Aquatic Ecological Risk and Climate Change: A Survey

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Abstract

Aquatic ecological risks, driven by climate change and emerging contaminants, pose significant challenges to water ecosystems worldwide. This survey paper explores the interdisciplinary approaches necessary for managing these risks, emphasizing the integration of diverse scientific perspectives and advanced technologies. Key areas of focus include the impacts of climate change on water quality, the role of emerging contaminants, and the importance of sustainable catchment management strategies. The survey highlights the critical need for real-time data collection and advanced modeling techniques to improve ecological risk assessments and inform adaptive management strategies. It underscores the significance of integrating microbial research into climate change frameworks and developing biophysical models to predict species responses, thereby enhancing ecosystem resilience. The paper also discusses the policy implications of these findings, advocating for societal and cultural shifts alongside technological advancements to achieve sustainable environmental outcomes. The conclusion emphasizes the necessity of integrated management strategies to mitigate the compounded impacts of climate change and emerging contaminants, ensuring the long-term sustainability of aquatic ecosystems.

1 Introduction

1.1 Contextualizing Aquatic Ecological Risk

Aquatic ecological risk arises from the interplay of climate change, human activities, and technological advancements, posing significant threats to ecosystems globally. Infrastructure developments, such as roads, disrupt ecological niches, complicating the interactions between anthropogenic activities and natural habitats under changing climatic conditions [1]. The effects of climate change on mountain ecosystems exemplify broader environmental shifts, highlighting the urgency of addressing these risks [2].

Sustainable water allocation amidst climate uncertainty is vital for managing these risks, particularly given the global significance of water resource management in the face of climate change [3]. Technology's dual role in environmental issues—both mitigating and exacerbating climate change impacts—complicates the landscape of aquatic ecological risks [4].

The redistribution of biodiversity due to climate change has profound implications for ecosystems and human well-being, necessitating the integration of these dynamics into global frameworks and decision-making processes [5]. The economic repercussions of marine ecosystem shifts are increasingly acknowledged, with corporate and financial actors facing exposure to marine tipping points [6]. Additionally, microorganisms play a crucial role in climate change biology, influencing ecosystem sustainability [7].

Coral reef ecosystems, particularly vulnerable to climate change and anthropogenic pressures, illustrate the global significance of aquatic ecological risks, where cumulative impacts are evident [8].

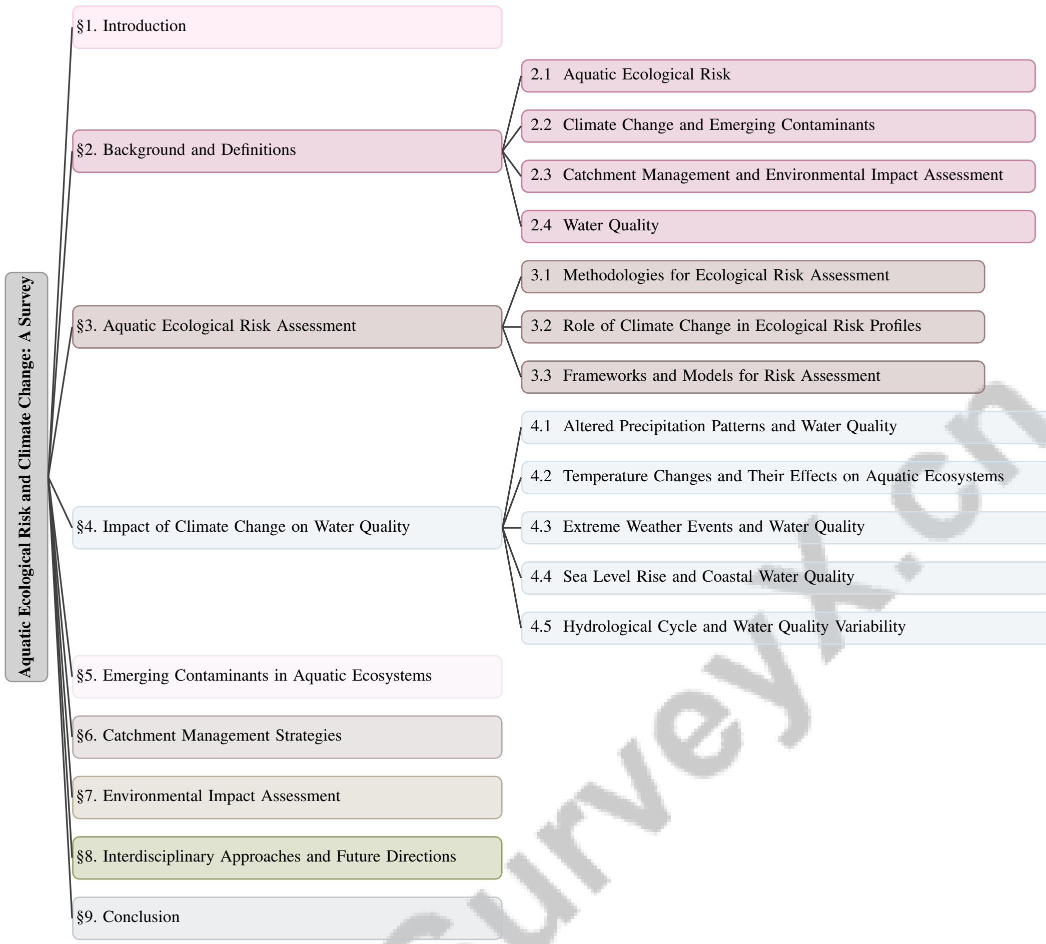


Figure 1: chapter structure

Local climate dynamics, such as those in Turkey, provide insights into potential future trajectories of climate change [9]. The societal impact of research, measurable through innovative metrics like Altmetric data, underscores the broader implications of scientific findings on climate change [10].

Ensuring agricultural sustainability amidst climate change is critical, emphasizing the need for interdisciplinary efforts to sustainably feed a growing global population [11]. Predicting species responses to climate change through biophysical models that elucidate organism-environment interactions is essential for developing robust scientific frameworks [12]. Collectively, these studies highlight the global significance and urgency of aquatic ecological risks, underscoring the necessity for comprehensive, interdisciplinary approaches to mitigate the compounded impacts of climate change and emerging contaminants on aquatic ecosystems.

1.2 Interdisciplinary Importance

Addressing aquatic ecological risks necessitates an interdisciplinary approach that integrates insights from diverse scientific fields to develop effective solutions. The convergence of social and natural sciences fosters innovative perspectives essential for tackling climate change [13]. This integration is reinforced by frameworks categorizing climate change solutions into distinct fields, emphasizing the importance of combining mitigation and adaptation strategies [14].

Environmental risk assessments in aquatic ecosystems significantly benefit from interdisciplinary methodologies that leverage diverse scientific expertise [15]. The expanding body of climate change research across multiple disciplines underscores the challenges and necessity of collaboration to synthesize and effectively apply this knowledge [16].

Moreover, integrating machine learning into climate strategies exemplifies the critical role of interdisciplinary collaboration, facilitating innovative solutions to complex environmental challenges [17]. The intersection of neurobiology with ecological and evolutionary perspectives further illustrates how interdisciplinary approaches can enhance our understanding of ecosystem dynamics [18].

The moral imperative to transition rapidly to a post-fossil fuel world emphasizes the urgency of interdisciplinary efforts to safeguard future generations from climate change impacts [19]. A polycentric approach to climate change, which prioritizes local and regional actions alongside global treaties, highlights the importance of diverse disciplinary contributions in crafting effective climate strategies [20].

Incorporating multiple lines of scientific evidence through holistic approaches enhances adaptation and risk management effectiveness by providing region-specific climate information [21]. Understanding microorganism-climate interactions further emphasizes the need for interdisciplinary approaches, as these interactions significantly influence climate dynamics [7]. The call for transdisciplinary research to develop sustainable agricultural practices underscores the role of various scientific disciplines in addressing agricultural challenges [11]. These interdisciplinary efforts are essential for tackling the multifaceted challenges posed by aquatic ecological risks and ensuring the resilience of aquatic ecosystems in the face of climate change.

1.3 Structure of the Survey

This survey is meticulously organized to provide a comprehensive examination of aquatic ecological risks within the context of climate change. The introduction contextualizes these risks and emphasizes the interdisciplinary importance of addressing these challenges. The subsequent background and definitions section elucidates key concepts, including aquatic ecological risk, climate change, emerging contaminants, catchment management, environmental impact assessment, and water quality, establishing a foundational understanding of the interconnectedness of these elements.

The survey progresses to explore methodologies for aquatic ecological risk assessment, highlighting the influence of climate change on risk profiles and the role of emerging contaminants. The following section analyzes the effects of climate change on water quality, focusing on critical factors such as altered precipitation patterns, temperature fluctuations, increased frequency of extreme weather events, rising sea levels, and variations in the hydrological cycle. This examination is essential for understanding the complex interplay between industrial growth and environmental impacts, as recent research trends emphasize the importance of sophisticated modeling techniques for effective prediction and mitigation [16, 22].

Emerging contaminants in aquatic ecosystems are scrutinized, focusing on their types, sources, ecological impacts, and the challenges they pose to water quality management. The section on catchment management strategies discusses sustainable approaches, nature-based solutions, adaptive management, and the significance of policy and stakeholder engagement.

Environmental impact assessments are crucial for effectively managing aquatic risks, particularly by integrating real-time data collection and addressing uncertainties associated with emerging contaminants in water systems. This approach facilitates monitoring pollutants, such as pharmaceuticals and endocrine-disrupting chemicals, while enhancing the assessment of their ecological and human health risks. Utilizing methodologies that incorporate satellite observations and energy data provides timely, spatially-disaggregated insights into the environmental impacts of water reclamation processes and associated risks, ultimately guiding policymakers in implementing more effective standards and mitigation strategies [23, 24]. The survey culminates with a discussion on interdisciplinary approaches and future directions, advocating for integrated frameworks, technological innovations, and enhanced communication across disciplines to improve ecosystem resilience and water quality management.

The synthesis of key findings underscores the urgent need for integrated management strategies that address the multifaceted challenges posed by climate change and emerging contaminants, highlighting their compounded effects on aquatic ecosystems. This approach is essential for mitigating the adverse impacts of rising temperatures and extreme weather events while enhancing the resilience of both wildlife and human habitats. Collaborative efforts combining diverse strategies—ranging from technological innovations to socioeconomic considerations—are critical for effectively safeguarding these ecosystems in an increasingly volatile climate [14, 16, 25, 26].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Aquatic Ecological Risk

Aquatic ecological risk involves potential adverse impacts on ecosystems due to stressors such as climate change, pollution, habitat alterations, and human activities. This field emphasizes the intricate interactions among these stressors and the adaptive capacities of aquatic life. High biodiversity among primary producers, like phytoplankton, supports ecosystem resilience despite competitive interactions [27]. However, environmental contaminants, including heavy metals in areas like the Huixian wetland, pose significant risks to ecosystems and human health [28]. Climate change further complicates these interactions by altering predator-prey dynamics and increasing the frequency of unfavorable conditions [29]. Estimating exceedance regions highlights the inherent uncertainty in aquatic risk assessments [30], while microorganisms' roles in climate biology underscore their importance in ecosystem resilience [7].

Human activities, such as fishing and tourism, exacerbate these risks, necessitating a balance between ecological health and economic pursuits [8]. The environmental impact of AI and ML technologies, particularly their energy consumption, presents additional challenges [23]. Agricultural practices, including synthetic fertilizer overuse, contribute to contamination, linking terrestrial and aquatic ecological risks [11]. Climate-induced shifts in species distributions disrupt ecosystems, affecting societies reliant on these systems [5]. Addressing aquatic ecological risk requires comprehensive, interdisciplinary research to tackle the challenges posed by climate change, pollution, and anthropogenic stressors.

