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Review Paper

Climate resilience: Safeguarding air and water Quality

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Abstract

Climate change deeply affects air and water quality, posing problems for sustainable management of the environment. Global temperatures are on the rise, precipitation reconfiguration and extreme weather events alter pollutant dynamics and amplify public health risks while threatening fragile ecosystems. These issues require a multifaceted approach involving policy, technology, and community engagement. Adaptation strategies can also include early warning systems, regulations, and technology (for example: investment emissions reduction, urban pollution control, and climate-resilient water) to make smart choices, the report added. Nature-based solutions (NbS) like wetland restoration and green infrastructure are sustainable solutions to improve air and water quality. The advancements in technology, such as Artificial Intelligence and the Internet of Things (AIoT), allow for real-time monitoring and data-based interventions. Predictive models also enable proactive management, and long-term planning. Funding these efforts will require green finance mechanisms, such as carbon credits and eco-bonds. Using financial instruments, societies can scale-up adaptation initiatives and catalyze resilience. In the end, adaptive governance that combines innovative policies, collaboration, and technology can safeguard air and water resources while dampening climate risks. That is how we help ensure public health, stable ecosystems and sustainable development as the climate changes.

Keywords: Air quality, Climate Adaptation strategies, Climate change, Climate-resilient, Ecosystem stability, Global temperatures, Nature-based solutions, Water quality.

Introduction

Climate change and environmental destruction are two of the interconnected threats facing the future of our planet[1]. These have emerged as a result of, among others, the present development race that the increasing global population is undergoing without noticing the drastic modifications that are being made towards natural systems, nor the effects that they bring with them[2-4]. In fact, since the Industrial revolution, natural resource extraction along with fossil fuels have formed the basis of the global economy, in addition to transformation of the land through urbanization, intensive agriculture and other land-use changes that have led to such environmental change that three times more land has been converted into human use than that of forested land[5,6]. Burning fossil fuels for transportation, electricity and heat has been particularly significant in increasing greenhouse gases (GHGs) in our atmosphere and altering global temperature and precipitation patterns[7]. The global average temperature in 2022 was approximately 0.86°C above the 20th century average (13.9°C). This marked the 46th consecutive year (dating back to 1977) of global temperatures being above the 20th century average. In addition, the pattern of precipitation has altered around the globe[8]. Climate change is a major problem and has been already felt globally through extreme weather and related disasters, such as forest fires in Australia and the U.S., accelerated melting of high-latitude ice sheets, sea-level rise, changes in river flow regimes, extreme rainfall in China, droughts in South Africa, extinction of species, and emergence and transmission of infectious diseases, among other problems[9,10]. Because climate change presents a threat to both humans and environmental systems, it is important to explore solutions to mitigate the impact of climate change before it is too late[11].

Experts are increasingly recognizing that preparatory strategies to adapt to climate change are as important to consider as mitigation strategies to counteract the effects of global warming. This is because even if all at humans-made emissions stopped overnight, the climate will continue to change[9]. Given that it will take decades for efforts to mitigate climate change to have a discernible effect on rising temperatures, it is vital to reconfigure global systems to cope advances already in motion and that are likely to continue into the future. That may mean devising and implementing approaches in all of our global development systems to adapt to and be resilient in the face of climate change[9]. Such measures include: For example, constructing sea walls to shield coastal populations from rising sea levels or developing crops that require less water to fight drought. For Severe Weather preparing, we would be able to utilize artificial intelligence (AI), high-resolution monitoring and simulation, and satellite-based remote sensing to help build

Earth system and climate models drawing from current and historic data and records indicating how often and how severe these situations can be, which can then be leveraged to predict when and where future extreme weather situations can take place – and to anticipate the level of impact they can cause, as well as also protect, if respective warning systems exist, Helenos, people and nature for high risk areas[12]. Indeed, climate change adaptation involves ensuring people are aware of how to cope with the effects of climate change, that they are affected to be able to respond, and their risk and vulnerability are reduced, as well, citizens, researchers and policymakers need to be collaborative in addressing which specific measures related to climate change adaptation should be taken and at what level[13].

Another common thread running through this epoch is a call for decisive action to reduce anthropogenic GHG emissions because failing strong decisive action will on its own intensify global warming and changing climate patterns[14]. As the Intergovernmental Panel on Climate Change outlines, GHG emissions should peak by 2025 (at the latest) and should be reduced by 43% by 2030, and we need to make sure that carbon neutrality will be achieved by 2050 to limit global warming to 1.5°C by that time of this century, as set out in the Paris Agreement, which was signed by the large majority of the countries[5].

