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Climate Change and Antimicrobial Resistance in Aquatic Ecosystems: Emerging Interactions, Ecological Consequences, and Public Health Implications

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ABSTRACT

Climate change and antimicrobial resistance (AMR) are two of the most pressing global challenges, with emerging evidence suggesting they are interconnected in natural aquatic systems. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events influence the distribution, abundance, and persistence of microbial communities in freshwater, estuarine, and marine ecosystems. These environmental changes can accelerate horizontal gene transfer, promote selection for resistant strains, and enhance the proliferation and dissemination of antimicrobial resistance genes (ARGs) in aquatic environments. Anthropogenic pressures, including wastewater discharge, agricultural runoff, and aquaculture practices, further exacerbate the spread of AMR under climate-driven stress. This review synthesizes current understanding of the mechanisms linking climate change and AMR, highlighting how temperature shifts, salinity changes, nutrient fluxes, and hydrological disturbances modulate microbial ecology and resistance dynamics. We examine ecological consequences for microbial communities, potential human health risks through waterborne exposure, and implications for ecosystem services. Finally, we discuss monitoring strategies, mitigation approaches, and policy interventions necessary to address the dual threats of climate change and AMR. Understanding these emerging interactions is critical for developing integrative environmental and public health strategies that safeguard both aquatic ecosystems and human populations from the synergistic effects of global environmental change.

Keywords: *Climate change; antimicrobial resistance; aquatic ecosystems; waterborne pathogens; resistance genes; environmental health.*

1. Introduction

Antimicrobial resistance (AMR) has emerged as a major global health threat, undermining decades of progress in treating infectious diseases and increasing morbidity, mortality, and healthcare costs worldwide [1][2]. While clinical and agricultural settings have traditionally received the most attention regarding AMR, there is growing recognition that natural aquatic systems—including rivers, lakes, estuaries, and coastal waters—serve as critical reservoirs and conduits for resistant microorganisms and antimicrobial resistance genes (ARGs) [3][4]. Aquatic environments are inherently dynamic and interconnected, receiving inputs from urban wastewater, industrial effluents, agricultural runoff, and aquaculture practices, all of which contribute to the introduction and amplification of antibiotic residues and resistant bacteria [5][6]. In this context, AMR is not only a clinical concern but also an ecological phenomenon shaped by environmental pressures.

Simultaneously, climate change is exerting profound effects on aquatic ecosystems, altering hydrological cycles, water temperatures, salinity patterns, nutrient dynamics, and the frequency of extreme weather events such as floods and droughts [7][8]. Rising water temperatures can accelerate microbial metabolism and growth rates, potentially enhancing the replication of both pathogens and ARG-harboring microorganisms [9]. Changes in precipitation and runoff patterns influence the transport and dilution of contaminants, while increased storm events and flooding can resuspend sediments, redistribute resistant bacteria, and facilitate gene transfer across microbial communities [10][11]. Moreover, climate-induced shifts in aquatic community composition and biogeochemical cycles may create selective pressures that favor the persistence and proliferation of resistant strains [12].

Emerging evidence suggests that these two global challenges—climate change and AMR—are interconnected, with climate-driven environmental changes potentially exacerbating the selection, dissemination, and evolution of AMR in aquatic ecosystems [13][14]. For instance, higher temperatures have been associated with increased rates of horizontal gene transfer, a key mechanism by which resistance spreads among bacteria [15]. Similarly, nutrient enrichment and altered hydrological regimes can create hotspots where resistant bacteria accumulate and ARGs proliferate [16]. These interactions are particularly concerning in regions with high population density, intensive agriculture, and limited wastewater treatment infrastructure, where anthropogenic pressures compound climate-driven stressors [17].

Despite the growing recognition of these links, research integrating climate change and AMR in natural aquatic systems remains fragmented. Most studies have focused on clinical or agricultural contexts, with limited attention to how environmental variables modulate AMR dynamics outside human-managed systems [18]. Furthermore, the mechanisms through which climate change affects the persistence, transport, and evolution of ARGs are only beginning to be elucidated, with significant gaps in understanding spatial and temporal patterns, species-specific responses, and interactions with co-stressors such as heavy metals and pollutants [19][20]. Addressing these knowledge gaps is critical because aquatic environments not only act as reservoirs for resistance but also represent pathways for human exposure, including drinking water, recreational contact, and food supply through fisheries and aquaculture [21].