2.2 Climate Change and Emerging Contaminants

The interaction between climate change and emerging contaminants poses significant challenges to aquatic ecosystems. Climate change, driven by anthropogenic emissions, leads to global warming and natural disasters that transform aquatic environments [22]. Predicting climate sensitivity is complicated by diverse feedbacks, impacting forecasts of climate impacts on aquatic systems [31]. Hydrological cycle alterations, as observed in Turkey, affect temperature and precipitation patterns, impacting aquatic habitats [9].

Emerging contaminants, such as heavy metals and synthetic chemicals, exacerbate these challenges by threatening aquatic life. Heavy metals in wetlands, like Huixian, illustrate industrial pollution's detrimental effects [28]. The presence of these contaminants in wastewater treatment plants indicates their potential to disrupt ecosystems [24]. Climate-induced hydrological changes compound these dynamics, threatening aquatic system resilience. Climate variability can heighten extinction risks in predator-prey systems when adverse conditions align with critical life stages [29]. The varied responses of mountain ecosystems to climate change illustrate the diverse impacts of climate dynamics [2]. Hydropower systems' operations in a decarbonized European context exemplify climate change's effects on reservoir inflows, impacting aquatic habitats [32].

Addressing these issues requires strategic communication and cohesive global action, though political indecisiveness and technological limitations often impede progress. AI and ML innovations offer promising avenues for enhancing climate change mitigation and adaptation strategies [23]. The compounded impacts of climate change and emerging contaminants necessitate interdisciplinary approaches for robust conservation strategies. Enhanced analytical frameworks and adaptive management strategies are vital for mitigating these risks and ensuring aquatic environments' sustainability amid climatic and anthropogenic pressures [33]. Reliable climate change projections are crucial for informing policy-making and risk assessment, particularly in the context of uncertainty and dynamic international climate actions [34]. The oversimplification of climate change effects across diverse countries highlights the need for nuanced approaches considering geographical interrelations and varying impacts across regions [35]. Accurate regional climate model outputs characterization is essential for understanding projections' impacts on biophysical systems and economic sectors.

2.3 Catchment Management and Environmental Impact Assessment

Catchment management and environmental impact assessments (EIA) are crucial for managing aquatic ecological risks, especially in the context of climate change and emerging contaminants. Effective catchment management, essential for water quality and ecosystem resilience, requires understanding land use, water flow, and ecological health interactions influenced by climate dynamics [24]. Strategies incorporate science-intensive technologies and engineering solutions for coastal and water management [36], balancing human needs with habitat preservation. Hierarchical research categorizations into hazard, susceptibility, and resilience provide frameworks for managing flood risks exacerbated by climate change [37].

Environmental impact assessments evaluate proposed projects' potential effects on aquatic environments, systematically identifying, predicting, and mitigating adverse impacts to support sustainable development. Integrating real-time data collection enhances EIAs' accuracy and relevance, facilitating effective ecological risk monitoring and management [6]. However, the interdisciplinary nature and rapid climate change literature expansion challenge maintaining a research overview essential for informed EIA decision-making [16]. Modeling ocean-atmosphere interactions, like ENSO, underscores the need for robust methodologies to understand climatic impacts on ecosystems, crucial for predicting water quality and availability changes [38]. Regional climate impact drivers, including heavy rainfall, drought, and fire weather, emphasize tailored management strategies addressing ecological risks in different contexts [39].

A polycentric climate change management approach, promoting diverse actor cooperation without relying solely on global treaties, is essential for effective catchment management and EIAs [20]. This approach facilitates localized solutions and stakeholder engagement, ensuring context-specific and adaptive management strategies. Despite challenges like data gaps and complex governance structures, innovative solutions such as water reclamation and ecological reuse address high pollutant loads and insufficient ecological flow in urban rivers [24]. Integrating catchment management and EIAs into broader environmental policies enhances aquatic ecosystems' resilience. However, the low percentage of climate change literature in policy documents indicates a need for improved researcher-policymaker communication to translate scientific insights into actionable strategies [10]. By fostering interdisciplinary collaboration and leveraging technological advancements, catchment management and EIAs significantly contribute to mitigating aquatic ecological risks and promoting sustainable water resource management.

2.4 Water Quality

Water quality, encompassing the physical, chemical, and biological attributes of water, is fundamental for aquatic ecosystems, determining their capacity to support life and meet human needs. Maintaining high water quality is critical for biodiversity preservation and ecosystem resilience while safeguarding human health. The interplay between soil erosion and water quality is significant, with climate change exacerbating these dynamics and influencing sediment transport and nutrient loading [40]. In regions like the Mediterranean, climate change intensifies water quality challenges, necessitating solutions such as constructed wetlands to mitigate pollution and climate impacts [41]. Monitoring systems in the Venice Lagoon highlight the need for efficient solutions to track water quality variations driven by anthropogenic and natural factors [42]. Managing extensive time series data from ecological observatories is crucial for assessing ecological risks and informing water management strategies [43].

Climate change impacts on water quality are emphasized by hydrological cycle alterations and increased greenhouse gas emissions, affecting soil moisture and evapotranspiration, leading to shifts in water availability and quality [44]. Analyzing datasets with physical and chemical parameters like pH, temperature, and nitrate concentrations provides essential insights into water quality influences [45]. The KZ method's capability to handle time series data with missing observations is vital for accurately tracking water quality trends [46]. Phytoplankton communities' resilience and biodiversity, supported by seed banks, play a crucial role in maintaining water quality by stabilizing ecosystems against environmental fluctuations [27]. However, the sustainability of technologies used in water quality monitoring and management must be considered, particularly regarding AI models' high energy consumption and $CO2$ emissions [47]. The impact of technological advancements on environmental degradation, especially in clean energy technologies and AI, complicates water quality management [4].

Maintaining high water quality standards is crucial for safeguarding ecosystems and human health, necessitating a comprehensive understanding of water dynamics influences, such as pollution from heavy metals and climate change impacts. Effective management strategies must be implemented, drawing on thorough ecological risk assessments, particularly in regions with high human activity, to mitigate contaminants' adverse effects and ensure wildlife and human community resilience amid ongoing environmental challenges [14, 48, 49].

3 Aquatic Ecological Risk Assessment

Category	Feature	Method
Methodologies for Ecological Risk Assessment	Ecological Dynamics Scenario Customization Data and Pattern Analysis	D[50] AC[34] CMM-AEIM[23], MHM[51]
Role of Climate Change in Ecological Risk Profiles	Dynamic Data Processing	ABM[8], FAIR-TS[43], CRCER[30], MDRO[3]
Frameworks and Models for Risk Assessment	Trend and Sensitivity Analysis Event Interaction Analysis	KZ[46], MC-LR[31] ECA[33]

Table 1: This table provides a comprehensive overview of various methodologies, features, and methods employed in ecological risk assessment within aquatic environments. It categorizes the approaches into three main areas: methodologies for ecological risk assessment, the role of climate change in ecological risk profiles, and frameworks and models for risk assessment. Each section highlights specific techniques and tools that enhance the understanding and management of ecological risks posed by environmental stressors.

Effective methodologies for ecological risk assessment are crucial in addressing the challenges posed by environmental stressors. Table 1 presents a detailed categorization of methodologies and tools used in aquatic ecological risk assessment, highlighting their significance in addressing environmental challenges. Table 4 offers a comprehensive comparison of different methodologies employed in ecological risk assessment, emphasizing their distinct analytical techniques, predictive capabilities, and interdisciplinary integration. This section delves into various methodologies employed in aquatic ecological risk assessments, emphasizing their roles in quantifying risks and informing management strategies. A thorough understanding of these methodologies is vital for navigating the complexities of aquatic ecosystems and ensuring their resilience amid changing environmental conditions.

3.1 Methodologies for Ecological Risk Assessment

Method Name	Analytical Techniques	Predictive Capabilities	Interdisciplinary Integration
MDRO[3]	-divergences	Scenario Tree	Various Data Sources
CMM-AEIM[23]	Satellite Data Analysis	Assess Environmental Changes	Earth Observation Data
AC[34]	Climate Model Emulator	Probabilistic Climate Projections	Emissions Scenarios Integration
MHM[51]	Markov Random Field	Probabilistic Projections	Multiple Climate Variables
D[50]	Simulation Study	Forecast Ecological Outcomes	Diverse Scientific Disciplines

Table 2: Overview of methodologies for ecological risk assessment, highlighting analytical techniques, predictive capabilities, and interdisciplinary integration. This table provides a comparative analysis of five methods, including MDRO, CMM-AEIM, AC, MHM, and D, illustrating their unique approaches to addressing ecological challenges.

Ecological risk assessment methodologies are essential for understanding and mitigating the impacts of stressors such as climate change, pollution, and habitat alterations in aquatic environments. These methodologies provide structured approaches for quantifying risks and guiding ecosystem management. The Multistage Distributionally Robust Optimization (MDRO) method exemplifies recent advancements by addressing uncertainties in water allocation through conditional distributions based on -divergences, thereby enhancing decision-making under uncertainty [3].

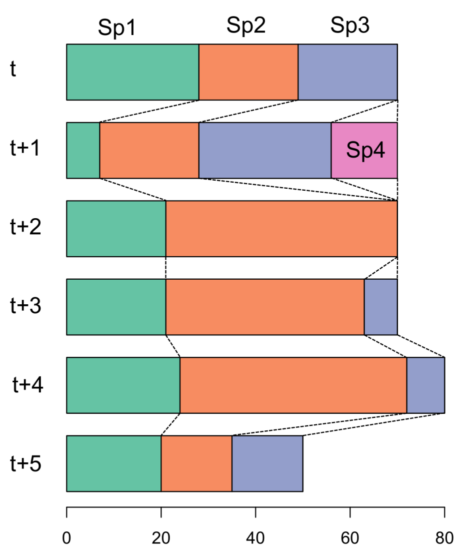
Machine learning techniques have transformed risk assessments by enhancing predictive capabilities. Techniques such as Linear Regression, Support Vector Regression (SVR), XGBoost Regressor, and Random Forest Regressor model complex environmental interactions, crucial for predicting geographic distributions and ecological dynamics [45]. Additionally, machine learning aids in estimating functional diversity using diffusion maps constructed from species abundance data, showcasing AI's potential in ecological assessments [23].

Advanced analytical techniques, like the Continuous Spatio-Temporal Decomposition Method (CSTDM), enhance ecological risk assessment by decomposing climate series into trend, seasonal, and cycle components while addressing spatial heterogeneity and missing data [52]. The AIRCC-Clim tool, which generates regional probabilistic climate change projections, offers user-defined emissions scenarios that improve understanding of future climatic impacts on aquatic ecosystems [34].

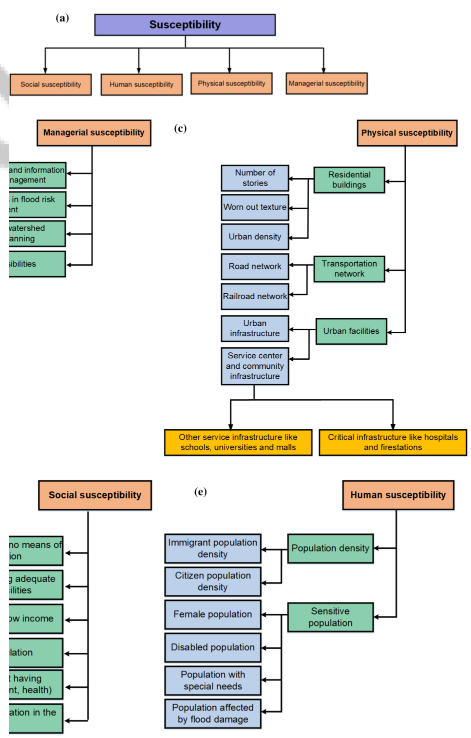
Statistical models designed for spatial analysis, incorporating hierarchical structures to represent spatial dependencies among climate variables, are instrumental in analyzing multivariate outputs from regional climate models [51]. The multi-RCM ensemble framework captures a broader range of climate scenarios, enhancing the reliability of climate change projections and informing risk assessments [53].