This necessitates a rapid and unprecedented transition from the existing carbon-based energy to low-carbon energy. Despite the rapid growth of renewable and clean energy sources, the world remains off track to meet its Paris Agreement climate targets. Though previous pledges call for massively reduced GHG emissions (2030), an ever-growing challenge is how to move emerging economies with complementary goals of carbon-neutrality with economic development.

Proposed approaches that are consistent with long term sustainable development objectives to mitigate climate change. These areas include specifically, transforming and integrating food, water, and energy systems, protecting and developing carbon sinks, and contributing to carbon dioxide (CO_2) capture, use and storage[5,8]. Reducing climate change also involves altering human behavior, lifestyle and diet. With climate change threatening everyone, there is no time to waste and the global community must unite now to take decisive action to prevent dangerous climate change from becoming reality[15].

This paper examines the relationship between climate resilience and the protection of ambient air and water quality. It tackles important questions, such as: i. How does climate change affect air and water quality?, ii. How to foster resilience in these areas? iii. Like policies, technologies, and community engagement - how can these elements come together to reduce risks and achieve sustainable outcomes?

The paper provides actionable insights for policy makers, practitioners, and researchers to build upon by distilling state-of-the-art research, policy developments, and implementation endeavors. Ultimately, the goal is to identify a path forward that protects and ensures that our air and water resources not only survive but thrive amid climate challenges.

Drivers of climate change

Climate change has been an ongoing process since the beginning of Earth's history, with average temperatures on the planet shifting over millions of years, usually due to changes in the composition of the atmosphere. Contributing to these changes are natural forces including volcanic activity, solar radiation fluctuations, and shifts in the orbit and tilt of the Earth[16]. However, for the last two centuries, man-made activities have significantly contributed to climate change (more on this later) by altering the surface albedo (reflectivity) of the Earth, and in turn, the amount of heat the Earth absorbs. The impact of human activities on surface albedo: One of the primary ways that human activities have affected Earth's surface albedo is through land use changes such as deforestation and urbanization[17]. Trees and other vegetation absorb sunlight, as do green-roofed buildings, and reflects less of it into space than bare ground or urban surfaces, a change that increases the heat absorbed by the planet. Even more crucially, burning fossil fuels for energy releases a great deal of CO_2 from auxiliary wells[7]. On the contrary, human activities release large amounts of greenhouse gases (GHGs) like methane (CH_4), nitrous oxide (N_2O), Ozone (O_3), chlorofluoromethanes (CFCs), and hydrochlorofluoromethanes (HCFCs) into the atmosphere. These mills block outgoing long wave radiation from the Earth that would scatter into space, which has a warming impact on the planet[9].

Impacts of climate change on air quality

Climate change affects not just the planetary physical environment, but also represents a huge risk to human health, food security, and ecosystems, according to the World Meteorological Organization (WMO)[18]. One of the most immediate and significant impacts of climate change is air quality, which is key to life on our planet[19]. The pathways through which climate change impacts air quality, including ozone and particulate matter (PM), deposition of substances from the atmosphere and extreme events.

Ozone formation: These high temperatures lead to atmospheric stability generated by a so-called “dome”, which keeps anthropogenic emissions, such as nitrogen oxides (NOx), volatile organic compounds (VOCs), and carbon monoxide (CO), trapped. This process encourages the development of more air pollutants, especially ground-level ozone (O_3)[19]. Elevated ozone levels:

Effects on health: Chronic exposure is associated with increased risk of respiratory diseases, cardiovascular morbidity, and premature death, particularly in sensitive populations (children, elderly, and people with pre-existing medical conditions)[20,21].

Environmental effects: High levels of ozone can harm vegetation, causing decreased agricultural production and reduced productivity of forests.
Particulate Matter (PM): Climate change alters weather patterns and makes wildfires frequent, major sources of particulate matter ($PM_{2.5}$ and PM_{10})[20,22]. The chemical compositions of these particles are complex and represent serious health hazards:

Wildfires: Increasing temperatures and persistent drought conditions stimulate wildfires, which in turn increase ambient concentrations of PM.

Health impacts: Long-term exposure to PM is associated with increased risk for acute myocardial infarction, ischemic heart disease, respiratory disease, cerebro vascular disease, and premature mortality[21].

Impacts on economy: Higher healthcare expenses & decreased workforce productivity from PM-related diseases.

Table-1: Major sources of PM and associated health risks.