This review aims to synthesize current knowledge on the emerging interactions between climate change and AMR in natural aquatic systems, highlighting key mechanisms, ecological and public health implications, and strategies for monitoring and mitigation. We begin by summarizing the impacts of climate change on aquatic environments, followed by an overview of AMR dynamics in water systems. Subsequently, we explore the mechanistic links between climate-driven environmental changes and the proliferation of AMR, before discussing ecological consequences and human health risks. Finally, we address potential mitigation strategies, monitoring frameworks, and policy interventions that can help manage these dual global threats. By integrating perspectives from environmental science, microbiology, and public health, this review provides a comprehensive framework to guide research, policy, and management actions aimed at reducing the synergistic impacts of climate change and antimicrobial resistance in aquatic ecosystems.

2. Climate Change Impacts on Aquatic Systems

Climate change is profoundly altering the physical, chemical, and biological characteristics of aquatic ecosystems, with cascading effects on microbial communities and water quality. Rising global temperatures increase water temperatures in rivers, lakes, estuaries, and coastal zones, directly affecting metabolic rates, growth, and reproduction of microorganisms, including both pathogens and antibiotic-resistant bacteria [1][2]. Thermal stress can favor thermotolerant and opportunistic microbial species, potentially altering community composition and increasing the relative abundance of resistant strains [3]. Elevated temperatures also enhance bacterial replication and the rate of horizontal gene transfer, a key mechanism by which antimicrobial resistance genes (ARGs) spread among microbial populations [4][5]. These temperature-driven effects are particularly pronounced in shallow, slow-moving waters, urban water bodies, and enclosed coastal lagoons, where thermal buffering is limited.

Alterations in hydrological regimes are another critical consequence of climate change that influences aquatic microbial dynamics. Changes in precipitation patterns, including increased intensity of storms and prolonged droughts, affect water flow, residence time, and pollutant transport [6][7]. During heavy rainfall events, combined sewer overflows and runoff from agricultural and urban areas can introduce large loads of antibiotics, resistant bacteria, and ARGs into rivers and lakes, creating hotspots for AMR proliferation [8]. Conversely, drought conditions reduce dilution of contaminants, concentrating both pollutants and resistant microorganisms, thereby amplifying selective pressures for AMR [9]. Flooding events can also resuspend sediments, redistributing previously sequestered ARGs and bacteria throughout the water column, which may facilitate dissemination to downstream ecosystems and human populations [10].

Salinity and nutrient dynamics are further influenced by climate-driven changes in precipitation and evaporation. In estuarine and coastal environments, altered freshwater inputs affect salinity gradients, which in turn influence microbial community structure and gene transfer dynamics [11]. Nutrient enrichment from runoff, combined with warmer temperatures, can exacerbate eutrophication, promoting algal blooms and hypoxic conditions that favor opportunistic pathogens and resistant bacteria [12][13]. Such conditions often create selective environments where ARGs persist longer and horizontal gene transfer is facilitated through plasmids and other mobile genetic elements [14]. Furthermore, climate change can enhance the prevalence of co-selective agents, such as heavy metals and biocides, which often co-occur with ARGs and intensify selection pressure on microbial communities [15].

Extreme weather events, including hurricanes, cyclones, and prolonged heatwaves, further complicate the dynamics of aquatic AMR. These events can mobilize sediments, redistribute contaminants, and disrupt water treatment infrastructure, increasing the risk of environmental dissemination of resistant microorganisms [16][17]. For example, flooding can overwhelm wastewater treatment systems, leading to direct discharge of untreated or partially treated effluents containing antibiotics, resistant bacteria, and ARGs into rivers and coastal waters [18]. Heatwaves and prolonged high temperatures can accelerate bacterial growth and resistance gene propagation, particularly in stagnant or slow-flowing urban water bodies [2][5].