Network-based approaches contribute to risk assessment by identifying optimal sequences for species reintroductions based on their centrality in ecological networks, facilitating ecosystem restoration and resilience [10]. Additionally, frameworks that merge open datasets and apply classification schemes leverage deep learning models for classification, highlighting the integration of data-driven approaches in ecological assessments [7].

These methodologies underscore the importance of integrating diverse analytical tools and interdisciplinary insights to advance ecological risk assessment, ensuring the resilience and sustainability of aquatic ecosystems amid ongoing environmental challenges. A balanced approach to technological innovation, as highlighted by frameworks assessing the benefits and harms of technological systems, further emphasizes the need for careful consideration of technological impacts in ecological assessments [4]. Table 2 presents a comprehensive overview of various methodologies employed in ecological risk assessment, emphasizing their distinct analytical techniques, predictive capabilities, and interdisciplinary integration.



(a) Temporal Dynamics of a Species in a Food Web[50]



(b) Understanding Susceptibility in Urban Planning and Management[37]

Figure 2: Examples of Methodologies for Ecological Risk Assessment

As shown in Figure 2, the methodologies for ecological risk assessment are effectively illustrated through two visual representations. The first image, "Temporal Dynamics of a Species in a Food

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Web," depicts fluctuations in species abundance over time within an ecological food web, essential for understanding ecosystem dynamics and associated risks. The second image, "Understanding Susceptibility in Urban Planning and Management," presents a flowchart that systematically breaks down factors influencing urban planning and management, emphasizing the complexity and interconnectivity of ecological risks in urban environments. Together, these examples underscore the diverse methodologies employed in ecological risk assessment, providing valuable insights into both natural and urban ecosystems [50, 37].

3.2 Role of Climate Change in Ecological Risk Profiles

Climate change significantly alters ecological risk profiles in aquatic environments by modifying fundamental climatic and ecological processes. Increased variability in climate variables, such as temperature and precipitation, raises the likelihood of extreme weather events, impacting population survival and adaptation [54]. These changes necessitate the development of real-time data handling tools to dynamically adjust risk assessments and ensure timely identification and mitigation of ecological threats [43].

The economic implications of climate-induced tipping points are particularly pronounced in sectors like the fishing industry, where fleets from countries such as China, the US, Japan, and Norway face significant exposure to risks that could disrupt economic stability and employment [6]. Additionally, the interplay between climate change and ecological dynamics is complicated by tipping points affecting hydropower operations in Europe, where climate change influences water inflow and renewable energy penetration [32].

Theoretical frameworks, such as the Variable Territory (VT) model incorporating Allee effects, provide insights into how climate change affects predator-prey dynamics, further altering ecological risk profiles [29]. Integrating climate change into ecological models, particularly those evaluating cumulative impacts on marine ecosystems, highlights the necessity for adaptive management strategies to mitigate evolving risks [8].

As illustrated in Figure 3, the impact of climate change on ecological risk profiles encompasses key areas of ecological risks, economic implications, and methodologies. This figure categorizes the risks associated with aquatic environments, predator-prey dynamics, and marine ecosystems, while also addressing their economic implications on the fishing industry and hydropower operations. Furthermore, it presents various methodologies and frameworks that are essential for addressing these challenges.

Estimating equilibrium climate sensitivity is complicated by the multivariate nature of climate system responses, which evolve according to multiple eigenmodes rather than a single dominant mode [31]. This complexity necessitates methodologies that combine optimal prediction techniques with hypothesis-testing frameworks to accurately capture exceedance regions and inform risk assessments [30].

Incorporating diverse climate projections based on Global Circulation Models emphasizes the role of climate change in altering ecological risk profiles, underscoring the need for robust frameworks that accommodate varying climatic conditions [9]. The benchmark for quantifying maximum greenhouse gas emissions to align with the Planetary Boundary for Climate Change further illustrates the critical intersection of climate dynamics and ecological risk management [52].

Addressing these multifaceted issues requires strategic communication and cohesive global action. Enhanced analytical frameworks and adaptive management strategies are essential for mitigating these risks and ensuring the sustainability of aquatic environments amid ongoing climatic and anthropogenic pressures. Advanced methodologies like the MDRO method optimize allocations by integrating uncertainties into decision-making processes, thereby enhancing the resilience of ecological risk assessments [3]. Furthermore, real-time tools for monitoring plant needs and fertilizer availability provide valuable methodologies for improving ecological risk assessments in agricultural systems, showcasing the potential for interdisciplinary approaches to address climate change impacts [11].

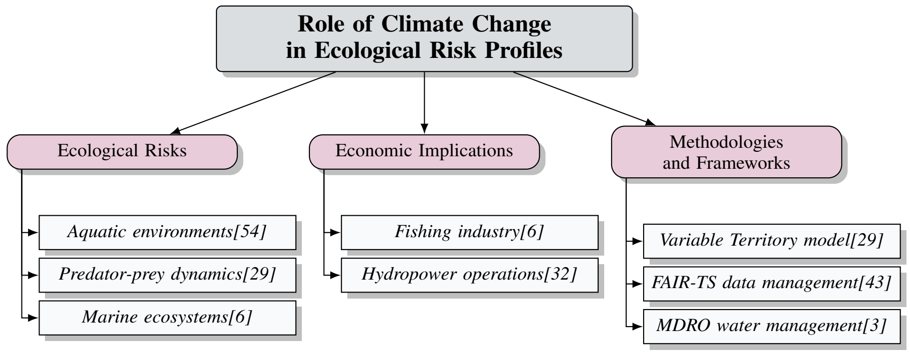

Figure 3: This figure illustrates the impact of climate change on ecological risk profiles, highlighting the key areas of ecological risks, economic implications, and methodologies. It categorizes the risks in aquatic environments, predator-prey dynamics, and marine ecosystems, along with their economic implications on the fishing industry and hydropower operations. Additionally, it presents various methodologies and frameworks addressing these challenges.

Method Name	Analytical Techniques	Interdisciplinary Integration	Adaptive Management
KZ[46]	Time Series Analysis	-	-
MC-LR[31]	Time Series Analysis	Diverse Fields	Regional Differences
ECA[33]	Simulation Models	Plant Science	Adaptive Management

Table 3: Comparison of Analytical Techniques, Interdisciplinary Integration, and Adaptive Management Across Risk Assessment Methods for Aquatic Ecosystems. This table outlines the distinct methodologies employed by the KZ, MC-LR, and ECA methods, highlighting their unique contributions to time series analysis, interdisciplinary integration, and adaptive management strategies. Such a comparison underscores the importance of combining diverse analytical tools to enhance ecological risk assessment and management.

3.3 Frameworks and Models for Risk Assessment

Frameworks and models for risk assessment in aquatic ecosystems are essential for understanding and mitigating the impacts of climate change and other anthropogenic stressors. These tools offer systematic approaches for evaluating potential risks and informing management strategies to enhance ecosystem resilience. The Kolmogorov-Zurbenko (KZ) time series analysis method, for example, provides a robust framework for predicting coastal water levels by deconstructing long-term trends and tidal components, improving the accuracy of risk assessments related to sea-level rise and coastal flooding [46].

The integration of diverse research methodologies into comprehensive frameworks is exemplified by the categorization of studies into 25 European Research Council (ERC) panels, mapping existing methods and studies based on their relevance to Climate Action [55]. This organization facilitates the identification of gaps in current research and the development of targeted strategies for addressing aquatic ecological risks. Table 3 provides a comparative analysis of various risk assessment methods for aquatic ecosystems, detailing their analytical techniques, interdisciplinary integration, and adaptive management strategies.

Simulation models exploring predator-prey dynamics under various climate scenarios provide insights into the potential impacts of climate change on ecological interactions. These models utilize custom software platforms to simulate different climate function parameters, focusing on predator survival time and emphasizing the importance of adaptive management strategies in mitigating ecological risks [29].

The Multivariate Climate-Land Response (MC-LR) method represents a significant advancement in estimating equilibrium climate sensitivity, capturing long-term dynamics from short transient warming simulations more effectively than traditional methods [31]. This method enhances understanding of climate change impacts on aquatic ecosystems, informing risk assessment frameworks with improved predictive accuracy.

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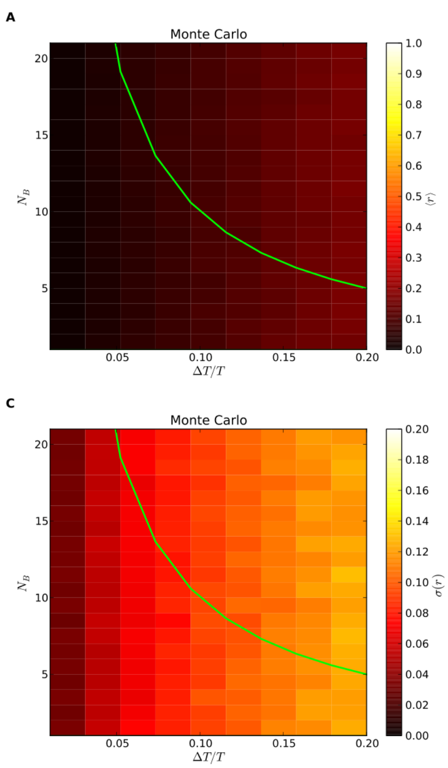
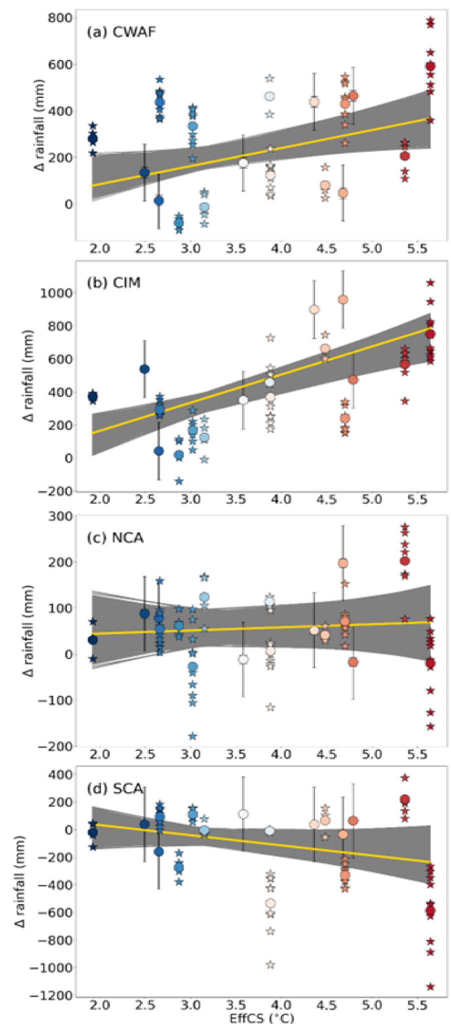
Dynamic grouping models, which allow for varying minimum mitigation rates based on regional characteristics, offer a nuanced approach to climate change mitigation compared to uniform rates in traditional frameworks like the RICE-N model [35]. These models account for regional differences in vulnerability and resilience, providing tailored strategies for managing aquatic ecological risks.

The frameworks and models discussed highlight the critical need for a transdisciplinary approach that combines diverse analytical tools and insights from fields such as plant science, engineering, computer science, and social sciences to enhance ecological risk assessment. By integrating these interdisciplinary perspectives, we can address complex environmental challenges posed by agricultural practices and the environmental impacts of artificial intelligence, ultimately leading to more effective and sustainable solutions for ecological risk management [11, 23]. Leveraging innovative methodologies and adaptive management strategies enhances the resilience and sustainability of aquatic ecosystems in the face of ongoing environmental challenges.



(a) Monte Carlo Simulation Results[33]



(b) Effect of Effective Climate Sensitivity on Rainfall Changes in Different Regions[39]

Figure 4: Examples of Frameworks and Models for Risk Assessment

As shown in Figure 4, understanding the frameworks and models that underpin risk evaluation is crucial for effective environmental management. The example illustrates two key methodologies: Monte Carlo simulations and analyses of effective climate sensitivity. The Monte Carlo simulation results, depicted in a scatter plot, provide insights into the probabilistic outcomes of environmental variables, specifically the ratio of T/T against the number of particles,

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39].

