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Integrated One Health Strategies for Sustainable Potable Water Systems and Ecosystem Protection

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ABSTRACT

The integrated One Health approach offers a comprehensive framework to address human, animal, and environmental health interconnections, particularly within potable water systems and ecosystem protection. This paper examines how an integrative approach can provide practical strategies for sustainable water management and ecosystem conservation, essential for ensuring safe drinking water. Healthy ecosystems provide vital services such as natural water filtration, groundwater recharge, and water flow regulation, necessary for maintaining safe and sustainable drinking water. Conversely, ecosystem degradation and polluted water systems, intensify health challenges and economic impacts, underscoring the urgent need for ecosystem protection and restoration. Critical challenges in adopting integrated One Health strategies include the standardization of monitoring systems, climate change impacts, and the need for community involvement. However, emerging technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and remote sensing provide innovative tools for more effective water quality monitoring and ecosystems, reinforcing policy frameworks and community-driven efforts. Successful case studies, like the Bangladesh Arsenic Mitigation Program and California Wetlands Restoration, demonstrate the potential of integrated strategies to improve water quality and public health outcomes. Integrating water management, ecosystem conservation, and socio-economic factors can contribute to sustainable solutions that promote resilience, equity, and environmental integrity. In facing the increasing pressures from climate change and urbanization, it is crucial to adopt collaborative, cross-disciplinary strategies that recognize the interconnectedness of human, animal, and environmental health to safeguard potable water systems for future generations.

1. Introduction

The One Health approach is a holistic framework that recognizes the interconnectedness of human, animal, and environmental health. This paradigm is particularly relevant to water systems and ecosystems, as water quality directly influences the health of all three domains. The degradation of water systems can lead to a cascade of health issues (Izah et al., 2024a), including the spread of zoonotic diseases, which can be transmitted from animals to humans. For instance, stagnant water bodies are known breeding grounds for malaria vectors, which can significantly increase the risk of malaria infections in nearby human populations (Agegnehu et al., 2018). This illustrates the critical need for an integrated approach to managing water resources, as the health of ecosystems is intrinsically linked to human health outcomes.

Integrating human, animal, and environmental health in potable water management ensures safe drinking water and prevents waterborne diseases (Izah et al., 2024b,c,d, 2023a). The One Health framework promotes collaboration across public health, veterinary medicine, and environmental management sectors to tackle the complex challenges associated with water quality issues. For example, agricultural runoff containing nitrates can contaminate drinking water, leading to health risks such as methemoglobinemia in infants and other serious health concerns in humans and animals (Prata, 2022). By employing an integrated approach, stakeholders can develop comprehensive water safety plans that involve all aspects of water management, from source protection to treatment and distribution (Bänziger et al., 2022; Jacob et al., 2024a,b).

Despite the clear benefits of a One Health approach, several challenges hinder the sustainable management of potable water systems and ecosystem protection. One significant challenge is the need for standardized monitoring and evaluation frameworks to assess the effectiveness of One Health initiatives (Ghai et al., 2022). With robust data and evidence, it becomes easier to implement effective interventions or to allocate resources efficiently. Furthermore, many developing countries face additional barriers, such as limited financial resources and inadequate infrastructure, exacerbating the difficulties in managing water quality and protecting ecosystems (Musoke et al., 2016). These challenges necessitate a concerted effort to strengthen multi-sectoral collaboration and improve the capacity of health systems to respond to water-related health issues (Vesterinen et al., 2019).

Climate change significantly complicates water management and ecosystem health, as shifting precipitation patterns and increasing intensity of extreme weather events drive water scarcity and contamination, affecting human and animal populations (Phung et al., 2015). For instance, flooding can overwhelm wastewater treatment systems, releasing untreated sewage into water bodies and posing severe health risks (Prata, 2022). Additionally, rising temperatures promote the growth of harmful algal blooms, which produce toxins detrimental to health. Addressing these challenges necessitates a proactive and climate-resilient water management strategy that protects ecosystems while safeguarding public health.

The importance of technology in advancing One Health initiatives related to water quality is paramount. Innovations such as real-time water quality monitoring systems deliver essential data for efficient water resource management (Czyczula Rudjord et al., 2022). These systems detect anomalies and contaminants, enabling prompt interventions to avert health crises. Additionally, machine learning and artificial intelligence enhance predictive modeling for water quality, helping stakeholders anticipate and address potential risks (Ghoochani, 2023). Leveraging these technologies allows for a more effective implementation of the One Health approach, fostering informed decision-making and optimizing resource allocation.

Public awareness and community engagement are vital components of successful One Health initiatives. Educating communities about the importance of water quality and its impact on health can empower individuals to protect their water sources proactively (de la Rocque et al., 2023). Community-driven efforts to monitor and report water quality issues can complement governmental and organizational initiatives, creating a more comprehensive approach to water management. Furthermore, incorporating local knowledge and practices into water management strategies can enhance the effectiveness of interventions and foster a sense of ownership among community members (Ferrinho & Fronteira, 2023).

This paper explores the integration of One Health strategies to ensure sustainable potable water systems while protecting interconnected ecosystems. It emphasizes the need for interdisciplinary approaches to address the challenges posed by pollution, climate change, and resource inequities in water management. By aligning water governance with environmental and public health objectives, the study highlights pathways to achieve global sustainable development goals.

2. The Interconnection Between Potable Water Systems and Ecosystem Health

The interconnection between water systems and ecosystem health is crucial when considering potable water systems. Healthy ecosystems are essential in maintaining the quality and availability of potable water by providing key services that support water purification and regulation (Figure 1). Natural water treatment systems, such as wetlands and forests, serve as natural filters, removing pollutants from water before they enter potable water supplies. This filtration process significantly reduces reliance on artificial treatment methods, lowering costs and enhancing water quality for human consumption (La Notte & Dalmazzone, 2018; Obiefuna et al., 2013). Moreover, diverse ecosystems bolster the resilience of water systems, enabling them to adapt to changes and sustain their functionality over time (Xavier et al., 2023; Lopa et al., 2012). Table 1 shows the interconnections between ecosystems, potable water systems, and public health.