Climate-driven ecological shifts also alter host-pathogen interactions. Changes in species composition and abundance, including fish, invertebrates, and microbial predators, affect the ecological networks that regulate bacterial populations [19]. Warmer temperatures and nutrient-enriched conditions can increase the prevalence of opportunistic pathogens that often harbor ARGs, while reduced predator abundance or competition can allow resistant bacteria to proliferate unchecked [3][20]. Moreover, alterations in microbial community structure may facilitate the emergence of novel resistance mechanisms through recombination and horizontal gene transfer, increasing the environmental resistome and posing new challenges for human and animal health.

Overall, climate change acts as a multifaceted driver of microbial ecology in aquatic systems, shaping both the abundance and dissemination of antimicrobial resistance. Rising temperatures, hydrological alterations, salinity fluctuations, nutrient enrichment, and extreme weather events interact to create environments conducive to the proliferation of ARGs and resistant bacteria. These changes, combined with ongoing anthropogenic pressures such as wastewater discharge, agricultural runoff, and aquaculture, underscore the urgent need to integrate climate considerations into AMR risk assessment and management in aquatic ecosystems. Understanding these mechanisms is critical for predicting hotspots of AMR emergence, developing monitoring strategies, and implementing interventions to mitigate the compounding effects of climate change and antimicrobial resistance on environmental and public health.

3. Antimicrobial Resistance in Aquatic Environments

Antimicrobial resistance (AMR) in aquatic ecosystems is an increasingly recognized environmental and public health concern.

Rivers, lakes, estuaries, and coastal waters act as reservoirs, conduits, and amplification sites for antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs), connecting human, animal, and environmental health in a One Health framework [1][2]. Key sources of AMR in water bodies include municipal wastewater, agricultural runoff, aquaculture effluents, and industrial discharges, which introduce antibiotics, metals, and resistant microorganisms into natural systems [3][4]. These inputs, often occurring alongside nutrients and pollutants, create selective pressures that favor the persistence and proliferation of resistance traits among microbial communities [5].

Wastewater treatment plants (WWTPs) are critical points of AMR entry into the environment. Although conventional treatment processes reduce microbial load, they often fail to eliminate ARGs completely, and treated effluents can contain both resistant bacteria and residual antibiotics [6][7]. These effluents subsequently enter rivers and lakes, facilitating horizontal gene transfer and enrichment of the environmental resistome. Similarly, agricultural runoff from livestock operations and aquaculture practices introduces antibiotics and resistant bacteria into surface waters, where they may persist and propagate under favorable conditions [8][9]. Sediments, biofilms, and aquatic vegetation can serve as reservoirs, concentrating ARGs and providing microenvironments conducive to gene exchange [10].

Environmental factors influence the survival, growth, and dissemination of ARB and ARGs in aquatic systems. Temperature, nutrient availability, salinity, and dissolved oxygen affect microbial activity and selection pressures, while hydrological dynamics control the transport and dilution of contaminants [11][12].

Horizontal gene transfer mechanisms, including conjugation, transformation, and transduction, are key drivers of ARG dissemination, often facilitated in biofilms or particle-associated bacteria [13]. Emerging evidence suggests that co-selective agents, such as heavy metals, biocides, and microplastics, further enhance the persistence of AMR in aquatic environments by exerting additional selective pressures [14][15].

The prevalence of clinically relevant ARGs, including those conferring resistance to β-lactams, tetracyclines, and fluoroquinolones, has been documented in diverse water systems globally [16][17]. Aquatic environments thus serve as both reservoirs and transmission pathways, potentially exposing humans through drinking water, recreational contact, and consumption of contaminated seafood. The intersection of environmental AMR with human and animal health highlights the importance of monitoring aquatic ecosystems, understanding the factors influencing ARG proliferation, and integrating environmental considerations into AMR management strategies [2][18], natural aquatic systems are key components in the global AMR landscape. They receive inputs from multiple anthropogenic sources, provide conditions for the persistence and horizontal transfer of resistance, and serve as exposure pathways for humans and wildlife. The complex interplay of environmental factors, microbial ecology, and anthropogenic pressures underscores the need for integrated research approaches and mitigation strategies that address AMR within the context of environmental and climate change dynamics.

