices are managed.

In the climate change scenario, the dynamic between the anthropogenic pressure and natural variability is amplified. Exposure and vulnerability are impacted by socioeconomic development, whereas the ability to handle extreme events is dependent on adaptive infrastructure and governance structures. Therefore, hydrological extremes are not only physical but also socio-hydrological processes that occur as a result of interactions between humans and nature. **Figure 1** represents a conceptual representation of hydrological extremes and the physical, climatic, and anthropogenic drivers of these extremes and their interactions [2,26,27].

2.5. Integrated Conceptual Framework and Implications

The conceptual framework of hydrological extremes is integrated to identify the reciprocal influence of climate drivers and catchment processes in the context of human actions and cross-scale interactions between the three. This structure offers a logical foundation whereby predictive models are correlated to risk assessment strategies where many uncertainties, non-stationarity, and system complexity are explicitly considered. The framework helps to do a better projection and provide valuable knowledge on how to make adaptive and resilient water management strategies in the face of climate change by placing hydrological extremes in a more robust climate-hydrology-society context[28].

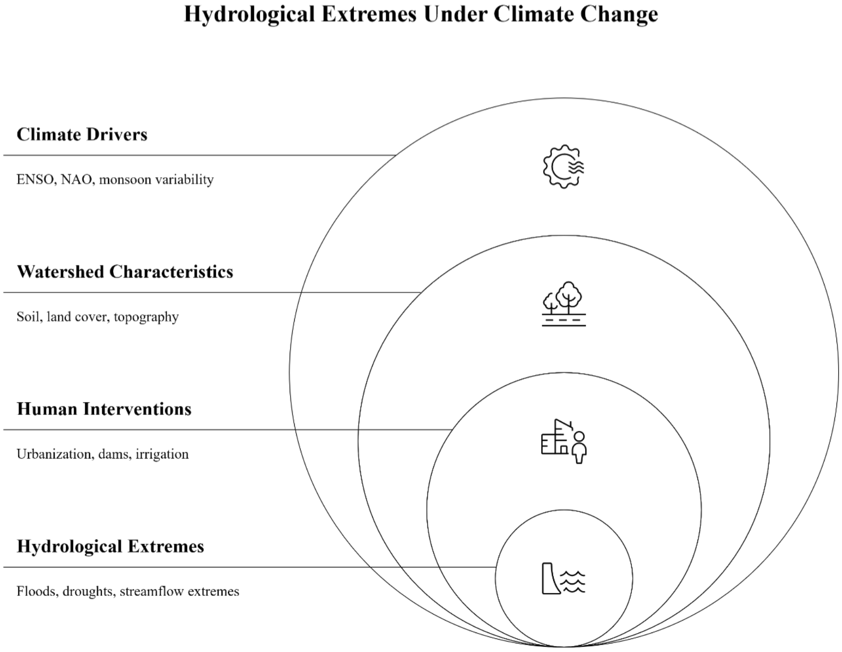

Figure 1. Conceptual diagram illustrating the interactions among climate drivers, watershed processes, anthropogenic influences, and hydrological extremes, as well as their links to exposure and vulnerability.

2.6. Methodological Framework and Evaluation Criteria

This review follows an analytical model to critically assess the major modeling schemes employed in the prediction of the hydrological extremes in the context of climate change. Instead of providing models descriptively, the review explores statistical, process-based, and data-driven models in terms of the assumptions, their application, and their known limitations. Statistical methods, such as extreme value theory and regression methods, are usually based on past statistics and also often assume the hydrological processes remain stationary, which might not be the case in the shifting climate conditions. Process-driven hydrological models are physically based models of water movement and, thus, can be simulated in scenarios, but parameter uncertainty, structural error, and bias in climate model inputs can influence the model. The use of data-based and machine learning is becoming more common with its ability to fit nonlinear relations in complex hydroclimatic data, but they can be prone to overfitting and lack extrapolation to other data points outside the training range. Another aspect that is reviewed is the failure modes of both approaches in non-stationary and compound extreme conditions, and the conventional models might underestimate risks, in this case. Specific focus is provided to uncertainty propagation, such as uncertainty that arises from climate projections, structures of hydrological models, and parameter estimation. Lastly, hybrid models, which combine process-based frameworks with machine learning algorithms, are also considered as promising solutions to enhance predictive performance, minimize biases, and strengthen hydrological risk evaluation in changing climatic conditions[29].

3. Advances in Predictive Modeling

Under climate change, the prediction of hydrological extremes has been a major issue in hydrology because the interactions between the atmospheric and terrestrial factors and human factors are very complex. Precise prediction is needed in the early warning scheme, disaster preparedness, and management of water resources. The development of predictive models has seen an important development over the last decades, including classic statistical models, to complex process-based simulations, and even more interesting data-driven models. Both modeling strategies have their own benefits and drawbacks, and the combination of both approaches has become one of the potential solutions to the increased predictive accuracy and reliability [6,30].

3.1. Statistical and Empirical Models

Statistical and empirical models have been a long-standing main instrument of hydrology, specifically to analyze historical data and estimate the likelihood of the occurrence of extreme events [31]. The basis of these methods is extreme value theory (EVT), which is a strict set of theories used to describe the tails of hydrological distributions, including maximum flows and minimum streamflows. Generalized Pareto Distribution or GPD and Generalized Extreme Value or GEV models are commonly used to determine the period of the returns and the probability of unprecedented events. NSA, an analysis technique that takes into consideration the time-varying climatic and anthropogenic factors, has gained prominence in the changing climatic conditions to enable hydrologists to record the changing trends in extreme event levels and frequency. Multivariate and copula-based models are an extension of traditional EVT in that they take into account relationships between more than two hydrological variables, e.g., river flows and rain intensities, and thus multivariate models are better at representing compound and spatially correlated extremes. Although widely used, statistical models are highly dependent on adequate past data and might not be able to extrapolate outside of the conditions observed, especially under conditions that have never been recorded in history [6,32,33].