Feature	Multistage Distributionally Robust Optimization	Machine Learning Techniques	Continuous Spatio-Temporal Decomposition Method
Analytical Technique	Conditional Distributions	Regression Models	Trend Decomposition
Predictive Capability	Enhanced Decision-making	Complex Interactions	Spatial Heterogeneity
Interdisciplinary Integration	Uncertainty Management	AI Integration	Climate Series Analysis

Table 4: This table provides a comparative analysis of three prominent methodologies utilized in aquatic ecological risk assessment: Multistage Distributionally Robust Optimization, Machine Learning Techniques, and Continuous Spatio-Temporal Decomposition Method. Each method is evaluated based on its analytical technique, predictive capability, and interdisciplinary integration, highlighting their unique contributions to understanding and mitigating ecological risks in aquatic environments.

4 Impact of Climate Change on Water Quality

Understanding climate change's impact on water quality is crucial due to its profound challenges. This section explores how climate change affects aquatic ecosystems, focusing on altered precipitation patterns that shape hydrological processes and pollutant transport, influencing water quality in both freshwater and marine environments. The analysis emphasizes the intricate relationships between precipitation variability and water quality across diverse ecological contexts.

4.1 Altered Precipitation Patterns and Water Quality

Climate change-driven alterations in precipitation patterns significantly affect water quality by modifying rainfall intensity, frequency, and distribution. These changes increase runoff and erosion, transporting pollutants into water bodies, impacting ecosystem health and public safety. Extreme precipitation events exacerbate nutrient loading and alter water chemistry [56, 39]. Regions experiencing hydrological shifts show increased evaporation and precipitation extremes, necessitating robust modeling techniques [57]. Infrastructure like roads complicates these dynamics, exacerbating precipitation effects on aquatic systems [1]. Advanced modeling techniques, such as those assessing mangrove distributions, provide insights into coastal ecosystem impacts [58].

Daily streamflow patterns, influenced by human activities, illustrate challenges posed by altered precipitation on water quality, affecting sediment and pollutant transport [45]. Methodologies like the Wasserstein distance capture chlorophyll pattern differences, highlighting the need for advanced analytical techniques [59]. The potential collapse of the Atlantic Meridional Overturning Circulation (AMOC) under certain scenarios highlights broader implications for global water dynamics [60]. The AIRCC-Clim tool generates climate projections for emissions scenarios, aiding understanding of future precipitation changes and impacts on water quality [34]. Evaluating models using ensemble outputs from regional climate experiments emphasizes projected changes in seasonal temperature and precipitation, crucial for assessing future water quality dynamics [51].

These insights underscore the need for integrated monitoring and modeling strategies to forecast and address changing precipitation patterns' impacts on water quality. Such approaches are vital for safeguarding aquatic ecosystems and public health, especially given increasing extreme weather frequency and socioeconomic factors exacerbating these challenges. Collaborative efforts combining climate change mitigation strategies will be crucial for a comprehensive response to these environmental issues [14, 22, 26].

4.2 Temperature Changes and Their Effects on Aquatic Ecosystems

Temperature changes due to climate change significantly affect aquatic ecosystems and water quality. Models project significant warming trends throughout the 21st century, necessitating understanding and mitigation of these impacts [53]. In Turkey, temperatures are expected to rise by 1°C to 6°C by century's end, affecting aquatic ecosystems [9]. Intensified weather extremes, including heatwaves and droughts, alter thermal regimes and hydrological cycles [54]. The hydrological cycle's thermodynamics, particularly water's phase transitions, affect energy flows and water availability [57]. Rising temperatures in northern Tuscany threaten groundwater availability, stressing aquatic systems [61].

Temperature changes also influence aquatic community dynamics. Simulations indicate seed banks help maintain community stability amid varying interaction strengths and temperature fluctuations, highlighting biodiversity's role in resilience [27]. Rainfall data variability reflects climate change's complex impacts on water quality, necessitating continuous monitoring and adaptive management [62]. The relationship between Effective Climate Sensitivity (EffCS) and drought challenges water quality, reducing availability and increasing pollutant concentrations [39]. These insights emphasize the need for comprehensive frameworks to address temperature changes' multifaceted impacts on aquatic ecosystems and water quality, ensuring sustainability and resilience.

4.3 Extreme Weather Events and Water Quality

Climate change-exacerbated extreme weather events significantly impact aquatic ecosystem water quality. Rising greenhouse gas emissions increase event frequency and intensity, necessitating effective climate attribution methodologies [63]. Rising ocean levels threaten coastal communities and ecosystems, underscoring the need for comprehensive risk assessments and adaptation strategies [46]. Extreme events, such as hurricanes, floods, and droughts, alter water quality by changing sediment transport, nutrient loading, and pollutant dispersion. Increased runoff and erosion transport contaminants into water bodies, degrading quality and threatening aquatic life. Autonomous Surface Vehicles (ASVs) document underwater weather events, revealing significant water quality trends, highlighting their role in environmental monitoring [45].

To illustrate the complex interplay between extreme weather events and water quality, Figure 5 presents a hierarchical categorization of these impacts, emphasizing the effects of climate change, the tools available for monitoring, and the strategies for adaptation. Quantifying uncertainty in exceedance estimates across spatio-temporal contexts is crucial for understanding extreme weather impacts on water quality [30]. Tools like AIRCC-Clim, with user-friendly interfaces and probabilistic scenario generation, inform climate policy decision-making and enhance water management resilience [34]. Integrating advanced modeling techniques and real-time monitoring predicts and mitigates extreme weather impacts on water quality. By harnessing advanced climate change adaptation technologies (CCATs) and fostering transdisciplinary collaborations, policymakers and environmental managers can formulate robust strategies to safeguard aquatic ecosystems and promote sustainable water resource management. These approaches address escalating climate change challenges, enhancing ecosystem resilience and integrating diverse scientific insights and stakeholder perspectives. Leveraging artificial intelligence and natural language processing streamlines data analysis and policy formulation, enabling cohesive climate-related risk responses and effective mitigation and adaptation alignment [11, 64, 36, 14, 47].

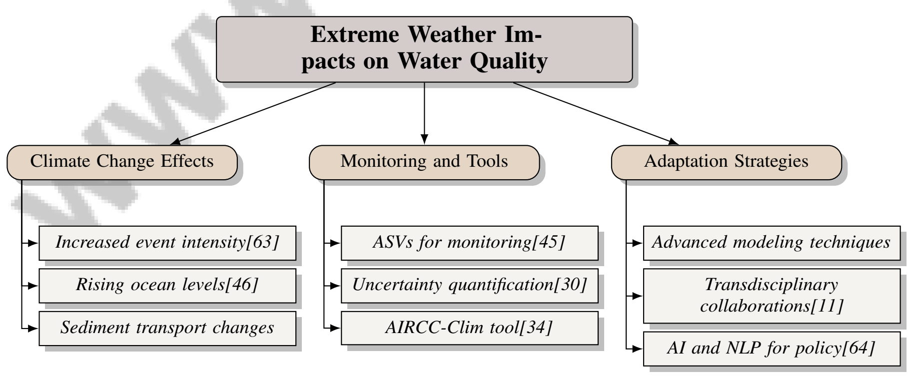

Figure 5: This figure illustrates the hierarchical categorization of the impacts of extreme weather events on water quality, highlighting climate change effects, monitoring tools, and adaptation strategies.

4.4 Sea Level Rise and Coastal Water Quality

Sea level rise, driven by climate change, threatens coastal water quality, affecting natural ecosystems and human communities. Ocean level rise primarily results from solar irradiation and atmospheric pollution, elevating temperatures and accelerating glacier melting [46]. These processes cause coastal inundation, resulting in saltwater intrusion into freshwater systems, degrading water quality.

Sea level rise, exacerbated by rapid urbanization, increases coastal town and city vulnerability, heightening flooding and erosion risks. This phenomenon compounds existing challenges related to physical, economic, social, and environmental factors, as communities face more frequent and severe flooding events that can overwhelm infrastructure and disrupt local economies. Enhanced resilience measures, including improved coping and adaptive capacities, are essential to mitigate these risks and protect vulnerable populations from the compounding effects of hydrological extremes and marine ecosystem tipping points [37, 6, 26]. These events can mobilize pollutants from terrestrial to aquatic environments, further compromising water quality. Saltwater intrusion into estuaries and aquifers affects freshwater availability and quality, posing challenges for water supply and ecosystem health.

Efforts to address the knowledge gap regarding the impact of melting land ice on sea level rise are critical for developing effective adaptation strategies. Simplified approaches to understanding these dynamics can enhance public awareness and inform policy decisions aimed at mitigating the adverse effects of sea level rise on coastal water quality [65].

Integrating predictive models and advanced monitoring systems is crucial for assessing and understanding the impacts of sea level rise on coastal ecosystems. These tools enhance our ability to analyze long-term trends, simulate various environmental scenarios, and inform decision-making processes in response to climate change [22, 46, 66, 58]. Such insights into the spatial and temporal variability of sea level changes enable the development of targeted management strategies to protect coastal water quality and ensure the resilience of affected communities.

4.5 Hydrological Cycle and Water Quality Variability

Variability in water quality due to changes in the hydrological cycle is crucial for understanding climate change's broader impacts on aquatic ecosystems. The hydrological cycle, encompassing processes such as evaporation, precipitation, and runoff, is significantly influenced by climatic variations. These changes intensify the water cycle—leading to increased evaporation and precipitation—and amplify the frequency and severity of hydrological extremes like floods and droughts. Consequently, such variability can substantially alter water quality, as observed in regions like Germany, where shifts in the water balance are linked to climate change. Understanding these dynamics requires a comprehensive approach that considers both environmental and socioeconomic factors, as they play a crucial role in shaping the impacts of hydrological extremes [57, 39, 26]. Climate change-induced shifts in these processes can exacerbate water scarcity, affect nutrient cycling, and alter sediment transport, thereby impacting aquatic ecosystems and water quality.

Increased potential evaporation, as observed in Germany, underscores climate change's influence on hydrological dynamics, contributing to increased dryness and affecting water resources [57]. Understanding historical evapotranspiration trends is essential, providing insights into the interactions between climate change and human activities on the water cycle [67]. Energy flux biases in climate models are pivotal for understanding how climate change affects the hydrological cycle and water quality [68].

The variability in soil moisture, particularly under high emission scenarios like RCP8.5, highlights significant implications for water resources and vegetation, reflecting broader trends of increased soil dryness [44]. The Mediterranean Sea, projected to experience increased stirring and kinetic energy, illustrates how changes in hydrodynamic provinces and mixing characteristics can affect water quality [69]. Additionally, spatial shifts in coastal productivity, influenced by changes in upwelling winds and sea-land temperature gradients, further emphasize climate change's impact on water quality [70].

Current studies often overlook localized impacts of climate change on hydropower inflow, failing to adequately address variability introduced by different climate models [32]. Technological synergies between adaptation and mitigation efforts, particularly in infrastructure, are crucial for managing these hydrological changes, with significant overlaps in patents related to these technologies [36]. AI data-driven models facilitate rapid and real-time assessments of extreme events, enhancing the ability to attribute climate impacts and manage water quality variability [63].

The complexity of accurately estimating sea level rise, influenced by ocean depth variability and contributions from different ice sources, poses additional challenges for understanding hydrological impacts on water quality [65]. The contagion index, which quantifies exceedances in water quality, provides a valuable tool for understanding spatial variability in response to hydrological changes [56]. Collectively, these insights emphasize the need for comprehensive monitoring and adaptive management strategies to mitigate the impacts of hydrological variability on water quality, ensuring the resilience and sustainability of aquatic ecosystems.