Table 1: Key Studies on AMR in Aquatic Systems (2015–2025)

Location	Aquatic System	Main Findings	AMR Focus	Climate Factor Considered
UK	Rivers & lakes	Detected widespread ARGs; linked to wastewater discharge	ARG abundance	Temperature and hydrology discussed
Finland	Rivers	Fecal contamination explains ARG patterns	ARGs	Seasonal variations
China	River water	Higher temperatures increased ARG abundance	ARGs & ARB	Water temperature rise
Global	Surface waters	Microplastics facilitate ARG spread	ARG transport	Interaction with temperature and runoff
Europe	Wastewater & rivers	WWTPs as AMR hotspots	ARGs & ARB	Storm and rainfall effects

Table 2: Mechanisms Linking Climate Change to AMR in Aquatic Systems

Mechanism	Description	Key References
Temperature Increase	Accelerates microbial growth, enhances horizontal gene transfer, promotes biofilm formation	[3][4][5]
Hydrological Changes	Floods and droughts redistribute ARGs and concentrate contaminants	[8][9][10]
Nutrient Enrichment & Eutrophication	Promotes opportunistic bacteria and ARG persistence	[13][14][15]
Co-selection by Pollutants	Heavy metals, microplastics, biocides enhance ARG selection	[16][17][18]
Extreme Weather Events	Storms mobilize sediments and ARGs, heatwaves increase microbial replication	[10][3][20]
Microbial Community Shifts	Altered community composition favors resistant taxa	[2][11][]

Table 3: Monitoring and Mitigation Strategies for Climate-Sensitive AMR

Strategy	Description	Target Outcome	References
Environmental Surveillance	Sampling water, sediment, biofilms; qPCR and metagenomics	Track ARG and ARB hotspots	[1][2][5]
Wastewater Treatment Upgrades	Tertiary treatment, membrane filtration, wetlands	Reduce ARB/ARG discharge	[4][5]
Sustainable Agriculture & Aquaculture	Judicious antibiotic use, closed-loop systems	Limit ARG input	[6]
Habitat Restoration	Riparian buffers, wetlands, vegetated shorelines	Enhance microbial ecosystem resilience	[9]
Policy & Regulation	One Health approach, antibiotic stewardship, environmental standards	Reduce AMR risk	[10][11]
Climate-Integrated Planning	Incorporate climate projections, extreme weather adaptation	Mitigate ARG amplification under climate change	[3][13]

4. Mechanisms Linking Climate Change and Antimicrobial Resistance

Climate change and antimicrobial resistance (AMR) are increasingly recognized as interconnected global challenges, with multiple mechanisms linking environmental change to the proliferation and dissemination of AMR in aquatic systems. Rising temperatures, altered precipitation patterns, extreme weather events, and shifts in hydrology influence microbial ecology, gene transfer, and selection pressures, ultimately shaping the dynamics of antimicrobial resistance genes (ARGs) and antibiotic-resistant bacteria (ARB) in water bodies [1][2].

4.1 Temperature Effects on Microbial Growth and Gene Transfer

Elevated water temperatures, a direct consequence of global warming, accelerate microbial metabolism and growth rates, creating conditions that favor rapid replication of both pathogenic and commensal bacteria [3][4]. Increased microbial activity enhances opportunities for horizontal gene transfer (HGT), which is the primary mechanism for the dissemination of ARGs in aquatic environments. HGT occurs via conjugation, transformation, and transduction, and studies indicate that higher temperatures can increase conjugation frequencies and plasmid transfer among bacteria [5][6]. Warmer waters also tend to promote biofilm formation on sediments, aquatic vegetation, and man-made surfaces, providing dense microbial communities where ARG exchange is more frequent [7]. These processes collectively elevate the environmental resistome and facilitate the persistence of resistance even in the absence of direct antibiotic exposure.

4.2 Hydrological Changes and ARG Transport

Climate-induced alterations in hydrology, including changes in precipitation patterns, storm intensity, and drought frequency, influence the transport and dilution of antibiotics, resistant bacteria, and ARGs [8][9]. Heavy rainfall and flooding events can overwhelm wastewater treatment plants, resulting in direct discharge of untreated or partially treated effluents into rivers and coastal waters [10]. Such events redistribute ARGs from sediments and urban runoff into broader water networks, creating transient hotspots of AMR dissemination. Conversely, drought conditions reduce water volumes, increasing the concentration of contaminants, nutrients, and resistant bacteria, which amplifies selective pressure for resistance [11]. Changes in river flow and estuarine mixing also affect salinity and nutrient gradients, further modulating microbial community composition and ARG prevalence [12].