3.2. Process-Based Models

Process-based models are the simulation of the physical processes that contribute to the occurrence of hydrological extremes through the modelling of the interactions between climate, land surface, and hydrological systems. The flood and drought risks can be assessed using global and regional hydrological models, which can be coupled with general circulation models (GCMs) or regional climate models (RCMs) to perform the evaluation under various climate conditions. These models have elaborate descriptions of the processes of precipitation-runoff, snow build-up and melt, soil moisture, and groundwater interactions. A number of conceptual watershed models have been broadly used to model extreme flows and determine the effect of land-use change on hydrological extremes, including the Soil and Water Assessment Tool (SWAT) and the Hydrologic Modeling System (HEC-HMS) of the Hydrologic Engineering Center. Distributed models that are physically based offer greater spatial resolution, including heterogeneity in soil, vegetation, and topography that is essential in the prediction of localized processes like flash floods. Process-based models are especially useful in scenario testing and adaptation planning as they provide the opportunity to study the hydrological reaction to the changed climate conditions, land management practices, and infrastructure interventions. However, these models tend to be highly parameterized and need high-quality input data, and indeterminacies in climate predictions and model setups may be transferred to hydrological forecasts [34–36].

3.3. Data-Driven and Hybrid Approaches

Over the last few years, machine learning and artificial intelligence-based data methods have become a formidable means of forecasting hydrological extremes. Artificial neural networks, support vector machines, random forests, and deep learning models are methods that can represent non-linear relationships when the input data are complex and hydrological and meteorological datasets. These models are very good in short-term predictions and real-time usage, similar to flood and drought early warning systems. There has been an interest in hybrid modeling frameworks that combine process-based knowledge with data-driven algorithms to allow combining mechanistic knowledge with predictive flexibility. As a case in point, physically based outputs can serve as inputs or constraints of machine learning models, thus lessening overfitting and improving generalizability to new climate conditions. Assimilation of high-resolution remote sensing observations, re-analysis views, and on-site measurements can further enhance the predictive ability of data-driven models in which spatially explicit forecasts and enhanced hazard mapping can be made. Although these methods have significant benefits, there are still issues in the interpretability of the models, quantification of uncertainty, and extrapolation of model predictions, which are not observed in practice[29].

3.4. Model Evaluation and Validation

Proper foretelling of hydrological extremes is based not only on the model formulation but also on strict evaluation and validation. The most common metrics to determine model performance include Nash-Sutcliffe efficiency, root mean square error, mean absolute error, and extreme event-specific skill scores. The methods of cross-validation, bootstrapping, and hindcasting are also extensively used to evaluate the strength and external validity of the model. Enhanced predictive capability and uncertainty reduction through multi-model ensembles. The ensuing research has shown that multi-model ensembles (combinations of statistical, process-based, and data-based models) can lead to improved predictive skill and uncertainty reduction, especially when it comes to extreme or unprecedented events. Sensitivity analysis and quantifying uncertainty are vital elements of model assessment, which give an understanding of the percentage input by climate projections, parameter manipulations, and structural assumptions to overall forecasting[37,38]. The main categories of predictive models used to simulate hydrological extremes, along with their strengths and limitations, are summarized in **Table 2**.

Table 2. Comparison of statistical, process-based, and data-driven (including hybrid) predictive modeling approaches for hydrological extremes, including data requirements, advantages, limitations, and typical applications.

Model Type	Methodology	Data Requirements	Strengths	Limitations	Typical Applications
Statistical	EVT, GEV, GPD, copulas	Historical records	Probabilistic, simple	Poor extrapolation under nonstationarity	Flood/drought frequency analysis
Process-Based	SWAT, HEC-HMS, GCM-RCM coupling	Climate and hydrological inputs	Physically consistent, scenario testing	High computational cost, parameter sensitivity	Regional hydrology, climate impact studies
Data-Driven/ Hybrid	Machine learning, deep learning	Observational & remote sensing data	Nonlinear patterns, short-term forecasting	Interpretability, extrapolation	Real-time forecasting, early warning

The improvement of predictive modeling has greatly increased our capability to forecast the hydrologic extremes in climate change. Statistical and empirical models give insights in a probabilistic format based on historical information, process-based models are simulation-based on mechanistic responses to changing climatic and land-use states, and data-driven and hybrid approaches provide flexible and powerful mechanisms of capturing complex nonlinearities and real-time prediction. A combination of these approaches to hydrology, together with stringent validation and uncertainty analysis, is the cutting edge of hydrological forecasting. These developments established the foundation for further debate of risk assessment and realistic implementation in case studies where further innovation is needed to overcome the challenges of nonstationary, extreme values of compounds, and lack of data[39,40].

4. Risk Assessment and Uncertainty Analysis

Hydrological extremes need to be managed efficiently during climate change, not only through proper prediction of such events but also systematized knowledge of the dangers that these extremes would pose to society, ecosystems, and infrastructure. The risk assessment offers a systematic approach to the assessment of the possible outcomes, quantifies the uncertainties, and makes decisions on disaster preparedness, water resources management, and climate adaptation measures. Within the context of hydrology, predictive modeling is combined with risk assessment models to help researchers achieve the mapping of physical processes, climate prediction, and socio-economic effects into practical outputs[17,41].