Source	Examples	Health risks
Wildfires	Forest and grassland fires	Respiratory and cardiovascular issues
Urban Emissions	Industrial processes, traffic	Chronic obstructive pulmonary disease
Agricultural Fires	Crop burning	Lung cancer, asthma

Atmospheric deposition

Climate change can change how pollutants like sulfur, mercury and nitrogen are transported and deposited[23]. These changes contribute to: i. Acid precipitation: In cases despite pollution, acid rain leads to stimulation and disrupts surface chemistry. ii. Ecological impacts: Bioaccumulation and biomagnifications of toxic elements in aquatic and terrestrial food chains. iii. Health risks: Increased exposure to heavy metals like mercury via tainted water and food[21].

Extreme weather events: Climate change has caused extreme weather events to become more frequent and severe[24,25]. These events affect air quality in several different ways: i. Heat waves: Like icing on the cake, speed up ozone formation and escalate pollution levels. ii. Droughts: Raise dust and PM levels in the air. iii. Storms and floods: Introduce pollutants, including hazardous chemicals and pathogens, to air and water systems. iv. Wildfires: Emit huge amounts of PM, carbon dioxide and other pollutants.

Climate change impacts on water quality

Although the canonical responses to global warming have been the mitigation of greenhouse gas emissions through national and international schemes, climate change impacts are now being felt at regional and local scales[26]. Climate change is expected to impact the quality of water in local and regional settings by a number of different climate-driven pathways, including drought, increased precipitation, higher temperatures, and more frequency and intensity of extreme weather events[27]. According to the IPCC (2022), climate change will worsen water quality through rising stream temperatures and enhanced loading of nitrogen to rivers. Of the climate impacts the articles reviewed showed would have the most pronounced effect on water quality, increases in temperature and shifts to precipitation patterns were identified as most important.

Table-2: Types of extreme weather events and their effects on air quality.

Event type	Air quality impact	Examples
Heat waves	Increased ozone and PM levels	Europe, 2003
Droughts	Dust storms	Sahara Dust Storms
Wildfires	High PM and CO concentrations	California Wildfires, 2020
Floods	Spread of airborne contaminants	Pakistan Floods, 2022

Increase in temperature

As surface water temperature is strongly correlated with the ambient air temperature increasing temperatures associated with a warmer climate will also alter water temperatures[28]. Bi et al.[29] indicate that changing water temperatures will disrupt the normal aquatic ecological balance significantly through changes in water density, surface tension, and viscosity. Changes to water chemistry and thermal stratification are the most significant impacts on water quality. Elevation of water temperatures may elevate the potential for degraded water chemistry and anoxic conditions[28]. This is what can cause pollution to water with higher pollutants, microorganisms and bacterium[30]. Any degradation of water quality will increase the burden on water treatment systems to ensure that the public is not exposed to contaminated drinking water[31]. Ekstrom et al.[30] and Magee et al.[32] kroon when they state that higher temperatures inducing algal blooms may affect treatment of water supplies while also generating toxic conditions for water body consumers (e.g. recreational users, fish species, and grazing livestock)[30]. Both Chang et al.[33] and Feldbauer et al.[34] thermal stratification, driven by rising temperatures, is a major cause of poor water quality. Thermal stratification not only raises the likelihood of there being a depletion of oxygen in the deeper levels of the water, which in turn increases the potential for there to be undesirable algal blooms[33], but it can also have a very important effect on drinking water production[34]. Reservoirs of drinking water feature outlet structures that supply water at various depths and flow rates. The bio–geo–chemical processes dependent upon stratification and temperature governs water quality[34].

Precipitation: Not only climate change will have short-term effects on; regional precipitation, droughts and floods[29]. Precipitation patterns, intensity, and duration will affect overall water quality. Intense rainfall will not just raise contaminants in water bodies; but so, will droughts, with reduced flow rates leading to less dilution of pollutants[35].

According to Rodriguez and Delpla[36] the most significant effects of heavy rain on water quality are expected. There is widespread agreement that more intense rain and storms lead to higher concentrations of pollutants[28,29]. Moreover, it has become a well-known fact that the higher the rainwear, the more deteriorated water quality due to surface runoff, sedimentation, and nutrient inflow[35]. Coffey et al.[37] and Rodriguez and Delpla[36] highlight that the effects of changes in precipitation will not just be felt on surface water systems but also on groundwater systems.

Alterations in rainfall patterns may lead to flooding and drought events. Also, during flooding events, water treatment facilities can become flooded, a problem that impacts both overland and subsurface water[37]. Especially effects of droughts on groundwater such as increasing the contamination level and affecting quality[30,37].