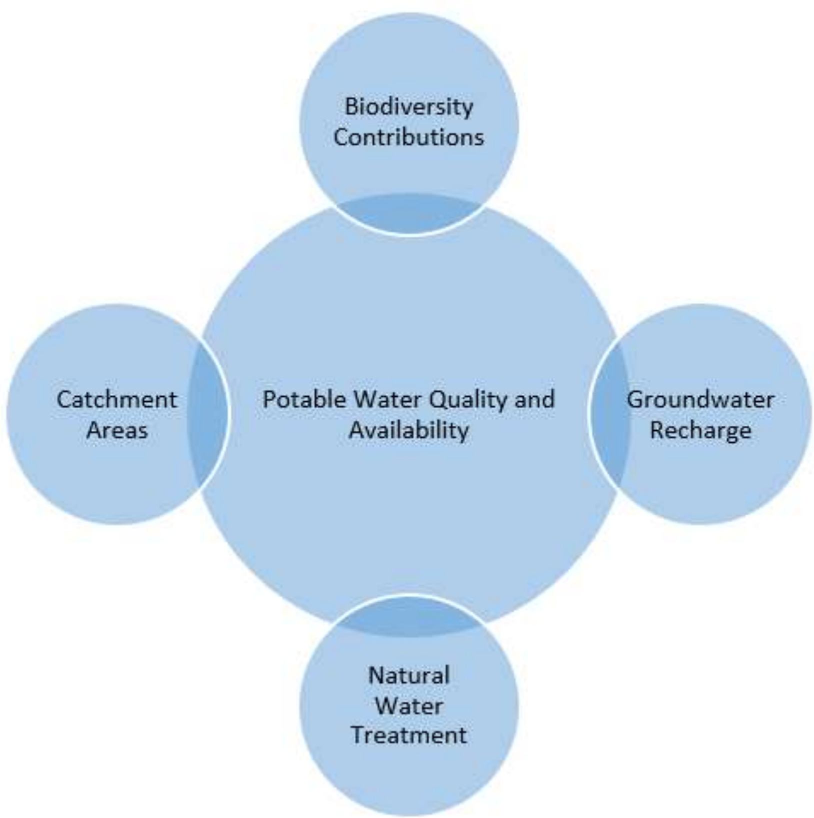

Figure 1: Role of Ecosystems in Ensuring Potable Water Quality and Availability

Table 1: Interconnections between ecosystems, potable water systems, and public health

Key Aspects	Impact on Potable Water Systems	Public Health Focus
Role of Ecosystems in Water Quality	Wetlands and forests act as natural filters, reducing pollutant loads.	Improved access to cleaner drinking water reduces waterborne disease risks.
	Groundwater recharge supports consistent potable water availability.	Ensures long-term water security and reduces reliance on unsafe sources.
	Catchment areas maintain water flow and limit sedimentation.	Minimizes the need for advanced water treatment processes.
	Microbial ecosystems aid in natural water purification.	Prevents pathogen proliferation in untreated or minimally treated water.
Impact of Polluted Water Systems	Contaminants infiltrate water supplies, requiring extensive treatment.	Exposure to pollutants like heavy metals and pathogens leads to diseases.
	Ecosystem degradation increases treatment costs for potable water.	Economic strain limits access to affordable, safe drinking water.
	Reduced natural filtration leads to lower water quality.	Increases prevalence of chronic illnesses linked to long-term exposure.
	Algal blooms disrupt water taste, odor, and safety.	Toxic blooms can cause gastrointestinal and neurological illnesses.
Disruptions in Water-Ecosystem Links	Industrial discharge contaminates drinking water sources.	Leads to acute and chronic health impacts from chemical exposure.
	Agricultural runoff causes eutrophication and algal blooms.	Algal toxins and pathogens increase health risks for communities.
	Urbanization intensifies runoff, carrying pollutants into water bodies.	Urban residents face higher risks of waterborne illnesses.
	Climate change reduces ecosystem resilience, affecting water supplies.	Increased health vulnerabilities due to water scarcity and contamination.

Wetlands are particularly valued for their ability to filter pollutants and improve water quality. They provide crucial habitats for various organisms that help break down organic matter and remove nutrients like nitrogen and phosphorus, which, if left unchecked, can contribute to eutrophication in water bodies (Obiefuna et al., 2013; Rebelo et al., 2018). Wetlands' capacity to retain sediments and nutrients further highlights their role in preserving the integrity of potable water sources. Studies have demonstrated that healthy wetlands can substantially enhance the quality of water flowing into reservoirs and treatment plants, easing the burden on artificial treatment systems (Rebelo et al., 2018; Krupa et al., 2019). This natural purification process is crucial for ensuring that the water provided to communities is safe for consumption.

Groundwater recharge is a vital function of healthy ecosystems, as it supports the replenishment of aquifers that provide essential sources of potable water. Ecosystems like forests and wetlands play crucial roles in maintaining the hydrological cycle, enabling rainwater to infiltrate the soil and recharge groundwater supplies (Keys et al., 2016; Hasim, 2021). Protecting these ecosystems is essential for sustaining groundwater levels, especially in regions with limited surface water resources. Furthermore, the interaction between vegetation and soil enhances the land’s infiltration capacity, promoting efficient groundwater recharge and ensuring a reliable potable water supply (Munang et al., 2011; Lopa et al., 2012). This underscores the importance of preserving and restoring ecosystems to secure future water availability.

Intact ecosystems in watershed regions are equally critical for maintaining consistent water flow and minimizing sedimentation in reservoirs used for drinking water. Healthy catchment areas regulate water flow, which is crucial for maintaining the quantity and quality of water available for human consumption (Vilhar & Simončič, 2012; Xavier et al., 2023). Vegetation in these areas stabilizes soils, preventing erosion and sediment runoff that can compromise water quality (Barınova & Mamanazarova, 2021; Lan et al., 2021). Additionally, intact ecosystems support natural filtration processes as water moves through the landscape, further improving the quality of water reaching treatment facilities (La Notte & Dalmazzone, 2018; Obiefuna et al., 2013). Consequently, conserving watershed ecosystems is crucial for safeguarding potable water supplies.