4.1. Conceptual Frameworks for Hydrological Risk

Hydrological risk has been most generally thought of as a product of hazard, exposure, and vulnerability. The hazard component means the possibility and the size of a severe hydrological phenomenon, such as floods, droughts, or compound events, which is an event that is made up of many interacting hazards. Exposure refers to the availability of people, infrastructure, agricultural lands, or ecosystems in areas that may be at risk of exposure to the hazard. Vulnerability represents the ease with which these factors can be spoiled or destroyed, which depends on the quality of structure, socio-economic status, political systems, and adaptive ability.

Conventional hazard-based methods that were mainly concerned with the likelihood of extreme events have proved inadequate in the new conditions of climate change, where nonstationary and changing land-use patterns both play a major role in changing risk landscapes. In current models, emphasis is placed on dynamic risk assessment, which includes time-varying climatic drivers, infrastructure building, demographic rise, and adaptive plans. Indicatively, probabilistic flood maps (together with demographic data) can be used to determine vulnerable regions that may be aggravated by future urban development, and scenario-based drought evaluations can be used to show critical water-stressed regions with different climate scenarios. These frameworks can be used to identify the areas of risk hotspots, the importance of risk mitigation initiatives, and to incorporate the hydrological risk into the wider environmental and socio-economic planning[42].

4.2. Probabilistic Risk Assessment Approaches

Probability methods have gained more and more prominence in the evaluation of hydrological risk, especially when it comes to climate change. Probabilistic methods measure the possibility of several outcomes, unlike deterministic methods, which only give one predicted outcome, and therefore, they help to make decisions under uncertainty. Frequency analysis techniques, Monte Carlo simulations, and Bayesian networks are methods that are commonly used to represent probability distributions of extreme events and possible effects.

The scenario-based analyses are especially useful in evaluating the hydrological risk of climate change. With the combination of outputs of general circulation models or regional climate models and hydrological models, researchers can assess risk in various Representative Concentration Pathways (RCPs) and emission scenarios. Through such analyses, it is possible to explore low-probability, high-impact events of interest to flood and drought management. Probabilistic risk assessment also offers a platform on which risk mitigation strategies, investment into infrastructure, and policy intervention are assessed, allowing cost-benefit analysis and prioritizing adaptive actions. Notably, spatial heterogeneity can be built into probabilistic methods, and this enables local risk measurements where the topography, land use, and exposure vary[34,35,43].

4.3. Sources and Characterization of Uncertainty

Uncertainty is a characteristic aspect of hydrological risk assessment, and it occurs due to various sources. The model structural uncertainty is due to variation in the representation of the hydrological processes in the statistical, process, and data-driven models. As an example, rainfall run-off models can differ in their approach to infiltration, snowmelt, and evapotranspiration, resulting in dissimilar predictions on extreme events. Parametric uncertainty demonstrates a lack of full information or fluctuation of the model parameters, including soil hydraulic features, roughness of the channel, or coefficients of evapotranspiration. The uncertainty in climate scenarios is due to the variations among the GCMs and the RCMs, the emission scenario, and even the downscaling. Uncertainty in observation is an additional risk factor, particularly where there is scanty hydrometeorological monitoring, which leads to a lack of calibration and validation information[44].

Ensemble modeling is popular for dealing with these types of uncertainties. It is through the combination of the outputs of various models that ensembles can represent the scope of the plausible outcomes, and therefore, they can describe probabilistic distributions and not some deterministic values. The use of sensitivity analyses, variance decomposition, and Bayesian inference is also used to determine the total risk estimate associated with individual sources of uncertainty. These methods help to increase the transparency and credibility of risk assessments so that the decision-makers are able to assess both the anticipated impacts and the confidence level in them.

4.4. Integration of Socio-Economic and Adaptive Factors

The hydrological risk cannot be purely a product of physical hazard only; the socio-economic status and adaptive capacity actually define the size of the possible effects. Population increase, urbanization, development of infrastructural facilities, and alteration in land use directly influence the exposure, whereas the governance, emergency preparedness, and adaptive strategies moderate the vulnerability. There is a growing trend in northern risk assessments to combine socio-economic scenarios (like the Shared Socio-economic Pathways (SSPs) of climate scenarios (RCPs) to test the combined effects of these two elements on hydrological extremes. As an illustration, encroachment into flood areas can substantially raise the risk of floods in cities, whereas better irrigation systems can reduce the effects of drought in farms[45,46]. Commonly used hydrological risk assessment models and their methodological features are summed up in **Table 3**. Flood mitigation strategies, such as early warning systems, reservoir management, floodplain zoning, and ecosystem-based solutions, are a part and parcel of mitigating risk. To measure the effectiveness of these strategies, it is necessary to couple the predictive models with the socio-economic measures so that the scenarios can be tested in terms of physical and societal change. This integration helps to achieve policy relevance in the risk assessment and will contribute to climate-resilient planning and investment decision-making[47,48].

Table 3. Overview of major risk assessment frameworks applied to hydrological extremes, including core components, methodological approaches, strengths, and key challenges.