5 Emerging Contaminants in Aquatic Ecosystems

5.1 Types and Sources of Emerging Contaminants

Emerging contaminants in aquatic ecosystems, such as pharmaceuticals, personal care products, hormones, and heavy metals, pose significant ecological risks due to their persistence and potential for bioaccumulation. Heavy metals, identified as particularly concerning, are prevalent due to industrial discharges, agricultural runoff, and urban wastewater, as evidenced by a synthesis of 176 reports [48]. Constructed wetlands are recognized as effective nature-based solutions for wastewater management, utilizing natural processes to mitigate the impact of these contaminants [41]. Innovative machine learning approaches offer efficient alternatives to traditional monitoring by enhancing the prediction of contaminant behavior in complex aquatic systems [71].

Figure 6 illustrates the classification of emerging contaminants in aquatic ecosystems, detailing their types, sources, and the research methodologies employed for understanding their impacts and management. This visual representation underscores the complexity of the issue and the necessity for integrating diverse methodologies. Future research should focus on increasing model complexity and incorporating additional pollution metrics to better understand contaminant interactions [22]. Biophysical models play a crucial role in elucidating aquatic species' responses to contaminants under novel conditions, informing conservation strategies [12]. Integrating advanced monitoring and predictive modeling is vital for comprehensively understanding emerging contaminants. By employing techniques like natural language processing and fostering transdisciplinary collaboration, researchers and policymakers can devise targeted strategies for sustainable water management, safeguarding ecosystems and promoting long-term environmental sustainability [14, 11, 64, 47].

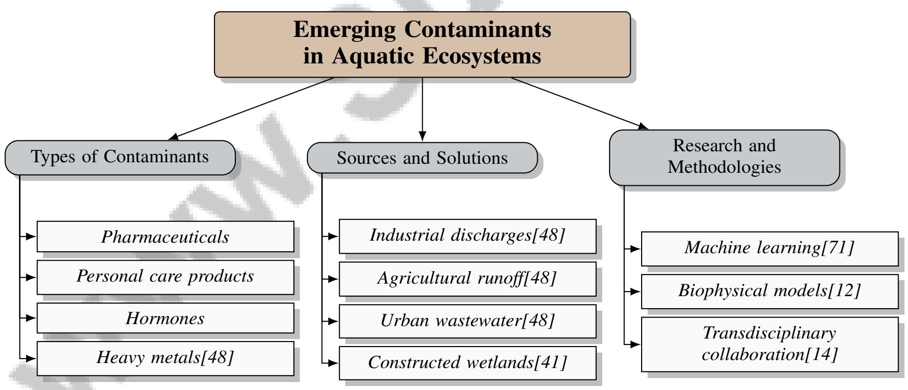

Figure 6: This figure illustrates the classification of emerging contaminants in aquatic ecosystems, detailing their types, sources, and the research methodologies employed for understanding their impacts and management.

5.2 Ecological Impacts on Aquatic Communities

Emerging contaminants disrupt aquatic communities by altering ecological interactions and threatening biodiversity. Pharmaceuticals, personal care products, and heavy metals interfere with mutualistic networks, destabilizing ecosystems and affecting community structures [72]. The resilience of aquatic ecosystems is crucial for recovery and maintenance of ecological functions. The flow-kick framework quantifies resilience against recurrent disturbances, providing insights beyond traditional metrics [73]. Climate change exacerbates these impacts by altering environmental conditions and nutrient cycling. Changes in snow cover duration and increased alpine vegetation modify nutrient dynamics, affecting resource availability for aquatic communities [2]. These alterations can shift species composition and

AI-generated, for reference only.

ecosystem functions, complicating biodiversity conservation. Advanced methodologies integrating ecological data into predictive models enhance understanding of biodiversity changes under climate scenarios, facilitating targeted management strategies [74]. Leveraging these insights allows for effective measures to protect aquatic communities and ensure ecosystem sustainability amid emerging contaminants and climate change.

5.3 Challenges in Water Quality Management

Managing water quality amidst emerging contaminants like pharmaceuticals, personal care products, and heavy metals presents significant challenges, compounded by the complexity of aquatic ecosystems and dynamic environmental conditions. While AI and machine learning improve predictive capabilities and real-time data integration, limitations persist in extrapolating under extreme climate scenarios [63]. A primary challenge is the sparse data distribution, particularly in regions with infrequent extreme events, complicating trend detection and modeling [75]. Model simulations may not fully capture real-world complexities, leading to potential inaccuracies in assessments [60]. Oversimplified climate impacts can result in overestimations or misinterpretations, especially regarding sea level rise [65]. Conflicts among water users further complicate management, requiring effective stakeholder engagement and real-time data integration to resolve these issues and enhance strategy resilience [58]. Current studies often overlook the full spectrum of climate impacts, particularly in localized contexts, posing additional challenges for management [9]. Future research should refine methods for quantifying uncertainties, improving model intercomparisons, and exploring policy implications [76]. Addressing these challenges and leveraging technological advancements can enhance water quality management, mitigating the impacts of emerging contaminants and ensuring ecosystem sustainability.

6 Catchment Management Strategies

Effective catchment management requires integrating innovative nature-based solutions and conservation strategies to address ecological challenges. By leveraging natural processes and technological advancements, these strategies enhance ecosystem resilience and mitigate environmental risks. This section explores frameworks and examples illustrating sustainable catchment management applications.

Figure 7 illustrates the hierarchical structure of catchment management strategies, encompassing nature-based solutions, adaptive management, and policy engagement. The figure highlights the integration of natural processes and technology, emphasizing the role of digital tools and social dynamics in adaptive strategies, as well as the importance of governmental policies and international cooperation in fostering effective policy and stakeholder engagement. This visual representation serves to reinforce the discussion by providing a clear overview of the interconnected elements essential for successful catchment management.

6.1 Nature-Based Solutions and Conservation Strategies

Nature-based solutions and conservation strategies are crucial for sustainable catchment management, offering efficient ways to mitigate ecological risks and enhance resilience. These strategies utilize natural processes to address environmental challenges, such as optimizing energy use and enhancing carbon sequestration in agriculture and forestry, contributing to climate change mitigation [17]. A notable advantage is the integration of low-cost, real-time data systems, like SENSWICH technology, which effectively monitors environmental parameters in challenging coastal environments such as the Venice Lagoon [42]. Vegetation dynamics play a vital role in influencing water flow and soil erosion, essential for maintaining ecological balance and preventing land degradation [40]. Incorporating local knowledge within polycentric systems enhances adaptability, allowing tailored solutions for specific contexts [20].

Network-based restoration approaches offer systematic frameworks to improve recovery efficiency, facilitating ecosystem function restoration crucial for aquatic environment sustainability [72]. Integrated monitoring systems fill data gaps, providing reliable information for informed decision-making in catchment management [77]. Predictive models, such as those for mangrove distribution, inform conservation policies, ensuring management efforts are based on robust scientific evidence [66].

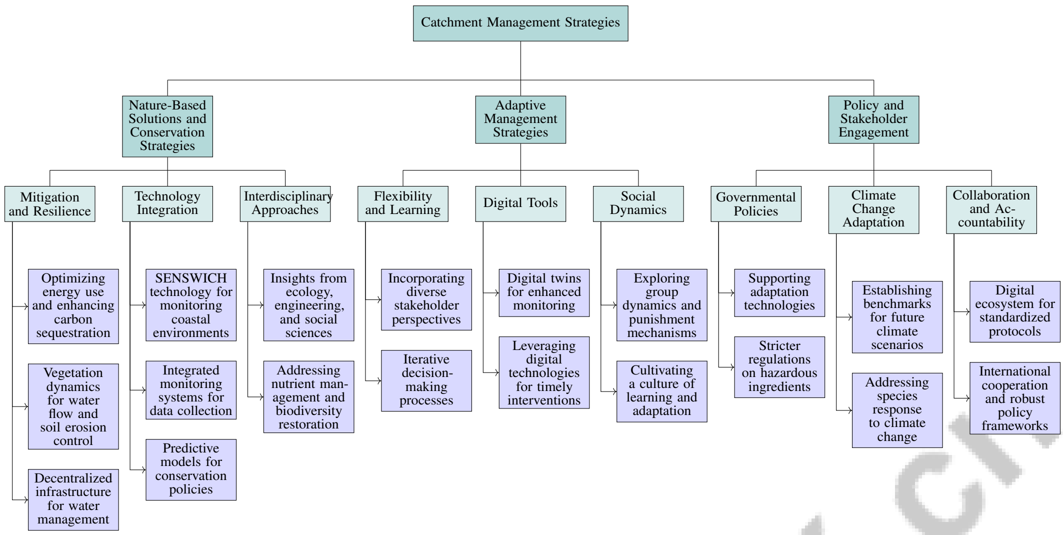

Figure 7: This figure illustrates the hierarchical structure of catchment management strategies, encompassing nature-based solutions, adaptive management, and policy engagement. It highlights the integration of natural processes and technology, the role of digital tools and social dynamics in adaptive strategies, and the importance of governmental policies and international cooperation in policy and stakeholder engagement.

Remote detection of magnetic signatures of vertically migrating plankton enhances ecological dynamics understanding without direct interference, supporting conservation efforts [78]. Agent-based models serve as decision support tools for testing management scenarios in ecosystems like coral reefs, exploring sustainable strategies adaptable to changing conditions [8]. The role of decentralized infrastructure in alleviating water shortages underscores nature-based solutions' potential to enhance water management and catchment resilience [3].

These strategies highlight the necessity of integrating natural processes with innovative technologies in catchment management. Interdisciplinary approaches enable stakeholders to develop comprehensive strategies that enhance aquatic ecosystem resilience, mitigate ecological risks, and promote long-term water resource viability. This integration involves insights from ecology, engineering, and social sciences to address complex challenges, including nutrient management, biodiversity restoration, and climate change impacts on marine environments [11, 72, 41, 6, 73].

6.2 Adaptive Management Strategies

Adaptive management strategies are essential for managing the dynamic nature of aquatic ecosystems, particularly in the context of climate change and emerging contaminants. These strategies emphasize flexibility, learning, and iterative decision-making to manage ecological risks effectively and enhance ecosystem resilience. A key aspect of adaptive management is incorporating diverse stakeholder perspectives and real-time data to inform decision-making and policy development [58].

Digital tools enhance monitoring and predictive capabilities in adaptive management. For example, digital twins in marine environments improve user interaction and integrate additional hydrological models, refining predictive models and enhancing management strategies' effectiveness [58]. Leveraging digital technologies allows adaptive management to better respond to environmental changes and uncertainties, ensuring timely and effective interventions.

Exploring variations in group dynamics and punishment mechanisms is crucial, as these factors can influence cooperative management success. Future research should assess these impacts on management outcomes and replicate studies across diverse participant backgrounds for generalizable findings [79]. Understanding social dynamics within management groups can inform the development of inclusive strategies that promote cooperation and shared responsibility among stakeholders.

The iterative nature of adaptive management fosters continuous learning and improvement, enabling managers to adjust strategies based on new information and changing conditions. This approach is particularly valuable in the face of climate change, where uncertainty is a significant challenge. Cultivating a culture of learning and adaptation within catchment management practices enhances resilience and responsiveness to environmental changes driven by climate change and human activities, thereby promoting long-term sustainability of aquatic ecosystems. This approach integrates transdisciplinary insights, facilitating innovative solutions like constructed wetlands that effectively manage water resources and improve biodiversity [11, 41, 64, 73].

6.3 Policy and Stakeholder Engagement

Policy and stakeholder engagement are critical for effective catchment management, particularly concerning climate change and emerging contaminants. Targeted governmental policies support research and development in adaptation technologies, fostering innovation and enhancing aquatic ecosystem resilience [36]. Stricter regulations on hazardous personal care ingredients are necessary to mitigate their impact on water quality, highlighting the need for comprehensive policy frameworks addressing emerging contaminants' sources [15].

As illustrated in Figure 8, the hierarchical structure of policy and stakeholder engagement in catchment management emphasizes the interconnectedness of governmental policies, stakeholder involvement, and climate change strategies. This framework underlines the importance of integrating diverse stakeholder perspectives into policy development, which is essential for effective governance in the face of climate challenges.