Biodiversity within aquatic ecosystems is crucial for maintaining water quality for human consumption. Microbial communities, for example, are vital for breaking down organic matter and recycling nutrients in water bodies (Ricketts & Lonsdorf, 2013; Barınova & Mamanazarova, 2021). A diverse range of microbial populations enhances the self-purification capacity of water systems, allowing them to effectively remove contaminants and maintain a balanced ecosystem (Liu & Lu, 2021; Hasim, 2021). This natural process is essential for ensuring water remains safe for human use by reducing harmful substances that could pose health risks (Keys et al., 2016; Lan et al., 2021). Therefore, preserving biodiversity in aquatic ecosystems is not only beneficial for ecological health but also for public health.

The impact of polluted water systems on ecosystems and human health is profound and multifaceted (Figure 2). Contaminated drinking water sources, often resulting from polluted ecosystems, can introduce toxic substances into potable water supplies, increasing the risk of disease within populations (Krupa et al., 2019; Keys et al., 2016). Heavy metals, pathogens, and chemical pollutants can infiltrate water systems through various pathways, including industrial discharges and agricultural runoff (Lan et al., 2021; Hasim, 2021). The consequences of drinking contaminated water are severe, ranging from acute infections to chronic illnesses, highlighting the urgent need for effective water management practices that prioritize ecosystem health (Xavier et al., 2023; Munang et al., 2011).

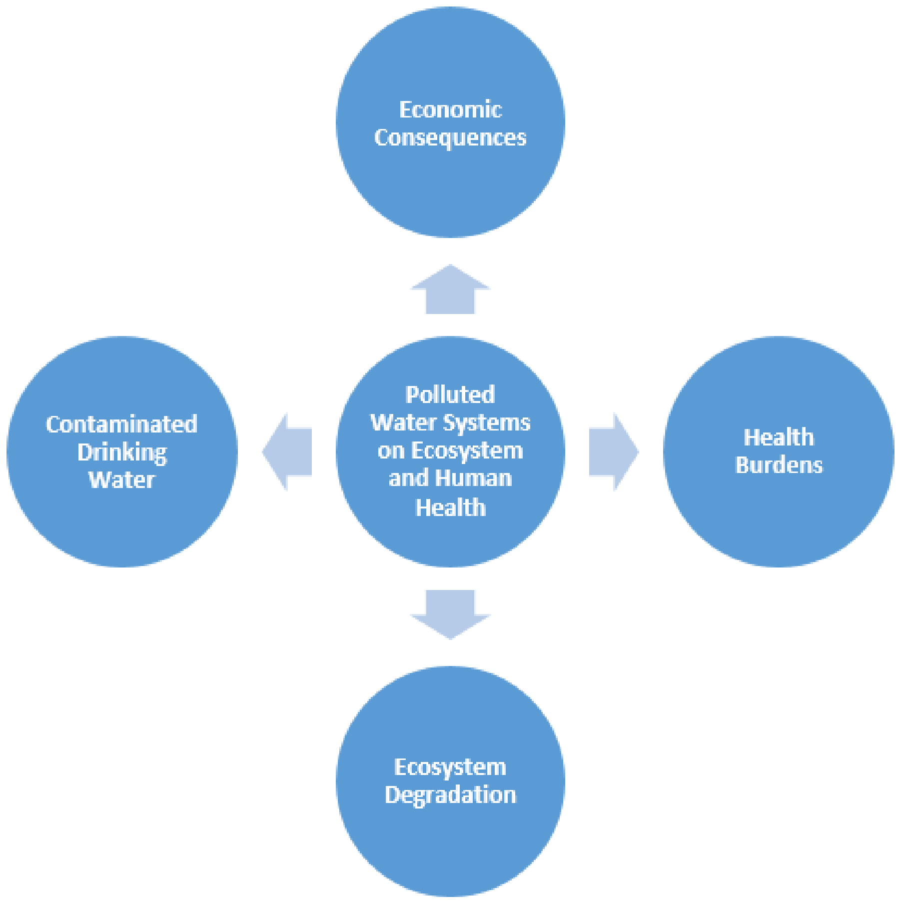

Figure 2: Impact of Polluted Water Systems on Ecosystem and Human Health

Ecosystem degradation exacerbates the challenges related to water quality and availability. The loss of biodiversity in aquatic ecosystems reduces their ability to naturally purify water, leading to higher treatment costs and limited access to safe drinking water (Kroll et al., 2012; Keys et al., 2016). As ecosystems become less resilient, their capacity to provide essential services such as water purification and nutrient cycling diminishes, increasing reliance on costly artificial treatment technologies (La Notte & Dalmazzone, 2018; Lopa et al., 2012). This economic burden disproportionately impacts vulnerable communities, underscoring the need for integrated water management approaches that account for ecosystem health and human needs (Zheng et al., 2016; Li et al., 2020).

The economic consequences of degraded natural water sources are significant, as they heighten the dependence on expensive water treatment technologies, making safe drinking water less affordable and accessible (Munang et al., 2011; Lopa et al., 2012). Communities reliant on polluted water sources often face increased healthcare costs and lost productivity due to waterborne diseases, creating a vicious cycle of poverty and health disparities (Xavier et al., 2023; Lan et al., 2021). Furthermore, ecosystem degradation can lead to the loss of livelihoods for communities that depend on natural resources for their income, further exacerbating the socio-economic challenges of these populations (Krupa et al., 2019; Keys et al., 2016). Investing in ecosystem protection and restoration is crucial for improving public health and securing long-term economic stability.

Several examples highlight disruptions in the water-ecosystem interdependencies that affect potable water systems. Industrial waste discharge into freshwater sources severely contaminates primary drinking water, such as rivers and reservoirs (Ogidi and Izah, 2024; Lan et al., 2021; Hasim, 2021). Hazardous substances from industrial processes can significantly compromise water quality, posing risks to human health and the environment (Xavier et al., 2023; Keys et al., 2016). Similarly, agricultural runoff, laden with excess nutrients and pesticides, can lead to eutrophication and harmful algal blooms, disrupting water treatment processes and diminishing the safety and taste of drinking water (Obiefuna et al., 2013; Lan et al., 2021). These disruptions underscore the urgent need for sustainable land-use practices to mitigate the negative impacts of human activities on water systems (Numbere et al., 2024).