Strategies for adapting to climate change impacts on air and water quality: Air and water quality is greatly affected by climate change, due to rising temperatures, changing precipitation patterns, and increasing frequency of extreme weather events. These environmental transformations compound pollution, degrade natural resources and amplify public health risks[38]. We need a multidimensional approach to these challenges, relying on governance, technological innovation, nature-based solutions, community engagement, and cross-disciplinary collaboration.

Governance and policy frameworks

Governance and policy frameworks for climate resilience that protect air and water quality can include:

Integrated Environmental Management (IEM): IEM reflects this, as it is the integrated management of land, water and living resources that promotes conservation and sustainable use in a balanced manner. For example, controlling nitrogen oxides (NOx) emissions can enhance the quality of air by reducing ozone formation and prevent water pollution by restricting the deposition of nitrogen into aquatic systems. IEM helps achieve efficiency by removing redundancies in policy and by creating synergies among environmental objectives. Integrated frameworks, as seen in such programs as the U.S. Clean Air Act, are effective[39].

The reduction of NOx emissions over this period has corresponded with measurable improvements in both air and water quality, revealing the connected benefits of multi-faceted policies.

Climate-resilient standards: This approach helps to make regulatory standards more climate-proof in the future. For instance, under hotter conditions ground level ozone formation increases, so air quality regulations have to factor that in. Likewise, water quality standards should consider elevated pollutant loads associated with extreme precipitation events references[40].

Adopting standards that are adaptive – like those used in the European Union's Water Framework Directive – allows the authorities to address new pollutants and changing baselines; they can ensure adequate environmental and public health protections are preserved[41].

Urban and regional planning: Components of sustainable urban planning include green infrastructure, pollution control zones, and waste management systems. In an effort to tackle localized air and water quality issues, cities like Singapore and Copenhagen have incorporated things like urban forests, green roofs and efficient wastewater treatment into their designs. Land-use planning helps reduce the risk of pollution by preventing industrial activities from coming up near sensitive sources of water or in the vicinity of living spaces[42].

International cooperation: Pollution does not respect borders so it requires a collaborative approach to management. And global collaboration is evident through transboundary air pollution agreements – the Convention on Long-Range Transboundary Air Pollution (CLRTAP), for example – and basin-wide water management frameworks. These arrangements create a common sense of responsibility, which seeks to collaboratively combat pollution[39].

Table-3: Strategies and outcomes of governance.

Strategy	Outcome
Integrated Environmental Management	Simultaneous improvement of air and water quality
Climate-Resilient Standards	Flexibility in addressing emerging challenges
Urban and Regional Planning	Mitigates localized air and water pollution
International Cooperation	Coordinated responses to transboundary issues

Technological innovations: Technological innovations addressing climate change include:

Advanced monitoring systems: IoT, remote sensing, and satellite imagery-powered monitoring technologies offer real-time information on air and water quality. The European Space Agency's Sentinel satellite program, for instance, observes changes in atmospheric and hydrological conditions around the world. These systems forecast pollution episodes and facilitate prompt interventions. Urban sites: Local sensor networks measure metrics like particulate matter ($PM_{2.5}$), appears with over 8,888 and ozone and nutrient levels in water. This data is used by governments and industries to create targeted mitigation plans[43].

Clean energy technologies: Adopting renewable energy cuts greenhouse gas emissions and scientists' pollutants. By substituting fossil fuel combustion, solar, wind and hydropower systems avoid air pollution. Denmark, for instance, widely adopted wind energy, and as a result, has drastically cut down emissions of sulfur oxides (SOx) and nitrogen oxides (NOx). Electrification of transportation and industrial processes also reduces the load of pollutants in air and water[44].

Enhanced wastewater treatment: Advanced wastewater treatment methods like membrane bioreactors and nutrient recovery systems effectively tackle pollutant loads. These systems eliminate emerging contaminants, like pharmaceuticals and microplastics, from water sources. It also enhances air quality by capturing methane from wastewater treatment plants in order to not emit this greenhouse gas[45].

Air pollution control: That includes technology like electrostatic precipitators, scrubbers, and carbon capture systems that enable industries to lower their emissions. They regulate particulate matter, SOx, and NOx levels, preventing these pollutants from impacting downstream air and water systems[46,47].

Nature-based solutions (NbS)

Nature-based Solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges, providing human well-being and biodiversity benefits. They also address major challenges like climate change; disaster risk reduction; food and water security; biodiversity loss and human health; and are essential to sustainable development.

Wetland restoration: Wetlands are natural filters that serve to lower pollutant loads in water and sequester carbon. Restoration projects in the Mississippi River Basin have drastically reduced agricultural runoff, resulting in a decline of harmful algal blooms that have also been found to cause significant impact to the water quality. Water quality isn't the only benefit – wetlands serve as carbon sinks, alleviating climate change and improving air quality by absorbing greenhouse gases from the atmosphere[48].