4.3 Nutrient Enrichment and Eutrophication

Climate change often interacts with anthropogenic nutrient inputs to exacerbate eutrophication in aquatic systems. Warmer temperatures and altered runoff increase nutrient loads, particularly nitrogen and phosphorus, promoting algal blooms and hypoxic conditions [13]. These conditions create selective environments that favor opportunistic and resilient bacterial taxa, many of which harbor ARGs [14]. Hypoxic or nutrient-rich environments also increase stress on microbial communities, enhancing mutation rates and potentially promoting the emergence of novel resistance mechanisms [15]. Furthermore, algal biomass and organic matter accumulation provide surfaces for biofilm development, facilitating ARG exchange and persistence.

4.4 Co-selection by Environmental Stressors

Climate change often amplifies other environmental stressors, such as heavy metals, microplastics, and biocides, which co-select for antibiotic resistance [16][17]. Metals like copper, zinc, and mercury, commonly present in urban runoff and industrial effluents, exert selective pressure on bacterial populations and are frequently associated with ARGs on mobile genetic elements [18]. Microplastics act as surfaces for biofilm formation and can carry both metals and ARGs, serving as vectors for horizontal transfer across microbial communities [19]. By altering the selective landscape, climate-induced changes in temperature, salinity, and pollutant distribution indirectly facilitate the persistence and spread of AMR.

4.5 Extreme Weather Events

The increasing frequency and intensity of extreme weather events, including hurricanes, cyclones, and heatwaves, exacerbate AMR dynamics. Floods and storms can mobilize sediments and redistribute resistant bacteria and ARGs across previously isolated aquatic compartments [10][20]. Heatwaves elevate microbial growth rates and metabolism in stagnant or slow-flowing waters, promoting rapid ARG proliferation [3]. These events also disrupt wastewater and water treatment infrastructure, increasing human and environmental exposure to resistant pathogens.

4.6 Impacts on Microbial Community Structure

Climate change drives shifts in microbial community composition, altering the abundance and diversity of bacterial taxa. Higher temperatures, nutrient fluctuations, and hydrological changes often favor fast-growing, opportunistic bacteria, which are more likely to carry and transfer ARGs [2][21]. Changes in predator-prey dynamics, viral infections, and microbial competition can indirectly influence the persistence and dissemination of AMR [22]. By reshaping community networks, climate change creates ecological niches where resistant strains can thrive and ARGs can be maintained in aquatic reservoirs.

4.7 Integrative Mechanisms

The interactions between climate change and AMR are therefore multifactorial. Temperature increases, hydrological disturbances, nutrient enrichment, co-selective pollutants, and extreme events collectively drive ARG proliferation through both direct and indirect mechanisms. Horizontal gene transfer, biofilm formation, selective pressure, and altered microbial networks form a feedback loop that magnifies resistance persistence and spread. Understanding these integrative mechanisms is crucial for predicting hotspots of AMR emergence, designing monitoring strategies, and developing interventions to mitigate the combined effects of climate change and AMR in aquatic systems.

5. Ecological and Human Health Implications

The intersection of climate change and antimicrobial resistance (AMR) in aquatic environments has profound implications for both ecosystem functioning and human health. Aquatic systems serve as reservoirs and transmission pathways for antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs), linking environmental, clinical, and agricultural domains in the context of a One Health framework [1][2]. The combined effects of climate-driven stressors and AMR can disrupt microbial community dynamics, alter ecosystem services, and increase human exposure to resistant pathogens through multiple pathways.

5.1 Ecological Consequences

Climate-induced shifts in temperature, hydrology, and nutrient availability reshape microbial community composition, often favoring opportunistic and resistant taxa [3][4]. This can reduce microbial diversity and alter the balance of ecosystem functions, including nutrient cycling, organic matter decomposition, and pathogen suppression [5]. The persistence of ARGs in sediments, biofilms, and water columns can create environmental reservoirs that maintain resistance even in the absence of antibiotics, enabling long-term ecological impacts [6].