Climate change challenges require robust policy responses and stakeholder engagement to ensure effective adaptation strategies. Establishing benchmarks for future climate scenarios is vital for providing comprehensive assessments that inform adaptation and policy responses [53]. The unpredictability of species responses to climate change and inadequate integration of these dynamics into policy frameworks illustrate current governance structures' limitations in adapting to rapidly changing biodiversity [5].

The proposed digital ecosystem enhances collaboration through standardized protocols and interfaces, essential for effective catchment management [43]. Transparency and standardized metrics for evaluating technology's environmental footprint are crucial for aligning technological advancements with environmental objectives [23]. Engaging stakeholders in sustainable agricultural practices is vital for effective catchment management, emphasizing collaborative approaches to address ecological risks [11].

International cooperation and robust policy frameworks are necessary for implementing mitigation strategies, ensuring coordinated and effective management of catchment areas. Establishing a legal framework to hold governments accountable for their climate commitments is critical, promoting transparency and accountability in catchment management [19]. By fostering collaboration among diverse stakeholders and implementing targeted policies, it is possible to enhance the resilience of aquatic ecosystems and mitigate the impacts of climate change and emerging contaminants.

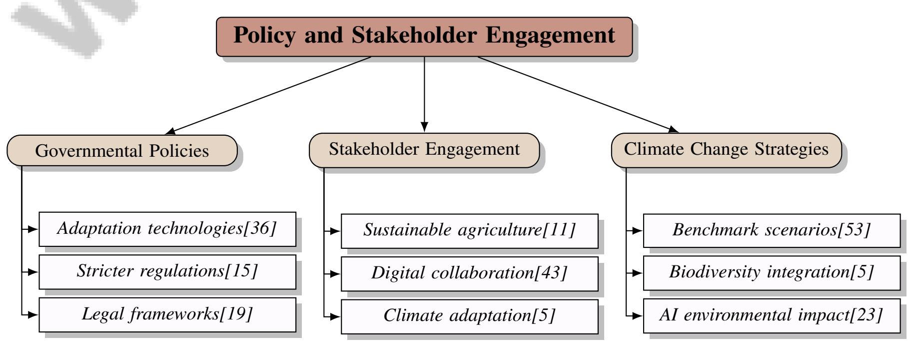

Figure 8: This figure illustrates the hierarchical structure of policy and stakeholder engagement in catchment management, focusing on governmental policies, stakeholder engagement, and climate change strategies.

7 Environmental Impact Assessment

Environmental impact assessments (EIAs) are pivotal for understanding the complex interactions between human activities and ecological systems. This section delves into the advancements in EIA methodologies, particularly emphasizing the integration of real-time data collection to enhance environmental monitoring and decision-making accuracy. The subsequent subsection will explore the implications of this integration for ecological risk evaluations and adaptive management strategies.

7.1 Integration of Real-Time Data Collection

Incorporating real-time data collection into EIAs significantly improves the precision and promptness of ecological risk evaluations. This dynamic monitoring approach facilitates adaptive management strategies that effectively address climate change and emerging contaminants. Although the European Commission's AI Act proposes regulating AI systems across various sectors, it overlooks the environmental impacts of AI, crucial for sustainable implementation [47]. Real-time data collection enables continuous environmental variable assessment, providing critical insights into ecosystem dynamics and the success of mitigation measures. This method swiftly identifies emerging threats and implements corrective actions, thereby bolstering aquatic ecosystem resilience. Additionally, refining utility and rewards frameworks enhances simulation accuracy in climate change negotiations, ensuring policy decisions are grounded in comprehensive, current data [35].

Utilizing real-time data in EIAs bridges the gap between scientific research and policymaking, fostering informed and transparent decision-making. By adopting advanced data collection technologies and encouraging interdisciplinary collaborations across fields like plant science, engineering, and social sciences, stakeholders can improve their capacity to monitor and respond to environmental changes. This integrated approach enhances ecological risk management and supports sustainable agricultural practices, as evidenced by innovative case studies demonstrating improved water and fertilizer use, real-time data visualization, and stakeholder engagement [11, 43, 47].

7.2 Quantifying Uncertainty and Predictive Accuracy

Benchmark	Size	Domain	Task Format	Metric
PCP-Bench[15]	20,500	Ecotoxicology	Ecological Risk Assessment	Risk Quotient, Measured Environmental Concentration
AI-Attribution[63]	1,000,000	Atmospheric Rivers	Climate Attribution	IWV, Attribution Skill
ETBM[67]	5,267	Hydrology	Evapotranspiration Estimation	R^2, KGE
VIC-Duero[80]	18	Hydrology	Hydrological Modeling	NSE, iQ
IMIL[77]	1,000,000	Environmental Monitoring	Ice Detection	Accuracy, F1-score
CMO-NRT[81]	180,000	Oceanography	Time Series Analysis	R2, RMSE
MGD[66]	500,000	Marine Biology	Geographic Distribution Prediction	Mean Squared Error, R2
W2[59]	28,583	Oceanography	Data-model Comparison	Wasserstein distance, RMSE

Table 5: Table illustrating a comprehensive overview of various benchmarks used in ecological and environmental modeling. Each benchmark is characterized by its size, domain of application, task format, and the specific metrics used for evaluation. This information is crucial for understanding the scope and applicability of different datasets in enhancing predictive accuracy and managing ecological risks.

Quantifying uncertainty and enhancing predictive accuracy in EIAs are crucial for developing robust strategies to manage aquatic ecological risks. The complexity of ecological systems and variability from climate change necessitate advanced methodologies for effective uncertainty capture and interpretation. Simulations examining catastrophic disturbances' consequences on population survival and adaptation provide insights into how selection pressure and mutation levels influence ecological outcomes [54].

Integrating real-time data with advanced modeling techniques is an effective strategy for improving predictive accuracy. This combination refines predictive models by incorporating real-time environmental data, reducing uncertainty and enhancing climate-related forecasts. These methodologies are critical for adaptive management strategies that respond to complex climate-related risks, leveraging interdisciplinary collaboration and technologies like generative AI algorithms to support informed decision-making and effective climate action [14, 64, 17, 26]. Probabilistic frameworks further quantify potential outcomes, providing a comprehensive understanding of risks associated with various management scenarios. Table 5 provides a detailed overview of representative benchmarks employed in ecological and environmental modeling, highlighting their relevance in the context of quantifying uncertainty and enhancing predictive accuracy in ecological impact assessments.

Machine learning and artificial intelligence offer promising avenues for improving predictive accuracy in ecological modeling. These technologies analyze large datasets and identify underlying patterns, enhancing forecasts of ecological changes and management intervention effectiveness. To align AI deployment with sustainability goals, evaluating AI systems' environmental impacts, including energy consumption and integrating environmental indicators into algorithms, is crucial to mitigate adverse effects. As AI increasingly addresses climate change and environmental degradation, a comprehensive framework for monitoring its lifecycle impact on natural resources is essential, informing policymakers and stakeholders to implement effective standards and policies that promote sustainable development while leveraging AI benefits [14, 23, 64, 47].

Enhancing climate prediction accuracy can also be achieved by refining simulation models that account for geographical variations and diverse climate scenarios. A multivariate hierarchical approach captures spatial dependencies, while methods for constructing confidence regions around exceedance areas in spatio-temporal processes allow for robust assessments of projected changes in seasonal temperature and precipitation, particularly in regions such as the western United States and Oregon, where identifying exceedance regions is crucial for effective environmental monitoring [51, 30]. By capturing the spatial and temporal heterogeneity of ecological processes, these models provide more accurate assessments of the potential impacts of climate change and human activities on aquatic ecosystems.

8 Interdisciplinary Approaches and Future Directions

8.1 Integrated Frameworks and Approaches

Addressing the complex challenges of aquatic ecological risks, particularly those influenced by climate change and emerging contaminants, necessitates integrated frameworks. These frameworks foster interdisciplinary collaboration by combining diverse methodologies and data sources to develop comprehensive ecological risk management strategies. Dynamic grouping models, for instance, enhance climate negotiation decision-making by accounting for regional socio-economic variations [35]. Advanced technologies like real-time data collection significantly improve ecological risk assessments by providing timely, accurate information to inform adaptive management [77]. Incorporating network-science principles into restoration strategies optimizes species reintroductions and biodiversity gains, underscoring the need for holistic frameworks [72]. Nature-based solutions, such as constructed wetlands, exemplify integrated approaches by leveraging natural processes for contaminant treatment, thus managing ecological risks effectively [41]. Additionally, polycentric systems that emphasize local actions and innovation demonstrate the effectiveness of decentralized approaches [20].

Future research should focus on developing technologies aligned with sustainable practices and narratives that enhance ecological well-being, ensuring technological advancements contribute positively to environmental objectives [4]. Integrating biophysical models with statistical approaches and fostering interdisciplinary collaboration are crucial for addressing climate change impacts on aquatic ecosystems [12]. By utilizing integrated frameworks and transdisciplinary approaches, stakeholders can devise comprehensive strategies for managing aquatic ecological risks, ensuring ecosystem resilience amid environmental challenges. Collaborative efforts that incorporate diverse scientific disciplines enhance understanding of ecosystem dynamics, improve resource management, and mitigate potential tipping points threatening marine and freshwater systems [11, 37, 6, 73].

8.2 Technological and Analytical Innovations

Technological and analytical innovations are essential for advancing the management of aquatic ecological risks, particularly under climate change pressures and emerging contaminants. These innovations include tools and methodologies that enhance monitoring, analysis, and real-time mitigation of ecological risks. For instance, integrating advanced sensor technology with cloud-based data aggregation, as demonstrated by SENSWICH, significantly improves monitoring capabilities, providing comprehensive insights into ecological dynamics [42]. Digital ecosystems with modular architecture and cloud readiness represent significant advancements in data management, facilitating efficient handling of ecological risk data and supporting adaptive management strategies [43].

Combining Earth Observation data with AI lifecycle assessments offers a novel approach to managing ecological risks associated with climate change, enhancing predictive capabilities and informing decision-making frameworks [23]. The AIRCC-Clim tool provides a user-friendly interface for generating climate change scenarios and risk measures, making it accessible for impact assessments and policy evaluations [34]. Innovations in hydrological modeling, such as the ESM-V model, enhance our understanding of hydrological processes, informing management practices in aquatic ecosystems and advancing predictions of water flow dynamics [40]. Furthermore, the benchmark developed for climate attribution studies accelerates analyses and improves uncertainty quantification [63].

Future research should explore applying these methods to complex stochastic models and systems affected by non-Gaussian noise, broadening the scope of technological innovations in ecological risk management [71]. Emphasizing advanced water treatment solutions and public acceptance is crucial for effectively managing water resources [3]. Integrating advanced technologies and analytical methods, alongside transdisciplinary collaborations across fields such as engineering, computer science, and environmental science, is essential for managing aquatic ecological risks effectively. These innovations enhance our ability to assess and mitigate impacts from emerging contaminants, improve water and nutrient management practices, and quantify resilience against climate change-induced disturbances. By ensuring the sustainability and resilience of aquatic ecosystems, these tools address pressing environmental challenges posed by pollution, climate variability, and human activities [11, 24, 73, 6, 47].

8.3 Future Directions and Policy Implications

Future research directions and policy implications are crucial for enhancing the resilience of aquatic ecosystems amidst climate change and emerging contaminants. A key research area involves refining data sources and methodologies to strengthen benchmarks in ecological risk assessments, essential for understanding climate change impacts on aquatic systems [52]. Integrating biodiversity dynamics into climate action plans is vital, as species redistribution due to climate change can exacerbate existing inequalities in resource access and human well-being [5]. Policy frameworks should incorporate these dynamics to ensure equitable resource management and bolster ecosystem resilience.

Transdisciplinary collaborations are necessary for addressing agricultural sustainability challenges, which directly affect aquatic ecosystems through runoff and nutrient loading [11]. Future research should focus on developing practical applications of transdisciplinary research to foster sustainable agricultural practices that mitigate these impacts. Advancements in climate modeling are crucial for enhancing prediction accuracy related to aquatic ecosystems. Future research should investigate extending current models to perturbed-physics and multi-model ensembles while integrating observational data to improve model accuracy [51]. Exploring methods to relax strict exogeneity assumptions and developing flexible procedures for estimating response functions can refine model selection criteria and enhance predictive capabilities [82].