Urban forests and vegetation: Aside from being directly involved in environmental health, urban forests and greenery serve two purposes. They take up particulate matter and other air pollutants and also handle storm water runoff, which lightens the load on municipal water systems. Singapore's vast urban forest network is a template for integrating green spaces into crowded populations[49].

Riparian buffers: Riparian buffers, or vegetated areas alongside water bodies, intercept sediments and nutrients preventing them from reaching aquatic systems. These buffers enrich biodiversity, providing ecosystem services such as water filtration and carbon sequestration[50].

Ecosystem rehabilitation: Restoring ecosystems such as mangroves and coral reefs increases their tolerance to climactic stressors. Mangroves serve as a buffer against storm surges, filtering pollutants in coastal zones, while coral reefs support rich marine life and help maintain the quality of coastal waters[51].

Table-4: Examples of Nature-based solutions and their benefits.

Solution	Climate impact addressed	Benefits
Wetland Restoration	Flooding, water quality	Pollution filtration, biodiversity
Urban Green Infrastructure	Heat islands, stormwater	Cooler microclimates, reduced runoff
Agroforestry	Drought, soil erosion	Enhanced soil health, carbon storage

Community-based and behavioral approaches

Community based adaptation to climate change (CBA) is a community driven process for communities to adapt to climate change. CBA initiatives can include:

Citizen science & citizen engagement: Citizen contributions to environmental monitoring foster shared stewardship and enhance data coverage. Community-driven solutions, including reporting pollution incidents through mobile apps, increase citizen participation and transparency in governance[52].

Education and awareness campaigns: Educational campaigns can encourage sustainable practices such as lower vehicle emissions and less fertilizer. Such changes in conduct have the combined effect of moderating air and water pollution[53].

Utilizing traditional and indigenous practices: Traditional multi-use practices (like controlled burns to stop wildfires, or rainwater harvesting to conserve water) provide sustainable solutions that make sense on an ecological and cultural level[54].

Integrated research and collaboration: Climate change is a nexus problem and requires integrated research and collaboration:

Predictive climate models: New advanced climate models now combine air and water quality assessments so policymakers can take action on actionable insights. For instance, predictive models can be used to simulate the effects of future extreme weather events on pollution hotspots, allowing for targeted interventions to mitigate such effects[12].

Studies on health impacts: Because degraded air and water quality endangers public health, research studies on these health impacts show why adaptation steps can no longer wait. Studies connecting air pollution to respiratory illnesses or waterborne diseases to tainted supplies provide a portrait of the societal costs of inaction[21].

Cross-sector collaboration: Collaboration across disciplines ensures adaptation measures address interrelated challenges. Inter-sectoral alliances create joint strategies between health, agriculture, energy, and urban planning agencies and systems to provide comprehensive solutions that directly address the United Nations' Sustainable Development Goals (SDGs)[55].

Table-5: Research priorities and their implications.

Research area	Implication
Predictive Climate Models	Informs targeted adaptation strategies
Health Impact Studies	Guides resource allocation for health systems
Cross-Sector Collaboration	Aligns policies across multiple sectors

Conclusion

To guarantee ecosystems, human beings and economies thrive in a rapidly changing world, it is essential to boost climate resilience in order to safeguard air and water quality. With the advent of climate change and its exacerbation natural environmental problems, emerging stressors or those yet to be foreseen must not only strike crunching counterattack but proactive steps must be taken in advance to reduce risk and increase resilience. This means that addressing air and water quality requires a comprehensive approach which recognizes the interconnected nature of these systems and the cumulative impact that climate pressures can take on them, and also satisfies local needs. This chapter emphasizes the importance of building on science, fostering innovation, and shaping policy environments that help resilience become second nature. Key steps are strengthening monitoring systems, using nature's own way of coping, improving infrastructure, and at levels of local, national and international collaboration maker in a spirit of cross-sectoral cooperation. Co-developing solutions with communities placed on an equal footing with ourselves, in which equity and justice feature prominently, will also be equally important in ensuring that the benefits of building-resilience actions are broadly shared.

Faced with the twin challenges of climate change and purifying air or water quality, the strategy to pursue emphatically is one which marries environmental, social, and economic priorities simultaneously. Through enhancing systems' capacity to resist disturbance and deepening cultures of adaption, we safeguard a good future for all. In this way we can conserve crucial resources, take public health a few notches up, and guarantee continuing prosperity for the next generation.

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