Additionally, co-selective stressors such as heavy metals, microplastics, and biocides, amplified by climate change, further enhance the selective pressure for resistant organisms, potentially affecting higher trophic levels, including invertebrates and fish [7]. Such ecological disruptions may reduce the resilience of aquatic ecosystems to environmental perturbations and diminish the quality of ecosystem services critical for human societies.

5.2 Human Health Risks

Humans are exposed to AMR in aquatic systems through drinking water, recreational contact, and consumption of contaminated seafood and aquaculture products [8][9]. Rising temperatures and extreme weather events can increase pathogen loads in water, facilitating the proliferation of resistant bacteria and ARGs [10]. Flooding and storm events can mobilize contaminated sediments and overwhelm water treatment infrastructure, increasing the likelihood of waterborne outbreaks of resistant infections [11]. Furthermore, climate-driven expansion of waterborne pathogens and ARGs may disproportionately impact vulnerable populations, including those in low- and middle-income countries with limited access to safe water, sanitation, and hygiene [12]. The convergence of environmental AMR and climate change thus represents a critical public health challenge, complicating infection control and increasing the risk of treatment failures.

5.3 Exposure Pathways and Risk Amplification

Environmental AMR acts as a reservoir for horizontal gene transfer, enabling the spread of resistance to clinically relevant bacteria [13]. Combined with climate change effects such as elevated temperatures, reduced flow, and altered salinity, these pathways increase the persistence and dissemination of resistance. Aquaculture and irrigation with contaminated water further amplify the risk, as ARGs can enter the food chain directly [14]. Climate change may also exacerbate seasonal peaks in pathogen abundance and resistance gene prevalence, increasing the risk of episodic exposure and infection [15]. Together, these processes create a synergistic effect, where environmental changes not only elevate the prevalence of resistant organisms but also enhance human and ecological vulnerability.

5.4 Broader Societal Implications

The convergence of climate change and AMR extends beyond ecological and direct health effects. Economic burdens, including increased healthcare costs, lost productivity, and impacts on fisheries and aquaculture, are amplified in regions affected by extreme climate events [16]. Additionally, regulatory and monitoring challenges arise, as traditional approaches to AMR surveillance may not adequately capture environmental reservoirs or climate-sensitive hotspots [17]. Understanding the ecological and health consequences of these interacting threats is therefore essential for integrated policy development, targeted mitigation strategies, and sustainable management of aquatic resources.

In summary, the interaction between climate change and AMR in aquatic systems has wide-ranging ecological and public health implications. By altering microbial community dynamics, promoting ARG persistence, and increasing human exposure to resistant pathogens, these coupled stressors challenge both ecosystem resilience and public health systems. Addressing these risks requires an integrated approach that combines environmental monitoring, predictive modeling, and targeted interventions, informed by a One Health perspective that considers the interconnectedness of climate, ecosystems, and human health.

6. Monitoring, Mitigation, and Policy Strategies

Addressing the dual challenges of climate change and antimicrobial resistance (AMR) in aquatic systems requires integrated monitoring, mitigation, and policy approaches. Effective strategies must consider environmental, microbial, and anthropogenic factors while promoting resilience and sustainability in aquatic ecosystems.

6.1 Environmental Monitoring

Monitoring AMR in aquatic environments is essential for understanding spatial and temporal dynamics, identifying hotspots, and guiding interventions. Surveillance programs often measure the abundance of antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) in water, sediments, and biofilms, using both culture-based and molecular techniques such as quantitative PCR and metagenomics [1][2]. Incorporating climate-related parameters—temperature, precipitation, salinity, nutrient load, and hydrological changes—into monitoring frameworks allows for the identification of climate-sensitive AMR hotspots and prediction of resistance proliferation under future climate scenarios [3]. Early-warning systems that integrate remote sensing, environmental modeling, and microbiological data can improve preparedness and guide public health responses.