Urbanization and infrastructure development also significantly contribute to water quality degradation. The proliferation of impervious surfaces in cities increases runoff into potable water sources, carrying pollutants and sediments that compromise water quality (Aghoghovwia et al., 2018; Ogamba et al., 2015; Vilhar & Simončič, 2012; Keys et al., 2016). As urban areas expand, the natural filtration services provided by ecosystems are often reduced, resulting in increased reliance on artificial treatment methods to maintain safe drinking water (Munang et al., 2011; Lopa et al., 2012). Addressing this urban challenge requires integrating green infrastructure solutions, such as green roofs and permeable pavements, to improve water quality and promote sustainable urban development (Xavier et al., 2023; Liu & Lu, 2021).

Climate change disrupts the delicate interconnection between water systems and ecosystem health. Changes in precipitation patterns can undermine the reliability of ecosystem services essential for maintaining potable water supplies (Keys et al., 2016; Hasim, 2021). Variations in rainfall intensity and frequency increase runoff and sedimentation, degrading water quality in reservoirs and treatment facilities (Lan et al., 2021; Lopa et al., 2012). Additionally, rising temperatures can accelerate the growth of harmful algal blooms, jeopardizing both water safety and availability (Xavier et al., 2023; Munang et al., 2011). Addressing these climate-induced challenges necessitates adaptive management strategies, ecosystem resilience, and sustainable water resource use.

3. One Health Framework for Potable Water Systems

The One Health framework adopts a holistic approach to understanding the interconnectedness of human, animal, and environmental health, with a particular focus on potable water systems. This approach is essential for tackling the complexities of water management, emphasizing how water quality influences health outcomes across diverse sectors. By encouraging collaboration among public health experts, environmental scientists, and policymakers, the One Health framework fosters integrated strategies to manage potable water systems more effectively (Morseletto et al., 2022; Gerrity et al., 2013).

A key principle of the One Health approach to potable water management is grounded in the recognition that human, animal, and environmental health are deeply interconnected and mutually dependent. This perspective underscores the importance of assessing water quality within the context of the entire ecosystem. For instance, contaminants from agricultural runoff can degrade water sources, threatening human health, aquatic ecosystems, and biodiversity (Onyango et al., 2015). By leveraging a One Health lens, stakeholders can better identify and mitigate pathways for disease and contaminant spread, enabling more targeted and effective interventions to protect human and ecological well-being (Pecson et al., 2015).

Preventative strategies form a core component of the One Health framework for managing waterborne diseases and contamination. This proactive approach focuses on minimizing contamination risks at the source, shifting away from reactive solutions that address problems only after they occur. These strategies prioritize community education and engagement, equipping individuals with the knowledge to adopt safe water practices and identify environmental hazards at an early stage (Onyango et al., 2015). Integrated testing and monitoring systems further enhance this approach by enabling the early detection of contamination, and facilitating timely interventions to safeguard public health (Morseletto et al., 2022).

A holistic approach to water quality assessment is another vital element of the One Health framework. This approach integrates microbiological, chemical, and ecological indicators to assess water safety and quality thoroughly. Conventional methods often focus solely on chemical parameters, overlooking critical environmental factors that impact water systems (Morseletto et al., 2022). By broadening the scope of analysis, stakeholders can more effectively identify potential risks and design targeted mitigation strategies. For example, monitoring biodiversity in aquatic ecosystems can reveal crucial insights into the overall health of water bodies and their ability to filter pollutants naturally (Saidani et al., 2019).

Preserving ecosystems is a core focus of the One Health framework, essential for the long-term sustainability of water resources. Healthy ecosystems are important for conserving water quality, offering natural filtration and sustaining diverse species' habitats (Morseletto et al., 2022). Protecting critical habitats such as wetlands and forests not only supports biodiversity but also enhances the resilience of water systems to the impacts of climate change and human activities. For example, wetland restoration has been reported to improve water quality by reducing nutrient loads and filtering pollutants from runoff (Morseletto et al., 2022).

Adopting circular economy principles is increasingly recognized as a key strategy for reducing environmental pressures on potable water systems.

Circular economy approaches focus on minimizing waste and maximizing resource efficiency, significantly improving the sustainability of water management practices (Morseletto et al., 2022; Attaran et al., 2023). Initiatives such as wastewater recycling and nutrient recovery can convert waste into valuable resources, reducing reliance on freshwater across all sectors while helping mitigate pollution (Morseletto et al., 2022; Attaran et al., 2023). By embracing these principles, water utilities can develop more resilient systems equipped to tackle the challenges of population growth and climate change (Morseletto et al., 2022; Attaran et al., 2023).

Several case studies demonstrate the successful application of One Health strategies in potable water management. A prominent example is the Bangladesh Arsenic Mitigation Program, where integrated testing and community health interventions were employed to address arsenic contamination in drinking water sources. This program underscored the importance of community engagement and education in promoting sustainable water practices, illustrating that local involvement is critical to the success of public health initiatives (Onyango et al., 2015). The program introduced practical solutions that lowered arsenic exposure and enhanced overall health outcomes by instilling a sense of ownership within the community.

Another compelling case study is the California Wetlands Restoration for Water Filtration project, which showcases the vital role of wetland ecosystems as natural water purifiers. This initiative brought together ecologists, policymakers, and urban planners to restore wetland habitats, enhancing their capacity to filter pollutants from municipal water supplies (Morseletto et al., 2022). Beyond improving water quality, the project also helped preserve biodiversity and strengthen the resilience of local ecosystems, highlighting the multifaceted benefits of integrating ecological principles into water management strategies (Morseletto et al., 2022).

Uganda's WASH (Water, Sanitation, and Hygiene) Program exemplifies the integration of public health monitoring with ecological assessments to combat waterborne diseases. Addressing the root cause of water-related health issues, the program improved biodiversity and lowered healthcare costs, demonstrating its broad co-benefits (Onyango et al., 2015). A One Health approach created synergies between health and environmental outcomes, ultimately fostering more sustainable and effective water management practices (Morseletto et al., 2022).