Developing high-resolution climate models and adaptation strategies is essential for understanding the socio-economic impacts of climate change and formulating effective mitigation measures. By exploring these diverse research avenues, stakeholders can devise robust strategies to enhance aquatic ecosystem resilience, ensuring the sustainability of these critical systems amid ongoing environmental challenges such as climate change, nutrient loading, and habitat degradation. This approach emphasizes transdisciplinary collaboration among scientists, engineers, and social scientists, facilitating the integration of innovative technologies and stakeholder perspectives to address complex interactions within these ecosystems effectively and mitigate potential tipping points threatening marine productivity and biodiversity [11, 6, 64, 73].

8.4 Communication and Collaboration Across Disciplines

Effective communication and collaboration across disciplines are crucial for addressing the multi-faceted challenges posed by ecological risks in aquatic ecosystems. Integrating diverse scientific perspectives fosters innovative solutions and enhances understanding of complex environmental dynamics. Interdisciplinary collaboration is essential for synthesizing knowledge from fields such as ecology, hydrology, climate science, and social sciences, enabling the development of comprehensive strategies for managing ecological risks. The polycentric approach to climate change management emphasizes local and regional collaborations, highlighting the importance of diverse disciplinary contributions in crafting effective strategies [20].

The development of integrated monitoring systems provides comprehensive and systematic approaches to environmental observation, underscoring the necessity of effective communication and data sharing across disciplines [77]. These systems facilitate the integration of diverse data sources, enabling a holistic understanding of ecological processes and improving the accuracy of ecological risk assessments. Digital ecosystems with modular architecture and cloud readiness further support interdisciplinary collaboration by enhancing data management and sharing capabilities [43].

Moreover, integrating machine learning and artificial intelligence into ecological modeling exemplifies the critical role of interdisciplinary collaboration, allowing for innovative solutions to complex environmental challenges [17]. The intersection of neurobiology with ecological and evolutionary perspectives further illustrates the potential for interdisciplinary approaches to deepen our understanding of ecosystem dynamics [18]. Future research should prioritize enhancing communication and collaboration across various scientific disciplines, including ecology, social sciences, and engineering, to tackle aquatic ecological risks effectively. This interdisciplinary approach is essential for developing sustainable practices that address issues such as biodiversity loss, water quality, and the impacts of climate change on aquatic ecosystems, fostering innovative solutions that integrate technical, social, and environmental perspectives [11, 83, 64, 5, 26]. By leveraging diverse scientific insights and technological advancements, stakeholders can devise robust strategies for mitigating the impacts of climate change and emerging contaminants, ensuring the resilience and sustainability of aquatic ecosystems.

9 Conclusion

Integrated management strategies are vital for addressing the complex challenges of aquatic ecological risks in the context of climate change and emerging contaminants. The survey underscores the importance of interdisciplinary collaboration in enhancing adaptation and vulnerability assessments, reflecting the growing body of climate change research. The identification of significant ecological threats posed by contaminants, such as heavy metals and personal care products, highlights the urgent need for improved environmental management and continuous monitoring.

The integration of microbial research into climate change frameworks is crucial, given microorganisms' critical role in the carbon cycle and climate mitigation efforts. Advancements in biophysical modeling enhance the accuracy of predicting species responses to climate change, informing effective management strategies for aquatic ecosystems. These insights demonstrate the necessity of incorporating diverse scientific perspectives to strengthen ecosystem resilience.

From a policy standpoint, the survey emphasizes that while technological advancements are instrumental in addressing environmental issues, they must be complemented by societal and cultural shifts to achieve sustainable outcomes. The development of integrated knowledge platforms leveraging advanced technologies is essential for refining climate policy and empowering informed decision-making among policymakers.

Additionally, the survey highlights that effective climate sensitivity should not be the sole criterion for selecting models in regional climate impact assessments, as multiple factors influence projected changes. This necessitates a comprehensive approach to environmental assessments and climate model evaluations. Collectively, these insights reinforce the critical role of integrated management strategies in mitigating the compounded effects of climate change and emerging contaminants on aquatic ecosystems.

References

[1] Henri Berestycki, Romain Ducasse, and Luca Rossi. Influence of a road on a population in an ecological niche facing climate change, 2019.

[2] M. Rogora, L. Frate, M. L. Carranza, M. Freppaz, A. Stanisci, I. Bertani, R. Bottarin, A. Brambilla, R. Canullo, M. Carbognani, C. Cerrato, S. Chelli, E. Cremonese, M. Cutini, M. Di Musciano, B. Erschbamer, D. Godone, M. Iocchi, M. Isabellon, A. Magnani, L. Mazzola, U. Morra di Cella, H. Pauli, M. Petey, B. Petriccione, F. Porro, R. Psenner, G. Rossetti, A. Scotti, R. Sommaruga, U. Tappeiner, J. P. Theurillat, M. Tomaselli, D. Viglietti, R. Viterbi, P. Vittoz, M. Winkler, and G. Matteucci. Assessment of climate change effects on mountain ecosystems through a cross-site analysis in the alps and apennines, 2019.

[3] Jangho Park and Guzin Bayraksan. A multistage distributionally robust optimization approach to water allocation under climate uncertainty, 2020.

[4] Bill Tomlinson, Andrew W. Torrance, and William J. Ripple. Scientists' warning on technology, 2023.

[5] Gretta T Pecl, Miguel B Araújo, Johann D Bell, Julia Blanchard, Timothy C Bonebrake, I-Ching Chen, Timothy D Clark, Robert K Colwell, Finn Danielsen, Birgitta Evengård, et al. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355(6332):eaai9214, 2017.

[6] Juan C. Rocha, Jean-Baptiste Jouffray, Frida Bengtsson, Bianca-Ioana Voicu, Paula A. Sánchez, and Victor Galaz. Identifying companies and financial actors exposed to marine tipping points, 2024.

[7] Ricardo Cavicchioli, William J Ripple, Kenneth N Timmis, Farooq Azam, Lars R Bakken, Matthew Baylis, Michael J Behrenfeld, Antje Boetius, Philip W Boyd, Aimée T Classen, et al. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17(9):569–586, 2019.

[8] Olivier Rousselle. Evaluation of the cumulated impacts on the marine resource of a socio-ecological coral system: approach by agent-based modeling, 2020.

[9] Mesut Demircan, Hüdaverdi Gürkan, Osman Eskioğlu, Hüseyin Arabacı, and Mustafa Coşkun. Climate change projections for turkey: three models and two scenarios. *Turkish Journal of Water Science and Management*, 1(1):22–43, 2017.

[10] Lutz Bornmann, Robin Haunschild, and Werner Marx. Policy documents as sources for measuring societal impact: How often is climate change research mentioned in policy-related documents?, 2016.

[11] Vesna Bacheva, Imani Madison, Mathew Baldwin, Mark Beilstein, Douglas F. Call, Jessica A. Deaver, Kirill Efimenko, Jan Genzer, Khara Grieger, April Z. Gu, Mehmet Mert Ilman, Jen Liu, Sijin Li, Brooke K. Mayer, Anand Kumar Mishra, Juan Claudio Nino, Gloire Rubambiza, Phoebe Sengers, Robert Shepherd, Jesse Woodson, Hakim Weatherspoon, Margaret Frank, Jacob Jones, Rosangela Sozzani, and Abraham Stroock. Transdisciplinary collaborations for advancing sustainable and resilient agricultural systems, 2024.

[12] Natalie J. Briscoe, Shane D. Morris, Paul D. Mathewson, Lauren B. Buckley, Marko Jusup, Ofir Levy, Ilya M. D. Maclean, Sylvain Pincebourde, Eric A. Riddell, Jessica A. Roberts, Rafael Schouten, Michael W. Sears, and Michael R. Kearney. Mechanistic forecasts of species responses to climate change: the promise of biophysical ecology, 2022.

[13] Flavio C. D. Moraes, Ana Lia Leonel, Pedro H. C. Torres, Pedro R. Jacobi, and Sandra Momm. Climate change and social sciences: a bibliometric analysis, 2020.

[14] Junze Zhang, Kerry Zhang, Mary Zhang, Jonathan H. Jiang, Philip E. Rosen, and Kristen A. Fahy. Avoiding the "great filter": An assessment of climate change solutions and combinations for effective implementation, 2022.

[15] Feng-Jiao Peng, Chang-Gui Pan, Min Zhang, Nai-Sheng Zhang, Ronja Windfeld, Daniel Salvito, Henriette Selck, Paul J Van den Brink, and Guang-Guo Ying. Occurrence and ecological risk assessment of emerging organic chemicals in urban rivers: Guangzhou as a case study in china. *Science of the Total Environment*, 589:46–55, 2017.

[16] Robin Haunschild, Lutz Bornmann, and Werner Marx. Climate change research in view of bibliometrics, 2016.

[17] David Rolnick, Priya L. Donti, Lynn H. Kaack, Kelly Kochanski, Alexandre Lacoste, Kris Sankaran, Andrew Slavin Ross, Nikola Milojevic-Dupont, Natasha Jaques, Anna Waldman-Brown, Alexandra Luccioni, Tegan Maharaj, Evan D. Sherwin, S. Karthik Mukkavilli, Konrad P. Kording, Carla Gomes, Andrew Y. Ng, Demis Hassabis, John C. Platt, Felix Creutzig, Jennifer Chayes, and Yoshua Bengio. Tackling climate change with machine learning, 2019.

[18] Angie Michaiel and Amy Bernard. Neurobiology and changing ecosystems: toward understanding the impact of anthropogenic influences on neurons and circuits, 2022.

[19] James Hansen, Pushker Kharecha, Makiko Sato, Frank Ackerman, Paul J. Hearty, Ove Hoegh-Guldberg, Shi-Ling Hsu, Fred Krueger, Camille Parmesan, Stefan Rahmstorf, Johan Rockstrom, Eelco J. Rohling, Jeffrey Sachs, Peter Smith, Konrad Steffen, Lise Van Susteren, Karina von Schuckmann, and James C. Zachos. Scientific case for avoiding dangerous climate change to protect young people and nature, 2012.

[20] Elinor Ostrom. Polycentric systems for coping with collective action and global environmental change. In *Global justice*, pages 423–430. Routledge, 2017.

[21] Valérie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L Connors, Clotilde Péan, Sophie Berger, Nada Caud, Y Chen, L Goldfarb, MI Gomis, et al. Climate change 2021: the physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, 2(1):2391, 2021.

[22] Anurag Mishra, Ronen Gold, and Sanjeev Vijayakumar. Analyzing the impact of climate change with major emphasis on pollution: A comparative study of ml and statistical models in time series data, 2024.

[23] Srija Chakraborty. Towards a comprehensive assessment of ai's environmental impact, 2024.

[24] Xiaohu Lin, Jingcheng Xu, Arturo A Keller, Li He, Yunhui Gu, Weiwei Zheng, Danyan Sun, Zhibo Lu, Juwen Huang, Xiangfeng Huang, et al. Occurrence and risk assessment of emerging contaminants in a water reclamation and ecological reuse project. *Science of the Total Environment*, 744:140977, 2020.

[25] Samer Fawzy, Ahmed I Osman, John Doran, and David W Rooney. Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, 18:2069–2094, 2020.

[26] Kwok P Chun, Thanti Octavianti, Georgia Papacharalampous, Hristos Tyralis, Samuel J. Sutanto, Pavel Terskii, Paola Mazzoglio, Dario Treppiedi, Juan Rivera, Nilay Dogulu, Adeyemi Olusola, Bastien Dieppois, Moctar Dembélé, Simon Moulds, Cheng Li, Luis Alejandro Morales-Marin, Neil Macdonald, Toundji Olivier Amoussou, Roland Yonaba, Salomon Obahoundje, Nicolas Massei, David M. Hannah, Sivarama Krishna Reddy Chidepudi, and Byman Hamududu. Unravelling compound risks of hydrological extremes in a changing climate: Typology, methods and futures, 2024.