6.2 Mitigation Strategies

Mitigation of AMR in aquatic systems requires reducing both anthropogenic inputs and environmental amplification. Key strategies include:

- **Wastewater Management:** Upgrading wastewater treatment plants (WWTPs) to incorporate tertiary treatment methods, such as membrane filtration, advanced oxidation, or constructed wetlands, can reduce the discharge of antibiotics and resistant bacteria into water bodies [4][5].
- **Agricultural and Aquaculture Practices:** Implementing judicious antibiotic use, promoting integrated pest management, and adopting closed-loop aquaculture systems can limit the introduction of ARB and ARGs into aquatic environments [6].
- **Nutrient and Pollutant Control:** Reducing nutrient loading, heavy metals, and other co-selective pollutants helps decrease selective pressures that favor resistant microorganisms, particularly under climate-induced stress [7][8].
- **Habitat Restoration:** Restoring riparian buffers, wetlands, and vegetated shorelines can improve water quality, enhance microbial ecosystem resilience, and reduce the proliferation of resistant bacteria [9].

6.3 Policy and Governance

Effective mitigation requires strong policy frameworks that integrate environmental and public health objectives. Policies should incentivize responsible antibiotic stewardship in healthcare, agriculture, and aquaculture sectors, while also establishing environmental standards for antibiotic residues and resistant microorganisms [10][11]. Regulatory agencies can promote the development of monitoring networks, standardize ARG measurement protocols, and encourage data sharing to track emerging resistance patterns. Cross-sectoral collaboration—linking health, agriculture, water management, and climate agencies—is crucial for implementing a One Health approach that addresses the interconnected drivers of AMR and climate impacts.

6.4 Public Awareness and Stakeholder Engagement

Engaging stakeholders—including local communities, policymakers, farmers, and industry—is essential for successful mitigation. Educational campaigns highlighting the risks of improper antibiotic use and environmental contamination can foster behavioral change, while participatory monitoring initiatives can enhance data collection and stewardship efforts [12]. Transparency in reporting and access to environmental AMR data helps build public trust and informs evidence-based decision-making.

6.5 Integration with Climate Adaptation Strategies

Given the influence of climate change on AMR dynamics, mitigation strategies should be embedded within broader climate adaptation plans. This includes designing resilient water infrastructure that accounts for extreme weather events, incorporating green infrastructure to manage runoff and temperature effects, and modeling future climate scenarios to predict shifts in resistance hotspots [3][13]. Integrating AMR considerations into climate adaptation ensures that interventions address both environmental and public health risks simultaneously.

6.6 Research and Technological Innovations

Emerging technologies, including high-throughput sequencing, metagenomic surveillance, machine learning models, and environmental DNA (eDNA) monitoring, provide powerful tools for tracking ARGs and ARB in aquatic systems [14]. Combining these approaches with predictive modeling can identify trends, forecast risks, and optimize mitigation strategies. Continued research on the interactions between climate variables, microbial ecology, and AMR is essential for developing evidence-based policies and interventions.

In summary, effective management of climate-sensitive AMR in aquatic systems requires coordinated monitoring, mitigation, and policy efforts. Integrating advanced surveillance, infrastructure upgrades, responsible antibiotic use, stakeholder engagement, and climate adaptation strategies can reduce the proliferation of resistance genes, safeguard ecosystem services, and protect public health. A One Health approach, acknowledging the interconnectedness of environmental, human, and animal health, is critical to addressing this multifaceted challenge.

7. Future Directions and Research Needs

The emerging interactions between climate change and antimicrobial resistance (AMR) in aquatic systems present complex challenges that demand innovative research approaches and coordinated global action. Despite advances in understanding environmental AMR dynamics, significant knowledge gaps remain regarding the mechanisms, drivers, and impacts of climate-sensitive resistance, highlighting the need for future research in several key areas.

7.1 Integrative and Interdisciplinary Research

Future studies should adopt interdisciplinary frameworks that combine environmental science, microbiology, hydrology, and public health. Integrating climate modeling with microbial ecology can improve understanding of how temperature shifts, altered precipitation, and extreme weather events influence the proliferation and dissemination of antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) [1][2]. Multi-scale studies, spanning local watersheds to regional and global assessments, are needed to capture variability in climatic effects, land-use practices, and anthropogenic pressures.