Successful implementation of One Health strategies in potable water management depends on strong cross-disciplinary collaboration. Creating multi-sectoral task forces that coordinate actions and share data across disciplines can significantly enhance the impact of interventions (Morseletto et al., 2022). Including experts such as ecologists, microbiologists, veterinarians, and urban planners in water governance committees, diverse perspectives are brought into decision-making, leading to more holistic and effective solutions (Morseletto et al., 2022). This collaboration fosters innovation and supports the development of policies rooted in scientific evidence, ultimately strengthening the resilience of water systems.

Public-private partnerships are also essential for driving technological advancements in water purification and ecosystem monitoring. By combining the strengths of both sectors, stakeholders can develop and deploy cutting-edge technologies that enhance water quality and safety (Morseletto et al., 2022). Additionally, community-driven initiatives, indigenous knowledge and local practices ensure that water management strategies are culturally sensitive and scientifically sound (Morseletto et al., 2022). This collaborative approach boosts water systems sustainability and empowers communities, fostering resilience and engagement.

4. Technological and Policy Innovations for Integrated Potable Water Management

Integrating emerging technologies into potable water management is transforming how we monitor and maintain water quality and ecosystems. Table 2 shows the technological and policy innovations for sustainable potable water management. The Internet of Things (IoT) revolutionizes water quality monitoring by enabling real-time data collection through smart sensors. These sensors can measure critical parameters such as pH, turbidity, and contaminant levels, providing immediate feedback on water quality. For instance, systems designed for aquaculture have successfully utilized IoT technology to monitor water conditions, ensuring optimal environments for aquatic life (Gleiser & Moro, 2023; Elmunsyah et al., 2019). By integrating sensor data into centralized systems, organizations can enhance decision-making processes through comprehensive insights gathered from distributed networks (Irawati, 2023; Wang, 2022). Moreover, IoT-based early warning systems can promptly alert stakeholders to contamination events or infrastructure failures, facilitating timely interventions (Kamal et al., 2019).

Table 2: Technological and Policy Innovations for Sustainable Potable Water Management

Focus Area	Strategies and Innovations	Sustainability Implications
Emerging Technologies	IoT: Real-time monitoring of water quality and infrastructure health.	Proactive issue detection reduces resource waste and prevents long-term environmental damage.
	Remote Sensing/GIS: Identifying pollution sources and monitoring land-use impacts.	Supports sustainable land management and conservation efforts, minimizing ecosystem degradation.
	AI/ML: Trend analysis, predictive maintenance, adaptive resource management.	Optimizes water system efficiency, conserving resources while ensuring equitable access.
	Biotechnology: Advanced filtration, biosensors for contaminants, microbial profiling.	Reduces reliance on chemical treatments, promoting eco-friendly water purification.
Policy Frameworks	One Health Integration: Cross-sectoral collaboration in water policies.	Harmonizes human, animal, and environmental health objectives, fostering long-term ecosystem resilience.
	Regulatory Standards: Enforcing strict pollutant discharge limits.	Maintains water quality and protects aquatic ecosystems, ensuring a sustainable supply for future generations.
	Incentives for Innovation: Subsidies for technology adoption, R&D funding.	Encourages sustainable technological advancements and widespread adoption of eco-friendly solutions.
	International Cooperation: Knowledge-sharing platforms, alignment with UN SDGs.	Promotes global accountability and collective progress in sustainable potable water management.
Community-Led Initiatives	Local Stewardship: Empowering communities with monitoring tools and water councils.	Enhances resource management accountability and reduces dependency on external systems.
	Indigenous Knowledge: Traditional practices like rainwater harvesting, sustainable use of natural water sources.	Preserves cultural heritage while promoting low-impact, resource-efficient water conservation techniques.
	Capacity Building: Training programs for technology adoption and public awareness campaigns.	Strengthens community resilience and supports grassroots-driven sustainability in water management.

Remote sensing and Geographic Information Systems (GIS) complement IoT technologies by offering tools to monitor land-use changes and their impacts on water resources. These technologies allow for the identification of pollution sources and the assessment of ecosystem health (Wang et al., 2018; Chi et al., 2020). By integrating remote sensing data with predictive modeling, water resource managers can anticipate changes in water availability and quality, which is crucial for effective water management strategies (Wang et al., 2018). Integrating these technologies enhances our understanding of water systems and supports the development of proactive measures to mitigate potential risks associated with water quality degradation.

Artificial Intelligence (AI) and Machine Learning (ML) further augment the capabilities of water management systems by enabling sophisticated data analysis. These technologies can detect trends and predict anomalies in water systems, allowing for more informed decision-making regarding resource allocation and maintenance schedules (Chang & Guo, 2020). For example, AI-driven models can analyze historical data to forecast future water quality conditions, thereby assisting in the planning and management of water resources (Drogkoula, 2023). Additionally, ML algorithms can facilitate adaptive management strategies that respond to changing environmental and anthropogenic factors, enhancing the resilience of water systems (Chang & Guo, 2020).

Biotechnological innovations also play a significant role in monitoring and managing potable water quality. Developing bioindicators and biosensors allow for detecting microbial and chemical contaminants in water sources (Drogkoula et al., 2023). These technologies can be integrated with IoT systems to provide real-time monitoring capabilities, ensuring that water quality standards are met consistently. Moreover, advancements in nanotechnology have led to the creation of advanced filtration and water treatment solutions that can effectively remove contaminants from water supplies (Izah et al., 2023b). Implementing microbial community profiling further aids in assessing ecosystem health, providing insights into the biological integrity of water bodies.

The policy frameworks supporting potable water resource management increasingly recognize the importance of integrating One Health principles, emphasizing the interconnectedness of human, animal, and environmental health. Effective policy design mandates cross-sectoral collaboration in water governance, ensuring all stakeholders are involved in decision-making (Drogkoula et al., 2023). Regulatory mechanisms are being established to enforce stringent standards for industrial and agricultural discharges into water bodies, thereby protecting water quality and ecosystem health (Drogkoula et al., 2023). Incorporating ecosystem services valuation into water management policies emphasizes the vital economic and social benefits of preserving healthy water ecosystems. Incentives for technological adoption are crucial for advancing integrated water management practices. Governments and local authorities increasingly provide subsidies for adopting innovative water technologies, facilitating the transition to more sustainable practices (Drogkoula et al., 2023). Funding for research and innovation in sustainable water management solutions is also essential for developing new technologies and methodologies to address emerging water resource management challenges (Drogkoula et al., 2023). International cooperation and frameworks, such as the United Nations Sustainable Development Goals (SDGs), align national water management goals with global sustainability objectives and foster collaborative efforts to improve water quality and accessibility.