Framework	Components	Methodology	Advantages	Challenges	References
Hazard–Exposure–Vulnerability	Hazard, exposure, vulnerability	Probabilistic, scenario-based	Integrates physical and socio-economic factors	Requires detailed data	Kaiser[49]
Probabilistic Risk Assessment	Probability distributions, scenarios	Monte Carlo, Bayesian networks	Quantifies uncertainty, supports decision-making	Computationally intensive	Sperotto et al.[50]
Multi-Hazard & Compound Risk	Multiple hazards, joint probabilities	Copula-based, integrated modeling	Captures compound events	Complex modeling, data-demanding	Fan et al.[51]

4.5. Emerging Methods in Risk Assessment

Recent developments in hydrological risk assessment are the application of high-resolution remote sensing data, machine learning to map vulnerabilities, and multi-hazard modeling. The modern assessment is increasingly taking into account aspects like compound and cascading events, like drought that causes the risk of wildfire or flood, followed by landslides. Another strategy embracing stakeholder input is becoming increasingly popular in terms of being able to capture local knowledge, enhance the model validation, and make the results more relevant to decision-making. The multi-criteria risk assessment frameworks have integrated physical, social, and economic, and offer a holistic perspective of the possible effects and adaptive alternatives[52,53]. In **Figure 2**, the inclusion of hazard, exposure, vulnerability, and uncertainty in assessing hydrological risk is demonstrated.

Climate change paved the way to hydrological extremes that need to be effectively managed through risk assessment and uncertainty analysis. By combining hazard characterization and exposure, as well as vulnerability and adaptive capacity, it is possible to have a better idea of potential impacts. Uncertainties in climate projections, model structure, and parameterization are solved using probabilistic approaches, scenario analysis, and ensemble modeling. The addition of socio-economic aspects and adaptive approaches also increases the relevance and applicability of risk assessment. The new approaches of multi-hazard modeling, remote sensing, and machine learning can provide new opportunities to enhance predictive ability and decision support. The combination of these strategies offers a solid base that can be applied in practice, as demonstrated in the following case studies, and outlines the current research priorities of improving the climate resilience of hydrological systems [54,55].

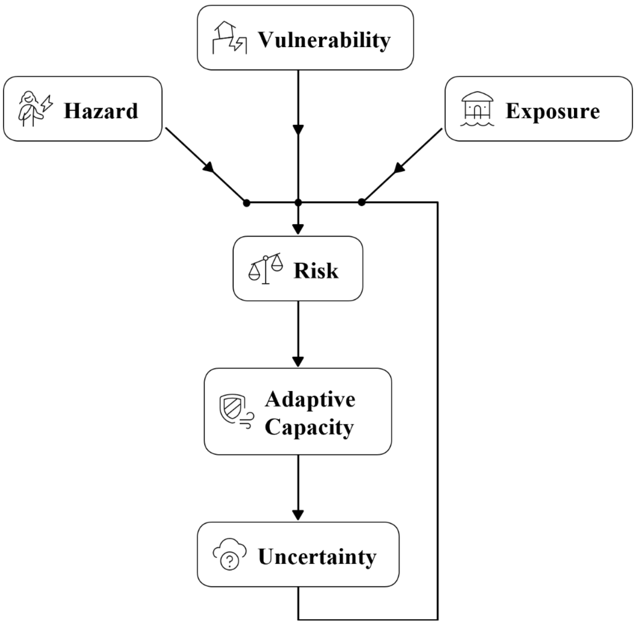

Figure 2. Framework for hydrological risk assessment under climate change, illustrating interactions among hazard, exposure, vulnerability, adaptive capacity, and key sources of uncertainty.

5. Case Studies of Hydrological Extremes: Detailed Examples and Insights

Hydrological extremes are both regional by nature, which is determined by the dynamics of climate, the nature of the watershed, and socioeconomic factors. To demonstrate how predictive modelling and risk analysis can be applied in practice, the following section explores some of the most well-documented examples of predictive modelling and risk analysis in various hydroclimatic settings: regional flooding in West Africa, droughts in East and Southern Asia, compound floods in coastal and delta areas, and extreme variability in temperate basins. These examples demonstrate the transformation of scientific approaches into practical knowledge and outline the main issues in the adaptation to climate change [27,56–58].

5.1. Flood Dynamics and Modeling in West Africa

The West African region has been classified as a hotspot of hydrological extremes because it has been sensitive to climatic changes, high population growth, and inadequate infrastructure to handle flood events. Two current studies can be taken as examples of flood assessment work in the area.

5.1.1. Large-Scale Flood Projections across West Africa

The analysis of two large-scale hydrological models (HMF WA and LISFLOOD) with bias-corrected CMIP6 climate models can help to gain new insights regarding the trends in floods in the West African region [59]. According to simulations using Shared Socioeconomic Pathways scenarios, frequency and magnitude of floods are expected to rise in most of the catchments across the region in the 21st century. As an illustration, 2-year and 20-year return period flood magnitudes were estimated to rise at 94% and 96% of stations, respectively, in the near future with 2 °C of warming and at comparable degrees to the end of the century, highlighting an overall intensification of flood risk. The results were obtained even in the wake of variations in the hydrological representations of the models, which underscores the strength of the climate signal in intensifying floods in the environment of climate change through warming. These projections are able to guide risk managers in planning the infrastructure of the region and the development of early warning systems [59,60].

5.1.2. Urban Flooding in the Sahel: Ouagadougou Case

In addition to massive basins, there are excessive localized rain events that have put a strain on urban hydrology in Sahelian cities. Ouagadougou, Burkina Faso, September 1, 2009, The Flood is one of the most massive urban hydrometeorological events ever to occur in West Africa and resulted in serious flooding for inhabitants. A multidisciplinary case study has associated synoptic weather conditions with the effects of floods and involved local stakeholders in enhancing the value of climate science in urban planning. Although it is difficult to attribute single events to climate change unambiguously, the case in point underscores how meteorological extremes are converted into urban flood risk in those settings with rapid urbanization, which lack proper drainage facilities. It also highlights the fact that cities that experience local impacts of the world-climate drivers need specific early warning systems and resilience plans [61].