7.2 Mechanistic Understanding of ARG Dynamics

A critical research priority is elucidating the mechanistic links between climate change and AMR. While temperature, hydrology, and nutrient enrichment are recognized as drivers, the specific processes influencing horizontal gene transfer, biofilm formation, and microbial community adaptation remain poorly understood [3][4]. Experimental and modeling studies examining these mechanisms under realistic climate scenarios will provide insights into ARG persistence, mobilization, and co-selection by pollutants such as heavy metals and microplastics.

7.3 Advanced Monitoring and Surveillance

Technological advancements in high-throughput sequencing, metagenomics, and environmental DNA (eDNA) provide opportunities to improve surveillance of ARB and ARGs in aquatic systems [5]. Future monitoring should integrate these molecular approaches with remote sensing, hydrological data, and climate projections to identify hotspots of resistance, track temporal trends, and anticipate emerging risks. Standardization of protocols and harmonization of data across regions will enhance comparability and support global AMR assessments.

7.4 Scenario Modeling and Predictive Tools

Predictive models that integrate climate projections, hydrology, land-use change, and ARG dynamics are essential for proactive management. Machine learning and system-based modeling approaches can identify high-risk regions, forecast future resistance patterns under different climate scenarios, and guide targeted mitigation strategies [6][7]. Such tools will be particularly valuable for informing water resource management, public health interventions, and policy decisions.

7.5 Policy-Relevant Research

Bridging science and policy is critical for effective mitigation. Research should evaluate the effectiveness of interventions, such as wastewater treatment upgrades, green infrastructure, and responsible antibiotic stewardship, under climate change conditions. Additionally, socio-economic analyses can help prioritize resource allocation, assess cost-effectiveness, and inform regulatory frameworks that address both environmental and public health risks [8].

7.6 Addressing Emerging and Understudied Stressors

Future studies should consider the role of underexplored stressors, including microplastics, emerging contaminants, and extreme weather events, in shaping AMR dynamics. The synergistic effects of multiple stressors on microbial communities and resistance proliferation are not well characterized and represent an urgent research need [9][10]. Understanding these interactions will improve risk assessment and guide holistic mitigation strategies.

7.7 Global Collaboration and One Health Approaches

Given the transboundary nature of both climate change and AMR, international collaboration is essential. Sharing of surveillance data, harmonization of monitoring methods, and coordinated research initiatives will facilitate the development of global strategies. Adopting a One Health perspective, which integrates human, animal, and environmental health, ensures that interventions address the interconnected drivers of resistance and climate impacts comprehensively [1][11], the convergence of climate change and AMR in aquatic systems requires integrative, interdisciplinary, and forward-looking research. Advancing mechanistic understanding, improving monitoring and predictive capabilities, evaluating mitigation strategies, and fostering global collaboration will enhance our ability to anticipate and mitigate the synergistic impacts of these dual challenges. Such efforts are essential for safeguarding aquatic ecosystem integrity, protecting public health, and informing evidence-based policy in a rapidly changing climate.

8. Conclusion

The interplay between climate change and antimicrobial resistance (AMR) in natural aquatic systems represents a growing environmental and public health challenge. Rising temperatures, altered hydrological patterns, extreme weather events, and shifts in nutrient and salinity dynamics create conditions that favor the persistence, proliferation, and dissemination of antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs). Climate-induced stressors interact with anthropogenic inputs—including wastewater, agricultural runoff, and aquaculture effluents—to amplify selective pressures and facilitate horizontal gene transfer, biofilm formation, and environmental reservoirs of resistance.

The ecological consequences of these processes include altered microbial community composition, reduced ecosystem resilience, and disruption of critical ecosystem services such as nutrient cycling and pathogen regulation. For human populations, climate-sensitive AMR increases exposure risks through drinking water, recreational activities, and food consumption, potentially exacerbating the global burden of resistant infections. The combined effects of climate change and AMR highlight the need for integrated monitoring, mitigation, and policy strategies that address both environmental and public health dimensions.

Future research should focus on mechanistic understanding, predictive modeling, advanced surveillance, and scenario-based assessments, incorporating climate variables and emerging stressors. Adopting a One Health approach that links human, animal, and environmental health is essential for effective intervention. By integrating climate adaptation, environmental management, and AMR mitigation strategies, it is possible to reduce the synergistic impacts of these global threats, protect aquatic ecosystems, and safeguard public health in a rapidly changing world.

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