Community-led initiatives and indigenous knowledge systems are integral to the success of integrated water management strategies. Empowering local communities to monitor water quality using low-cost, user-friendly tools enhances community engagement and stewardship (Drogkoula et al., 2023). Community water councils facilitate participatory decision-making, ensuring local voices are heard in water governance processes. Moreover, documenting traditional water conservation practices, such as rainwater harvesting and terracing, provides valuable insights into sustainable water management approaches that have been effective for generations (Drogkoula et al., 2023).

Integrating cultural norms and practices into modern water management strategies fosters a holistic approach to water resource management. By promoting the sustainable use of natural water sources based on indigenous ecological insights, policymakers can enhance the effectiveness of water management initiatives (Drogkoula et al., 2023). Capacity building and education are also critical components of community-led initiatives, as training programs empower communities to adopt and maintain water management technologies. Public awareness campaigns highlighting the importance of ecosystem protection in potable water sustainability further reinforce the need for collective action in safeguarding water resources (Drogkoula et al., 2023).

Bridging scientific knowledge with traditional practices is crucial for creating comprehensive water management solutions. Collaboration among scientists, policymakers, and local communities can generate innovative strategies that address modern challenges while valuing traditional knowledge. Integrating diverse perspectives promotes a more inclusive approach to water management, ensuring solutions are culturally relevant and tailored to specific contexts. By combining emerging technologies, robust policy frameworks, and active community engagement, stakeholders can establish sustainable and integrated potable water management practices.

5. Addressing Climate Change and Its Impacts on Potable Water and Ecosystem Health

Addressing impacts of climate change on potable water and ecosystem health is an urgent global priority requiring a multifaceted approach. Climate change poses significant threats to potable water systems and ecosystems by exacerbating water scarcity, degrading water quality, altering temperature regimes, and disrupting ecological balance (Figure 3). These factors interact with the hydrological cycle and ecosystem functions, with far-reaching consequences for human health and environmental sustainability.

Water scarcity is among the most pressing concerns, as climate change alters precipitation patterns, resulting in prolonged droughts and diminished freshwater availability. Research highlights global climate change as a primary driver of the current water scarcity crisis, severely affecting access to potable water resources worldwide (Nguyen et al., 2024). Regions already facing water stress are particularly vulnerable, as the changing climate amplifies weaknesses in existing water supply systems (Yoon et al., 2015).

Moreover, extreme weather events, including droughts and floods, are becoming more frequent and severe, further straining water resources and complicating management efforts (Balabukh et al., 2018). These challenges are particularly acute in developing regions, where climate change magnifies existing vulnerabilities, intensifying competition for limited water supplies (Codjoe & Atiglo, 2020).

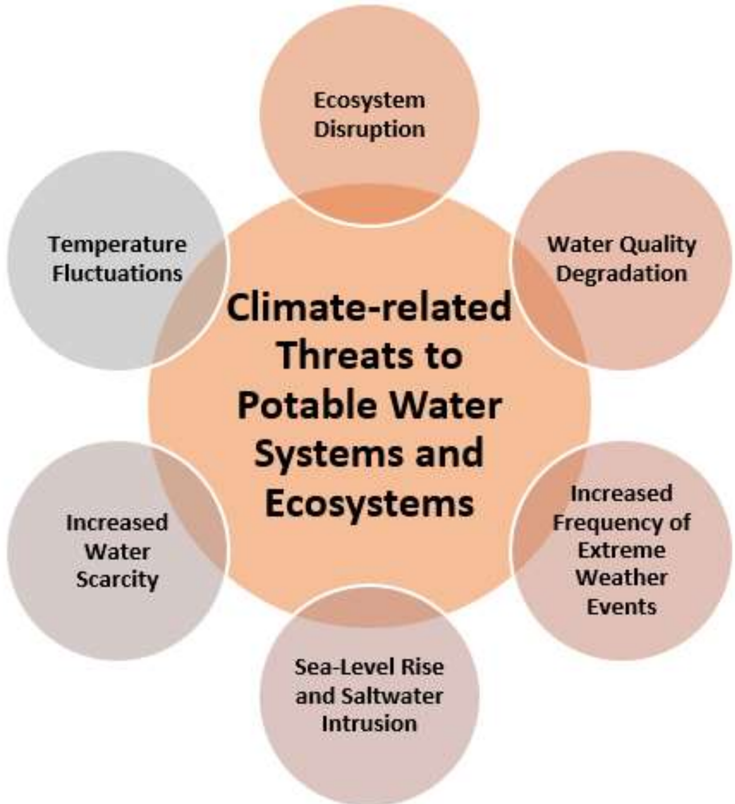

Figure 3: Climate-related Threats to Potable Water Systems and Ecosystems

Water quality degradation is another pressing issue linked to climate change. Extreme weather events such as heavy rainfall and flooding can overwhelm water treatment systems, contaminating drinking water sources (Cann et al., 2012). Rising temperatures further exacerbate the problem by promoting the proliferation of pathogens and harmful algal blooms, creating favorable conditions for microbial growth (Tang et al., 2021). Studies have shown a direct correlation between extreme weather events and outbreaks of waterborne diseases, underscoring the public health risks posed by climate-induced water quality issues (Lund et al., 2021). Beyond human health, water quality degradation also impacts aquatic ecosystems, disrupting food webs and contributing to biodiversity loss (Hadi & Seidu, 2019).