5.1.3. Storyline Analyses of West African Droughts and Floods

In addition to the projection studies, storyline methods are used to break down the way climate change could impact the magnitude, duration, and frequency of droughts as well as floods in West Africa. These studies show that future hydrologic extremes are a reflection of precipitation changes, floods can get larger and shorter in duration, and drought intensities differ spatially within the region. Storyline techniques are used in conjunction with probabilistic projections and seek out the possible sequences of extremes that are plausible and which could be missed by their frequency counterparts[62].

5.2. Flood Events in Other Basins: Transboundary and Coastal Contexts

Hydrological extremes also occur in transboundary river systems and coastal catchments, where combined drivers produce complex risk profiles.

5.2.1. Limpopo River Basin, Southern Africa

South Africa has done little to curb the impacts of the Limpopo River Basin, shared with Botswana, Zimbabwe, and Mozambique, which have been severe and aggravated by variations in the climate and socioeconomic pressures. A recent scenario-driven spatial flood hazard analysis used the HYPE (Hydrological Predictions for the Environment) model, which is a model driven by various Regional Climate Models using RCP 4.5 and RCP 8.5. Upon finding, there is a possibility that 50-year flood levels will rise by approximately 84% and 100-year floods by approximately 142% compared to the past. Moreover, the frequency of extreme rainfall was projected when it was found that intensity duration frequency (IDF) analysis showed the more frequent events, which are used to create floods. This integrated modeling, which incorporates the downscaled climate forecasting as well as hydrological simulation, is a direct input to transboundary adaptation planning, where we note that a series of floods can happen within a much shorter period than we had expected in the past[63].

5.2.2. Compound Flooding along U.S. Coasts

In the neighboring United States, coastal areas demonstrate how a combination of both fluvial and storm surge leads to the formation of increased risks to both infrastructure and community. A compound flood risk assessment framework incorporated large-scale river models with ocean reanalysis data to produce spatially distributed data on hazards. This practice has unveiled the finding that moderate storm surge caused by a hurricane and a large river discharge is enough to cause extreme coastal floods, especially when sea level rise raises the base water. Since single driver models may not capture compound flooding, this combination opens the way to forecasting hazards of coastal waters due to climate change[64].

5.2.3. Nile Basin Extreme Flooding under Climate Variability

The Nile Basin projected shifts in the magnitude and frequency of floods are examples of the effects of climate change on ancient transboundary water systems. An SSP2 4.5 and SSP5 8.5 forced climate-driven Soil and Water Assessment Tool model estimated a 63–85% increase in 100-year peak discharge events by the century end. Such results indicate that there are high possibilities that extreme floods will happen approximately once every ten years in extreme situations of emissions, which will be a greater risk to downstream nations that rely on the Nile water flow as the source of irrigation, energy, and livelihood. There is an urgent need to have effective regional cooperation and preparedness strategies to deal with these projected flood hazards[65].

5.3. Drought Case Studies: Resilience and Vulnerability in Asian and Semi-Arid Basins

Droughts may manifest as prolonged deficits in water availability that emerge more gradually but can lead to deep socio-economic stress.

5.3.1. Drought Risk in China's Xi River Basin

The Xi River Basin of southern China has been analyzed based on drought risk in the case of future climatic estimates. Researchers measured the increase and decrease in the frequency and severity of droughts within sub-basins using hydrological models, which were run under downscaled climate scenarios. The analyses found that water stress is bound to increase in the conditions of warming, especially where there will be extended dry periods and where agriculture and urban development increase water demand. This case helps to shape localized water allocation and conservation policies by suggesting the spatial patterns of drought risk that are necessary in future climate conditions[66].

5.3.2. California's Prolonged Drought and the "Ridiculously Resilient Ridge"

In the western United States, a major example of how a drought can be propagated by atmospheric circulation anomalies was a 2012–2017 period of prolonged drought in California. The high-pressure system that has been dubbed the Ridiculously Resilient Ridge in the northeast of the Pacific region displaced storm tracks and blocked precipitation during the winter, leading to some of the driest periods in recorded history. With climate change likely to put more similar atmospheric arrangements, the water managers are still faced with the challenge of how to foresee and avoid the worst effects of droughts. Although it is not a solitary hydrological case scenario, the incident is representative of how atmospheric drivers and landscape (in accordance with human water use) associate to generate prolonged drought situations.

5.4. Compound and Transition Events

Hydrological extremes increasingly occur not as isolated phenomena but as interacting events where one extreme predisposes another, complicating prediction and adaptation.

5.4.1. Drought-to-Flood Transitions

Recent studies have been done on the drought-flood transitions in the same catchment. One such study studied eight catchments that experienced historic transitions and discovered that alternative ways of defining drought and flood thresholds can radically change the number of events that are considered transitions. Notably, out of the eight historical transitions that had been well documented (using media, governmental, and scientific reports), the techniques used in the past based on the threshold had only identified three of these transitions. The result indicates the methodological difficulties of determining the sequence of compounds and indicates that risk management that does not consider the sequence of compounds may underrepresent exposure to the rapid environmental change[67].

5.4.2. Compound Flooding in the Mekong Delta

There are especially acute areas of low-lying coastal deltas that are subject to compound flood risk. The combination of rising sea levels, storm surges, and high river discharges in the Mekong River delta leads to severe floods. Tropical cyclone storm tides may also combine with maximum river flows, resulting in the large-scale inundation despite the absence of excessive rain. This compound mechanism has influenced millions of dwellers and gained more influence in the conditional strategies of management of deltas, such as investments in coastal defense and relief plans[68].

Representative real-world applications of predictive modeling and risk assessment for floods, droughts, and compound hydrological extremes are summarized in **Table 4**.