[27] Coralie Picoche and Frédéric Barraquand. Seed banks can help to maintain the diversity of interacting phytoplankton species, 2022.

[28] Liangliang Huang, Saeed Rad, Li Xu, Liangying Gui, Xiaohong Song, Yanhong Li, Zhiqiang Wu, and Zhongbing Chen. Heavy metals distribution, sources, and ecological risk assessment in huixian wetland, south china. *Water*, 12(2):431, 2020.

[29] Sylvain Gretchko, Jessa Marley, and Rebecca C. Tyson. The effects of climate change on predator-prey dynamics, 2018.

[30] Joshua P. French and Stephan R. Sain. Spatio-temporal exceedance locations and confidence regions, 2013.

[31] Robbin Bastiaansen, Henk A. Dijkstra, and Anna S. von der Heydt. Multivariate estimations of equilibrium climate sensitivity from short transient warming simulations, 2020.

[32] Ebbe Kyhl Gøtske and Marta Victoria. Future operation of hydropower in europe under high renewable penetration and climate change, 2021.

[33] Jonathan F. Donges, Carl-Friedrich Schleussner, Jonatan F. Siegmund, and Reik V. Donner. Event coincidence analysis for quantifying statistical interrelationships between event time series: on the role of flood events as possible triggers of epidemic outbreaks, 2016.

[34] Francisco Estrada, Oscar Calderón-Bustamante, Wouter Botzen, Julián A. Velasco, and Richard S. J. Tol. Aircc-clim: a user-friendly tool for generating regional probabilistic climate change scenarios and risk measures, 2021.

[35] Duo Zhang, Yuren Pang, and Yu Qin. Dynamic grouping for climate change negotiation: Facilitating cooperation and balancing interests through effective strategies, 2023.

[36] Kerstin Hötte and Su Jung Jee. Knowledge for a warmer world: a patent analysis of climate change adaptation technologies, 2022.

[37] Nazgol Tabasi, Mohammad Fereshtehpour, and Bardia Roghani. A review on flood risk conceptual frameworks and development of hierarchical structures for assessment criteria, 2024.

[38] Costas A. Varotsos and Arthur P. Cracknell. Modelling the coupling between ocean and atmosphere; the global signature of the el niño/la niña southern oscillation, 2017.

[39] Ranjini Swaminathan, Jacob Schewe, Jeremy Walton, Klaus Zimmermann, Colin Jones, Richard A. Betts, Chantelle Burton, Chris D. Jones, Matthias Mengel, Christopher P. O. Reyer, Andrew G. Turner, and Katja Weigel. Regional impacts poorly constrained by climate sensitivity, 2024.

[40] Stelian Ion, Dorin Marinescu, and Stefan-Gicu Cruceanu. Water flow model on vegetated hillslopes with erosion, 2024.

[41] Laura Garcia-Herrero, Stevo Lavrnic, Valentina Guerrieri, Attilio Toscano, Mirco Milani, Giuseppe Luigi Cirelli, and Matteo Vittuari. Cost-benefit of green infrastructures for water management: A sustainability assessment of full-scale constructed wetlands in northern and southern italy, 2023.

[42] Filippo Campagnaro, Matin Ghalkhani, Riccardo Tumiati, Federico Marin, Matteo Del Grande, Alessandro Pozzebon, Davide De Battisti, Roberto Francescon, and Michele Zorzi. Monitoring the venice lagoon: an iot cloud-based sensor nerwork approach, 2024.

[43] J. Bumberger, M. Abbrent, N. Brinckmann, J. Hemmen, R. Kunkel, C. Lorenz, P. Lünenschloß, B. Palm, T. Schnicke, C. Schulz, H. van der Schaaf, and D. Schäfer. Digital ecosystem for fair time series data management in environmental system science, 2024.

[44] Matilde García-Valdecasas Ojeda, Patricio Yeste, Sonia Raquel Gámiz-Fortis, Yolanda Castro-Díez, and María Jesús Esteban-Parra. Future changes in land and atmospheric variables: An analysis of their couplings in the iberian peninsula, 2024.

[45] Alice K. Li, Yue Mao, Sandeep Manjanna, Sixuan Liu, Jasleen Dhanoa, Bharg Mehta, Victoria M. Edwards, Fernando Cladera Ojeda, Maël Le Men, Eric Sigg, Hugo N. Ulloa, Douglas J. Jerolmack, and M. Ani Hsieh. Towards understanding underwater weather events in rivers using autonomous surface vehicles, 2023.

[46] Barry Loneck, Igor Zurbenko, and Edward Valachovic. Predicting coastal water levels in the context of climate change using kolmogorov-zurbenko time series analysis methods, 2024.

[47] Arnault Pachot and Céline Patissier. Towards sustainable artificial intelligence: An overview of environmental protection uses and issues, 2022.

[48] Chee Kong Yap and Khalid Awadh Al-Mutairi. Ecological-health risk assessments of heavy metals (cu, pb, and zn) in aquatic sediments from the asean-5 emerging developing countries: A review and synthesis. *Biology*, 11(1):7, 2021.

[49] scientific reports.

[50] Hideyasu Shimadzu, Maria Dornelas, and Anne E. Magurran. Measuring temporal turnover in ecological communities, 2016.

[51] Stephan R. Sain, Reinhard Furrer, and Noel Cressie. A spatial analysis of multivariate output from regional climate models, 2011.

[52] Steffen Petersen, Morten W. Ryberg, and Morten Birkved. The safe operating space for greenhouse gas emissions, 2022.

[53] J. Sanjay, R. Krishnan, M. V. S. Ramarao, R. Mahesh, Bhupendra Bahadur Singh, Jayashri Patel, Sandip Ingle, Preethi Bhaskar, J. V. Revadekar, T. P. Sabin, and M. Mujumdar. Future climate change projections over the indian region, 2020.

[54] Simone Vincenzi and Michele Bellingeri. Consequences of catastrophic disturbances on population persistence and adaptations, 2011.

[55] Nicandro Bovenzi, Nicolau Duran-Silva, Francesco Alessandro Massucci, Francesco Multari, Cèsar Parra-Rojas, and Josep Pujol-Llatse. Mapping sti ecosystems via open data: overcoming the limitations of conflicting taxonomies. a case study for climate change research in denmark, 2022.

[56] C. Fonseca, H. Ferreira, L. Pereira A. P., and Martins. Stability and contagion measures for spatial extreme value analyses, 2012.

[57] Axel Kleidon. Droughts in germany – why global climate change amplifies hydrological extremes, 2024.

[58] Yu Ye, Aurora González-Vidal, Alejandro Cisterna-García, Angel Pérez-Ruzafa, Miguel A. Zamora Izquierdo, and Antonio F. Skarmeta. Advancing towards a marine digital twin platform: Modeling the mar menor coastal lagoon ecosystem in the south western mediterranean, 2024.

[59] Sangwon Hyun, Aditya Mishra, Christopher L. Follett, Bror Jonsson, Gemma Kulk, Gael Forget, Marie-Fanny Racault, Thomas Jackson, Stephanie Dutkiewicz, Christian L. Müller, and Jacob Bien. Ocean mover's distance: Using optimal transport for analyzing oceanographic data, 2022.

[60] René M. van Westen, Elian Y. P. Vanderborght, Michael Kliphuis, and Henk A. Dijkstra. Substantial risk of 21st century amoc tipping even under moderate climate change, 2024.

[61] D. Secci, M. G. Tanda, M. D Oria, V. Todaro, and C. Fagandini. Impacts of climate change on groundwater droughts by means of standardized indices and regional climate models, 2022.

[62] Marcio Poletti Laurini. A continuous spatio-temporal approach to estimate climate change, 2017.

[63] Jorge Baño-Medina, Agniv Sengupta, Allison Michaelis, Luca Delle Monache, Julie Kalansky, and Duncan Watson-Parris. Harnessing ai data-driven global weather models for climate attribution: An analysis of the 2017 oroville dam extreme atmospheric river, 2024.

[64] Pradip Swarnakar and Ashutosh Modi. Nlp for climate policy: Creating a knowledge platform for holistic and effective climate action, 2021.

[65] Cedric Loretan and Andreas Müller. Sea level rise by climate change. an order-of-magnitude approach to an environmental problem, 2023.

[66] Lynn Wahab, Ezzat Chebaro, Jad Ismail, Amir Nasrelddine, and Ali El-Zein. A predictive model for geographic distributions of mangroves, 2021.

[67] Haiyang Shi. Evapotranspiration trends over the last 300 years reconstructed from historical weather station observations via machine learning, 2024.

[68] Chirag Dhara. Constraining global changes in temperature and precipitation from observable changes in surface radiative heating, 2020.

[69] Enrico Ser-Giacomi, Gabriel Jorda Sanchez, Javier Soto-Navarro, Soren Thomsen, Juliette Mignot, Florence Sevault, and Vincent Rossi. Impact of climate change on surface stirring and transport in the mediterranean sea, 2020.

[70] Nicolas Weidberg, Andres Ospina-Alvarez, Jessica Bonicelli, Mario Barahona, Christopher M. Aiken, Bernardo R. Broitman, and Sergio A. Navarrete. Spatial shifts in productivity of the coastal ocean over the past two decades induced by migration of the pacific anticyclone and bakun effect in the humboldt upwelling ecosystem, 2021.

[71] Yang Li, Shenglan Yuan, and Shengyuan Xu. Rare events in a stochastic vegetation-water dynamical system based on machine learning, 2024.

[72] Udit Bhatia, Tarik Gouhier, and Auroop Ratan Ganguly. Universal and generalizable restoration strategies for degraded ecological networks, 2018.

[73] Katherine Meyer, Alanna Hoyer-Leitzel, Sarah Iams, Ian Klasky, Victoria Lee, Stephen Ligtenberg, Erika Bussmann, and Mary Lou Zeeman. Quantifying resilience to recurrent ecosystem disturbances using flow-kick dynamics, 2018.

[74] Matthew Davidow, Cory Merow, Judy Che-Castaldo, Toryn Schafer, Marie-Christine Duker, Derek Corcoran, and David Matteson. Clustering future scenarios based on predicted range maps, 2022.

[75] Laurens de Haan, Albert Klein Tank, and Cláudia Neves. On tail trend detection: modeling relative risk, 2013.

[76] Valerio Lucarini. Towards a definition of climate science, 2004.

[77] Manu Tom, Melanie Suetterlin, Damien Bouffard, Mathias Rothermel, Stefan Wunderle, and Emmanuel Baltsavias. Integrated monitoring of ice in selected swiss lakes. final project report, 2020.

[78] Matt K. Fu and John O. Dabiri. Magnetic signature of vertically migrating aggregations in the ocean, 2022.

[79] Luo-Luo Jiang, Zhen Wang, Chang-Song Zhou, Jurgen Kurths, and Yamir Moreno. Assessing the impact of costly punishment and group size in collective-risk climate dilemmas, 2016.

[80] Patricio Yeste, Juan José Rosa-Cánovas, Emilio Romero-Jiménez, Matilde García-Valdecasas Ojeda, Sonia R. Gámiz-Fortis, Yolanda Castro-Díez, and María Jesús Esteban-Parra. Projected hydrologic changes over the north of the iberian peninsula using a euro-cordex multi-model ensemble, 2024.

[81] Piyu Ke, Xiaofan Gui, Wei Cao, Dezhi Wang, Ce Hou, Lixing Wang, Xuanren Song, Yun Li, Biqing Zhu, Jiang Bian, Stephen Sitch, Philippe Ciais, Pierre Friedlingstein, and Zhu Liu. Near-real-time monitoring of global ocean carbon sink, 2023.

[82] Xiaomeng Cui, Bulat Gafarov, Dalia Ghanem, and Todd Kuffner. On model selection criteria for climate change impact studies, 2023.

[83] Julian Dehne and Valentin Gold. Strategic communication and deliberation on climate change of different actor groups using twitter, 2023.

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