Temperature fluctuations associated with climate change are significantly altering aquatic ecosystems. Rising water temperatures reduce oxygen levels in water bodies, which is detrimental to many marine species (Tang et al., 2021). These changes can shift species distributions and community compositions, with some species thriving while others face decline or extinction (Tang et al., 2021). Additionally, the increased frequency of extreme temperature events exacerbates the vulnerability of aquatic organisms, especially those already stressed by habitat loss and pollution (Kim et al., 2010). Such biodiversity changes have profound implications, disrupting ecological interactions and degrading ecosystem health.

Ecosystem disruption is a critical consequence of climate change, with significant effects on the water cycle, wetland functionality, and forest cover. The loss of wetlands, for instance, diminishes their natural roles in water filtration and flood control, increasing vulnerability to flooding and water quality degradation (Fan et al., 2023). Similarly, deforestation and land-use changes reduce the capacity of landscapes to retain and regulate water, intensifying water scarcity (Yoon et al., 2015). Ecosystems are deeply interconnected, and disruptions in one area can trigger cascading effects across regions, compromising water availability and quality. This underscores the pressing need for integrated management strategies that focus on ecosystem-wide health (Davies et al., 2014).

The increasing frequency of extreme weather events presents significant challenges to water treatment systems. Intense storms and flooding can damage infrastructure, causing contamination and service disruptions (Kettle et al., 2023). Research indicates that rural water and wastewater systems are particularly vulnerable to these events due to limited resources and adaptive capacity (Kettle et al., 2023). The public health implications are severe, as compromised water systems heighten the risk of waterborne disease outbreaks, particularly among vulnerable populations (Cann et al., 2012). Enhancing the resilience of water treatment systems is crucial for mitigating the impacts of climate change on water quality and public health.

Sea-level rise and saltwater intrusion pose additional climate-related threats to potable water systems, especially in coastal regions. Rising sea levels increase the risk of saltwater contaminating coastal aquifers, jeopardizing freshwater supplies (Fan et al., 2023). This issue is expected to intensify in the coming decades, particularly in low-lying regions grappling with limited freshwater resources (Cann et al., 2012). Saltwater intrusion diminishes drinking water quality, impacts agricultural productivity and ecosystem health (Fan et al., 2023). Tackling these challenges requires innovative management strategies that blend mitigation and adaptation measures to safeguard coastal water resources.

Mitigation and adaptation strategies grounded in One Health principles are crucial for addressing the interconnected challenges of climate change (Figure 4). Integrated Water Resource Management (IWRM) provides a holistic framework that integrates human, animal, and ecosystem health into water management strategies (Mullin & Kirchhoff, 2018). This approach highlights the importance of collaboration among diverse stakeholders—governments, communities, and scientists—to develop sustainable practices that enhance resilience to climate change (Mullin & Kirchhoff, 2018). Pollution reduction initiatives, such as adopting eco-friendly agricultural practices and improving waste management systems, are vital for safeguarding water quality and preserving ecosystem health (Mullin & Kirchhoff, 2018).

Restoring ecosystem services is a game-changer for climate resilience. Reforestation and wetland revival, supercharge natural water filtration, fortify landscapes against erosion, and amplify water storage capacity, safeguarding our future one ecosystem at a time (Mullin & Kirchhoff, 2018). These efforts strengthen ecosystems' ability to deliver essential services that benefit human and environmental health (Mullin & Kirchhoff, 2018). Promoting climate-smart agricultural practices can optimize water use, reduce soil erosion, and protect water quality, ensuring sustainable food production and long-term resource availability (Mullin & Kirchhoff, 2018).

Figure 4: Mitigation and adaptation strategies aligned with One Health principles

Adapting infrastructure is pivotal for developing water systems capable of withstanding climate-related challenges. This includes upgrading treatment capacities and integrating flood control mechanisms to mitigate the effects of extreme weather events (Kettle et al., 2023). Investments in climate-resilient infrastructure reduce system vulnerabilities and ensure a reliable supply of safe drinking water during crises (Kettle et al., 2023). Strengthening public health surveillance and environmental monitoring systems is essential for tracking climate change impacts on waterborne diseases and ecosystem health. Enhanced monitoring is much more than being precautionary, it is a frontline defense. Swift responses to emerging threats, safeguard public health and fortify water security, keeping communities protected and resilient (Kettle et al., 2023).

Ecosystem-based solutions are critical for enhancing climate resilience (Figure 5). Natural systems such as wetlands and riparian zones serve as effective buffers, filtering pollutants, controlling floods, and ensuring water quality and availability (Mullin & Kirchhoff, 2018). Conserving biodiversity is equally essential, as diverse ecosystems are more stable and better equipped to adapt to climate change (Iyiola et al., 2024; Mullin & Kirchhoff, 2018). Restoring watershed ecosystems helps stabilize water supplies, mitigates the impacts of extreme weather events, and contributes to long-term water security (Mullin & Kirchhoff, 2018).

Community-driven initiatives and indigenous knowledge systems offer valuable solutions for mitigating the impacts of climate change on water resources. Traditional practices rooted in indigenous wisdom provide insights into sustainable land use and ecosystem management (Mullin & Kirchhoff, 2018). Empowering communities to monitor water quality and weather patterns strengthens local resilience and fosters a sense of stewardship over shared resources (Mullin & Kirchhoff, 2018). Capacity-building and education programs further enable communities to adopt sustainable water management and climate adaptation practices, ensuring long-term resilience and sustainability (Mullin & Kirchhoff, 2018).

Figure 5: Role of Ecosystem-based Approaches in Building Climate Resilience

Collaborative resource management is vital for creating effective water policies and conservation strategies. Bringing together local communities, governments, and scientists ensures that solutions are fair, inclusive, and sustainable (Mullin & Kirchhoff, 2018). Sustainable livelihoods like eco-tourism, smart agriculture, and forest management link community needs with ecosystem health, supporting the people and the environment (Mullin & Kirchhoff, 2018). Incorporating cultural values, such as respecting nature, into environmental practices fosters community involvement and long-term commitment to conservation efforts (Mullin & Kirchhoff, 2018).

6. Implications for Sustainable Development

Integrated potable water and ecosystem strategies have profound implications for sustainable development. Table 3 outlines the key impacts of such strategies. Achieving Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land), requires a holistic approach that links water management with ecosystem health. This integrated approach addresses immediate water needs while promoting long-term sustainability and resilience to climate change.