5.5. Lessons from Case Studies

In the case studies that are reviewed, some common lessons can be presented about hydrological extremes in climate change. Whereas climate signals tend to be strong, local impacts are significantly different. Time series of floods throughout Africa (West Africa and the Nile Basin) and flood projections exhibit definite climate-related tendencies, but the results of the area depend to a significant extent on watershed properties and primary climatic forces, as well as the choice of models[59]. Combining various modeling techniques significantly increases the relevance of the decisions made because the research indicates that integrating hydrological models with climate projections, socio-economic exposure data, and risk assessment frameworks yields more practical information than using individual outputs of the models.

The study of the compound and sequential extremes throws light on the shortcomings of the conventional single-event methods that tend to miss transitions and interactions between hazards[67]. Drought-to-flood transition and compound coastal flooding research suggests the importance of multivariate and process-based frameworks. The processes of urbanization and infrastructure/project expansion exacerbate hydrological risks, especially in Sahelian metropolitan areas and coastal deltas, which are rapidly expanding and exposed to the risks without a sufficient number of resources to manage them[61]. Lastly, doubts have been a key issue in all studies. Disagreements in climate projections, the structure of hydrological models, and the definition of thresholds support the significance of uncertainty quantification and scenario analysis as main components of credible and policy-relevant risk assessment.

Table 4. Case studies of hydrological extremes under climate change, summarizing regional context, dominant drivers, predictive modeling approaches, risk assessment focus, findings, and representative references.

Region/Basin	Type of Extreme	Drivers	Modeling Approaches	Risk Assessment Focus	Findings	Representative References
West Africa (regional scale)	Riverine floods	Intensified precipitation, warming, land-use change	Large-scale hydrological models (HMF-WA, LISFLOOD) driven by CMIP6 scenarios	Flood frequency, magnitude, spatial extent	Flood magnitudes for 2-yr and 20-yr events projected to increase at >90% of stations under 2 °C warming	Diop et al. [59]
Ouagadougou, Burkina Faso	Urban flash floods	Extreme rainfall, rapid urbanization, limited drainage	Event-based hydrometeorological analysis; stakeholder-informed assessment	Urban exposure and vulnerability	Lack of drainage infrastructure amplified flood impacts during the 2009 extreme rainfall event	Miller et al. [61]
Limpopo River Basin (Southern Africa)	Large-scale floods	Climate variability, extreme rainfall, basin-scale hydrology	HYPE hydrological model with RCM forcing (RCP4.5, RCP8.5)	Spatial flood hazard and return periods	50-yr and 100-yr flood magnitudes projected to increase by up to 84% and 142%, respectively	Ekolu et al. [62]
Nile River Basin	Extreme river flooding	Increased precipitation, climate variability	SWAT model driven by CMIP6 SSP scenarios	Peak discharge extremes, transboundary risk	100-yr floods projected to occur at decadal frequency under high-emission scenarios	Mathe et al. [63]
Sahel Region	Prolonged droughts	Reduced rainfall, high evapotranspiration	Statistical drought indices; remote sensing (NDVI, soil moisture)	Agricultural and socio-economic vulnerability	Drought severity strongly linked to food insecurity and water stress	Feng et al. [64]
Xi River Basin, China	Hydrological droughts	Climate change, increasing water demand	Distributed hydrological modeling with climate scenarios	Drought frequency and severity	Increased drought risk in sub-basins with high socio-economic exposure	Feng et al. [64]
Western United States	Compound drought–heatwave–flood events	Atmospheric blocking, warming, land–atmosphere feedbacks	Hybrid modeling (process-based + ML)	Multi-hazard risk to water and energy systems	Traditional single-hazard models underestimate compound risks	Anderson et al. [67]
U.S. Coastal Regions (CONUS)	Compound coastal flooding	Storm surge, river discharge, sea-level rise	Coupled river–coastal models; reanalysis data	Inundation risk under compound drivers	Moderate surges combined with river floods produce extreme coastal inundation	Wood et al. [68]
Mekong River Delta	Compound fluvial–coastal floods	Sea-level rise, storm tides, upstream discharge	Hydrodynamic modeling + climate scenarios	Population and infrastructure exposure	Compound flooding significantly increases inundation extent in delta regions	Wood et al. [68]

5.6. Comparative Synthesis and Transferable Insights

To achieve analytical consistency between the reviewed case studies, representative studies were identified using three criteria: peer-reviewed modeling analysis of hydrological extremes, a wide variety of hydroclimatic regions, and similar quantitative indicators, e.g., changes in return periods, changes in the magnitude of floods, and the severity of droughts or probabilistic risk measures. In all the examined areas, such as West Africa, the Nile Basin, Limpopo Basin, the Sahel, and some regions of East Asia, modeling studies show a consistent pattern of climate change affecting hydrological extremes by changing the probability, frequency, and intensity of an event, and not necessarily causing single floods and droughts. The prevailing trend in flood-oriented studies is the projection of rising peak discharges and shortening of the period of return with rising precipitation, whereas the drought-related studies find a long period of duration and high severity caused by low rainfall and high evapotranspiration. Although there are regional differences, several general lessons can be seen. To begin with, the projection of hydrological extremes is highly prone to a high level of uncertainty due to the effect of climate model forcing, the structure of the hydrological model, and parameterization of the model. Second, land-use change, reservoir operation, and socio-economic exposure are local factors that greatly alter the manifested impacts of climate-driven hazards. Third, there is some comparative evidence to propose that ensemble and hybrid modeling systems, coupled with standardized risk measures, are better measures of extreme-event risk in non-stationary climatic conditions. These lessons learned in general suggest that the study of hydrological extremes should be made more comparative and practical by incorporating integrated modeling and uncertainty-analysis risk assessment[69,70].