SDG 6 focuses on providing equitable access to safe drinking water through sustainable management. Incorporating ecosystem services into water management is essential to maintaining water quality and availability, especially in vulnerable areas. For example, urbanization often disrupts ecosystems critical for clean water supply, highlighting the need for strategic ecosystem-based management in sustainable development planning (Saputra et al., 2023). Additionally, promoting safe water practices and safeguarding ecosystems can significantly lower the prevalence of waterborne diseases, which remain a major public health concern in many regions (Handono et al., 2023).

Table 3: Implications of Integrated Potable Water and Ecosystem Strategies for Sustainable Development

Focus Area	Key Highlights	Impact on Sustainable Development
Contribution to SDGs	SDG 6: Clean Water and Sanitation: Improved water quality and access. SDG 13: Climate Action: Ecosystem-based mitigation and adaptation. SDG 15: Life on Land: Biodiversity conservation and ecosystem protection.	Supports global health goals, climate resilience, and biodiversity conservation.
Enhancing Health Equity and Access to Potable Water	Ensures marginalized communities access clean water. Reduces waterborne diseases and health disparities. Promotes equitable water governance and community involvement.	Improves health equity, social stability, and overall well-being.
Long-Term Economic, Social, and Environmental Benefits	Economic: Reduces water treatment and disaster costs, supports sustainable agriculture. Social: Enhances quality of life and reduces water conflicts. Environmental: Protects ecosystems, supports biodiversity, and improves water filtration.	Contributes to economic growth, social stability, and environmental sustainability.

In the context of climate action under SDG 13, adapting water systems to the impacts of climate change—such as increased droughts and floods—is vital for enhancing resilience. Ecosystem-based solutions, like wetland restoration for flood mitigation, can effectively reduce climate vulnerability while providing essential water filtration services (Tortajada, 2021). Sustainable water management practices that protect forests and other natural ecosystems contribute to carbon reduction, water quality and climate change (Erisman et al., 2011). The interdependence of water systems and climate resilience highlights the need for integrated approaches that integrate environmental and socio-economic factors.

The implications for biodiversity and ecosystem health under SDG 15 are equally significant. Healthy ecosystems are essential for filtering and storing water, and their protection is crucial for maintaining biodiversity. Restoring ecosystems, such as wetlands and forests, contributes to clean water supply and enhances biodiversity conservation (Sarastika, 2023). Ecosystems also play a critical role in mitigating environmental degradation and supporting essential ecosystem services related to water, which are vital for human well-being (Griebler & Avramov, 2015). The interconnectedness of ecosystem health and water quality underscores the need for a systems-thinking approach to environmental management. Addressing health equity and access to potable water is key to sustainable development. To bridge the gap in clean drinking water access, especially in rural and underserved areas, comprehensive strategies must be implemented with a strong focus on vulnerable populations (Hermawan et al., 2022). Socio-economic barriers to water access and sanitation can be overcome by fostering community participation in water governance and empowering local stakeholders to manage and protect water resources (Villada-Canela et al., 2021). This participatory approach enhances equity and strengthens community resilience by integrating water and ecosystem management into disaster preparedness and response plans (Gattringer et al., 2016). Improving water infrastructure in underserved regions is crucial for preventing waterborne diseases and improving public health. Investments in sustainable water infrastructure can significantly enhance health outcomes, especially in communities that have historically struggled with access to clean water (Herawati et al., 2021). Moreover, cross-sector collaboration involving health, environment, and education can raise awareness and improve access to clean water, fostering a more informed and engaged population (Lartigue, 2015). This collaborative approach ensures that water management strategies are inclusive and equitable.

The long-term economic, social, and environmental benefits of integrating potable water and ecosystem health are significant. Economically, preventing pollution and enhancing ecosystem services, such as natural filtration, can substantially reduce water treatment costs, leading to considerable savings for communities and governments (Blanchard et al., 2017). Sustainable agricultural practices, supported by integrated water management, can boost yields and improve livelihoods, contributing to greater economic resilience (Bian et al., 2013). Additionally, preserving clean water bodies and natural landscapes can attract tourism and recreational opportunities, providing further incentives for ecosystem protection (Koch et al., 2020).

The benefits of improved water management extend beyond health. Integrated water and ecosystem management can strengthen community resilience by reducing waterborne diseases and enhancing overall well-being (Samadi et al., 2022). Moreover, ensuring equitable access to water through inclusive policies helps all community members benefit from sustainable water practices, fostering social cohesion and stability (Huizenga et al., 2022). The social aspects of water management emphasize the need to incorporate human factors into environmental strategies.

Environmentally, biodiversity conservation through effective water management is crucial for maintaining ecosystems that support plant and animal life dependent on clean water (Griebler & Avramov, 2015). Restoring degraded ecosystems, such as wetlands and watersheds, improves water quality, enhances biodiversity and ecosystem resilience (Sarastika, 2023). Moreover, sustainable land and water use practices can greatly minimize industrial and agricultural runoff, safeguarding water resources and ecosystem health (Sacco et al., 2023).

7. Conclusion

Addressing the challenges of potable water and ecosystem health requires a holistic, integrated approach that unites policymakers, scientists, and local communities. The One Health framework provides a holistic approach to addressing human, animal, and environmental health, in water systems. This approach fosters the development of sustainable water management practices that prioritize ecosystem health, ensuring clean water supplies and promoting public health. However, several challenges remain, including standardized monitoring frameworks, climate change adaptation, and enhanced community participation in water governance. Overcoming these challenges will require coordinated efforts, cross-sector collaboration, and innovative solutions to ensure the long-term sustainability of water resources.

Integrating ecosystem protection into water management strategies is essential. Healthy ecosystems are important for purifying water, replenishing groundwater, and regulating flow—critical for securing safe drinking water. As pressures from urbanization, industrialization, and climate change intensify, adopting integrated approaches that recognize the value of ecosystems in safeguarding water quality and availability becomes increasingly important. The success of these strategies depends on fostering collaboration among stakeholders, leveraging emerging technologies, and engaging local communities. With concerted action, we can create resilient water systems that promote public health, protect biodiversity, and ensure equitable access to safe drinking water.

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