6. Emerging Trends, Challenges, and Future Outlook in Hydrological Extremes

Climate change is leading to hydrological extremes, which are changing rapidly due to the expansion of the hydrological cycle, changes in precipitation, rising temperatures, and increasing anthropogenic pressures. These extremes have become more complicated to understand and predict, given the combination of climatic, hydrological, and socio-economic factors. Recent studies point to the new trends in modeling, risk assessment, and adaptation, as well as the challenges that are continuously unsolved and that future research may explore[71].

6.1. Intensification and Changing Patterns of Hydrological Extremes

One of the patterns witnessed across the world is the increase in the intensity of hydrological extremes. This is because observational studies and climate projections have always shown that severe precipitation events are increasing in frequency and intensity in most areas, whereas droughts are increasing in length and intensity, especially in semi-arid and arid climates. As an example, more severe monsoon-induced floods have been witnessed in the Indian subcontinental region of South Asia, whereas long dry seasons have hit North China, affecting water sources. Flood and drought risks have increased in the western United States due to increased atmospheric moisture content and evapotranspiration caused by warming. Such alterations render the relevance of models that are able to reflect the non-linear and compound character of hydrological excesses[72].

New studies focus on the frequency, timing, and spatial coherence of extremes as well as the magnitude of extremes. The increasing acknowledgment of compound events as a significant issue has arisen since several hazards are simultaneously or sequentially present. Complex interactions are evident in coastal inundations due to the interaction of storm surge and river discharge or drought, which is then succeeded by flash floods of temperate basins. The need to know these events is through the integrated frameworks that are in a position to simulate multivariate dependencies and spatio-temporal correlations[72].

6.2. Advances in Predictive Modeling

Innovations in recent predictive modeling represent the combination of climate projections, process-based hydrology, and data-based approaches. There is an increase in the use of hybrid modeling frameworks, which are physically-based models together with machine learning algorithms to enhance forecasting competence, lower the cost of computation, and measure uncertainties in a superior manner. As an illustration, physics-informed machine learning models are more capable of simulating the effect of extreme precipitation events on runoff, without violating the hydrological conservation laws[73].

Climate models at high resolutions and downscaling methods are becoming more common to capture the local scale extremes, and ensemble methods are becoming feasible in order to characterize future events on a probabilistic basis. This probabilistic view is essential to risk assessment because it reflects the paradox of high uncertainty of the extrapolation to extremes of nonstationary climatic conditions. Simultaneously, with the improvement of remote sensing and earth observation technologies, real-time and high-resolution hydroclimatic data are now available, which allows more accurate monitoring and preempting extreme events[29].

6.3. Integration of Socio-Hydrological and Multi-Hazard Approaches

The extreme manifestations of hydrology are not considered as pure physical processes anymore; the socio-economic setting and human activity are part of the risk perception. New frameworks are being developed based on the socio-hydrological strategies, integrating human activities, land-use transformations, water management plans, and policy responses into hydrological models. As an example, irrigation withdrawals, city drainage alterations, and reservoir activities have an effect on the size and occurrence of extreme events. These human influences are accounted for and can improve predictive realism of the models with informed responses on adaptation strategies.

Moreover, multi-hazard and multi-compound risk models are becoming more popular. These methods quantify the risks and benefits of various hazards such as droughts, heatwaves, and floods, and assess the combined effects of these on infrastructure, agriculture, and ecosystems. This point of view is especially relevant in the conditions of climate change, when the likelihood of compound extremes is likely to increase. Multi-hazard assessments help to have a better picture of vulnerability and resilience, which should be used to prioritize the adaptation actions in different sectors[45].

6.4. Emerging Data and Technology Trends

Hydrological monitoring and prediction are being revolutionized through technological advances. There are remote sensing technologies that provide near-real-time observation at various geographies, such as satellite-based precipitation estimates, soil moisture sensors, and radar systems. The growing access to big data allows machine learning models to take advantage of large-scale data, detect complicated trends, and enhance short-term prediction of extremes. Combination with cloud computing and high-performance modeling platforms can offer quick simulations of a variety of climate scenarios and hydrological predictions.

Water management is also improving the decision support system through artificial intelligence. The early warning systems based on AI can process hydrometeorological data in real-time, and they can alert about floods or drought. Also, AI has the capability of streamlining the automation of reservoirs, water assignment, and city drainage systems to decrease exposure to extremes. These technological dynamics highlight the possibility of integrating predictive science with operational decision-making to increase climate resilience[74,75].

6.5. Challenges in Modeling and Risk Assessment

Nevertheless, there are still significant challenges, even in the light of methodological changes. Data is always a problem, particularly in developing areas where observational networks are few. This causes a restriction in the calibration and validation of models, which decreases predictive reliability. Climate change causes nonstationarity, which makes the conventional frequency-based analysis less representative of the extremes in the future. Multivariate models with strong dependencies are needed to capture the dynamics of compound events, which are difficult to estimate using limited data[41].

Another significant issue is model uncertainty, which is caused by the climate projections, the hydrological representations, and the choice of the parameters. It is very important yet not simple to quantify and communicate these uncertainties to the decision-makers. Also, scientific predictions are frequently translated into the action of adapting, but there are socio-political and institutional hurdles to such a process. The incorporation of cross-sectoral data and stakeholder views is still considered to be a major obstacle to operationalizing predictive models to achieve effective risk reduction[76,77]. Essential emerging trends, challenges, and future research directions in the study of hydrological extremes are summarized in **Figure 3**.

6.6. Future Outlook and Research Directions

The following frontier in the hydrological extreme study focuses on integrated, adaptive, and anticipatory studies. Future research will involve the improvement of the multi-scale modelling process, i.e., by linking global climate models with regional hydrological frameworks and local socio-economic information, as well as creating actionable predictions both spatially and over time. There should also be advancements in the study of compound and cascading events by creating frameworks depicting sequential and simultaneous extremes that include physical, social, and ecological interactions[78]. Moreover, new developments in data assimilation and real-time forecasting will be more dependent on remote sensors, IoT-related sensors, and high-frequency monitoring to serve near-real-time predictions and early-warning systems. There will be an increasing role of socio-hydrological modelling and resilience assessment through the inclusion of human behaviour, policy reactions, and adaptive capacity in predictive tools to enhance planning and decision-making. Emphasis will be placed further on the quantification of uncertainty and communication by use of ensemble modelling, probabilistic methods, and scenario analysis, so there is a clear presentation of the level of confidence which will be used to make a risk-based policy. Lastly, there will be a shift toward cross-disciplinary and participatory solutions, where hydrologists, climatologists, engineers, social scientists, and other interested parties will jointly create context-related and implementable solutions[29,79,80].

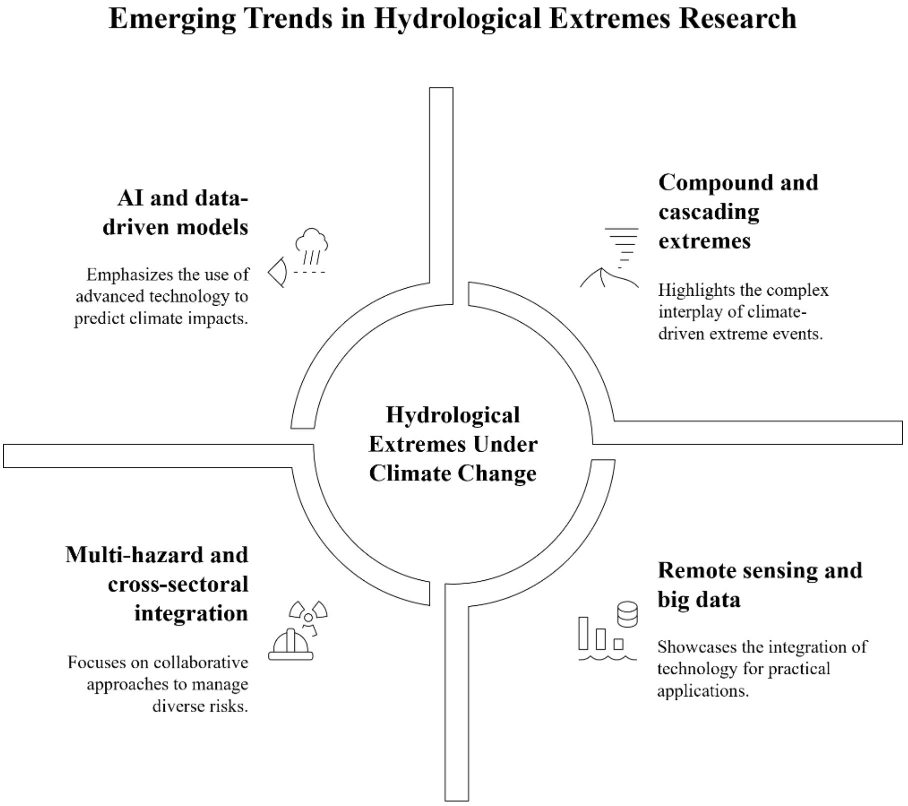

Figure 3. Synthesis of emerging trends, methodological innovations, and future directions in predictive modeling and risk assessment of hydrological extremes under climate change.

6.7. Implications for Policy and Water Resource Management

The simultaneous appearance of scientific developments and new trends predetermines the need to actively manage water resources. The predictive models that are used to inform the policies have to consider nonstationary effects of climate, spatially and temporally different hazards, and compound dangers. Vulnerability can be minimized by investing in resilient infrastructure, a dynamic water allocation system, and ecosystem-based solutions. The combination of predictive modeling and governance, community, and early warning systems can guarantee that science is transformed into practice and resilience to hydrological extremes, becoming more frequent and severe[81,82].

7. Conclusions

Climatic variability, land use changes, and socio-hydrological interactions are gradually affecting the hydrological extremes, such as floods, droughts, and compound events. This review has summarized the recent developments in predictive modeling and risk assessment methods adopted to learn and control these extremes in the non-stationary climate conditions. Statistical, process-based, and data-driven models are also useful but have significant weaknesses in terms of assumptions, data conditions, interpretability, and uncertainty. Hybrid and ensemble model frameworks have become promising in that they integrate physical process representation and predictive machines of machine learning to enhance the robustness of an extreme-event simulator.

Comparative analysis of modeling techniques and case studies indicates that the extremes of hydrological conditions are more likely to be seen as a change in probability and severity of occurrence as opposed to the certainty of climate change. In the various parts, the projections are very much consistent, with an upsurge in the magnitude of floods, distorted periods, and augmented risk of drought, but the degrees of such changes are unclear owing to variations in climate models, hydrological model frameworks, and local socio-environmental influences. In general, to enhance the predictive ability, one will need combined model strategies, uniform risk measures, and uncertainty treatment. Future studies must aim at highlighting the development of hybrid modeling frameworks, enhancing the availability of data, and enhancing the incorporation of hydrological science and risk-based water management and climate adaptation planning.

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