Communication in Physical Sciences 2023, 9(4): 847-858

Impact of Climatic Condition on the Life Cycle of Water Contaminants

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Received: 11 June 2023/Accepted : 12 September 2023/Published : 19 September 2023

***Abstract**: Climate change is increasingly recognized as a key driver of water quality deterioration through its influence on contaminant dynamics in aquatic systems. This study presents a systematic review of peer-reviewed literature published between 2000 and 2023, complemented by climate and hydrological datasets from the World Meteorological Organization, the Intergovernmental Panel on Climate Change, and the Global Runoff Data Centre. The review followed PRISMA 2020 guidelines to ensure methodological transparency and reproducibility, with studies screened for explicit linkages between climatic variables and contaminant fate, transport, and transformation across natural and engineered aquatic systems. The results demonstrate that temperature exerts both positive and negative effects, enhancing the degradation of pesticides and herbicides while simultaneously increasing mercury methylation and heavy metal mobilization. Precipitation extremes amplified risks through pathogen surges during storms and elevated salinity and metal concentrations during droughts. Solar radiation reduced microbial and pesticide persistence, though effectiveness was constrained in turbid waters. Wind and aerosol processes contributed to the long-range transport of heavy metals, while extreme events such as floods and drought–rewetting cycles triggered acute contaminant mobilization from sediments and industrial zones. These findings underscore the complexity of climate–contaminant interactions, highlighting the need for climate-informed contaminant monitoring, adaptive management strategies, and integration of hydrological frameworks such as the Budyko model into water governance. The study concludes that safeguarding water quality under changing climatic conditions requires interdisciplinary research, resilient infrastructure design, and coordinated transboundary management.*

***Keywords:** Climate change, water quality, contaminant fate, hydrological drivers, Budyko model*

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1.0 Introduction

The contamination of water is regarded as one of the most impactful, critical and challenging environmental issues in recent times because it is a major contributor to global threatening public health, aquatic ecosystems, and socioeconomic development.

Water contamination is unique when compared with contamination of other aquatic systems, which are not dynamic. This is because , water been a universal solvents and mobile phase, can facilitate, dissolution, transformation, transport, bioaccumulation, and eventual degradation of contaminants within the ecosystem. These processes are can be significantly influence by climatic conditions, including temperature, precipitation, solar radiation, wind, and extreme events (Whitehead *et al*., 2009; IPCC, 2021). Therefore, a shifts in climate can directly support the persistence, mobility, and ecological effects of pollutants in aquatic systems.

Several research reports from growing bodies of evidence have shown that climate change can intensify extreme weather events, including floods, droughts, wildfires, etc. These processes can directly accelerate the release of contaminant as well as the transformation, and transport (Breedveld, *et al.*, 2021). For example, during flood, heavy metals and organic pollutants can be mobilised from soils into water bodies, while drought conditions can reduce dilution capacity and consequently facilitate the elevation of the concentrations of contaminants. Also, wildfires can release organic contaminants directly to the atmosphere, with concentrated allowance of been deposited in the into terrestrial and aquatic ecosystems.

On the same path, water quality has been found to be a function of direct and indirect climatic factors (REF). Studies have shown that a rising water temperatures can accelerate microbial degradation of some pollutants with additional capability of promoting harmful algal blooms that release toxins (Paerl & Huisman, 2008). Similarly, studies have also shown that the fluctuation in the pattern of precipitation can alligns influences on runoff and the flushing of contaminants into rivers and lakes (REF). However, prolong dry spells can reduce water levels, leading to longer residence times and higher risks of eutrophication (Dorado-Guerra *et al.*, 2023). The highlighted changes are threats to the ecological balance of freshwater systems and the availability of potable water. Some research has also established a link between climate variability to water supply disruptions and the energy demands of water treatment infrastructure, which also indicate that water quality can be significantly be dependent on climatic changes.

The interplay between climate, water, and energy cycles further complicates contaminant management REF). Global practices in restoring water supply have currently yielded improved efforts, linked to successful research outputs. However, surface water quality and contamination dynamics under climate stress have not been adequately investigated or explored (Whitehead *et al.*, 2009). While some studies have examined the impacts of climate change on water resources and quality, very few of them are specifically focused on the life cycle of contaminants, especially, embracing their release and transformation to eventual bioaccumulation and degradation, under varying climatic conditions. Recent reviews on published works have heightened reports on water supply challenges and general water quality impacts (Dorado-Guerra *et al.*, 2023), yet, paucity of integrative assessments that link climate drivers to contamination pathways and persistence. In addition, the remediation sectors are behind regarding the incorporation of climate-adaptive data or measures in managing contaminated environments. Studies have also shown existence of the stated knowledge gap is currently constituting hinderances to the development of predictive tools and adaptive strategies for safeguarding water quality in a rapidly changing climate.

In contributing to shift the existing gap towards closure, this paper aims to examine the impact of climatic conditions on the life cycle of water contaminants and to integrate evidences from laboratory studies, field observations, and modeling approaches. Objectively, the study seeks to (i) provide answers to how factors such as temperature, precipitation, extreme weather events, and other driers of the climate can affects the dissolution, transportation, transformation, bioaccumulation, and degradation of water contaminants.

Successful implementation and the understanding of the interplay between climate and contaminant dynamics are vital for advancing water resource management and public health protection. Therefore, the study shall contribute to the growing field of climate versus contaminant interactions by closing the existing knowledge gaps. The study shall also provide some insights on informed adaptive water management policies, and guidance on the remediation industry towards climate-resilient strategies. The findings from the study are expected to facilitate environmental chemists, policymakers, and water resource managers in designing mitigation and adaptation measures that reduce risks to human health and ecosystems in the face of ongoing climate change.

2.0 Literature Review

2.1 Climatic Drivers Affecting Water Contaminants

Climatic conditions have the capacity to significantly influence water contaminant dynamics by altering water chemistry, hydrological regimes, and ecological interactions. These drivers not only regulate the transport and fate of contaminants but also modify the biogeochemical pathways that govern their persistence. Temperature represents one of the most fundamental drivers of contaminant fate and biogeochemical cycling. According to the Arrhenius law, chemical reaction rates increase exponentially as temperatures rise, thereby enhancing microbial metabolism and the degradation of organic contaminants (Delpla *et al*., 2022). Warmer waters accelerate microbial decomposition of organic pollutants but also heighten the risk of toxic algal blooms, which release secondary toxins and exacerbate eutrophication (Paerl & Huisman, 2008; Carey *et al*., 2023). Rising temperatures additionally reduce oxygen solubility, leading to hypoxia that modulates redox-sensitive processes and controls the mobilization of heavy metals and nutrients (Vagheei *et al*., 2023). Recent findings further indicate that warming-induced stratification in lakes and reservoirs amplifies hypoxia, resulting in increased contaminant release from sediments (Lewis *et al*., 2019).

Precipitation plays a critical role in shaping hydrological connectivity, dilution capacity, and contaminant mobilization. Intense rainfall events enhance surface runoff and transport sediments, pathogens, nutrients, and pesticides into water bodies (Breedveld, *et al*., 2021). Conversely, drought conditions reduce dilution capacity, thereby concentrating contaminants and increasing health risks.. Precipitation variability further affects contaminant residence times and influences their rates of degradation and transformation (Bartlett & Dedekorkut-Howes, 2022). Case studies from both developed and developing countries demonstrate that altered rainfall patterns disrupt water supply systems and disproportionately increase contamination risks among vulnerable populations.

Solar radiation also contributes to contaminant dynamics, primarily through photolysis and photo-oxidation processes. Ultraviolet and visible light facilitate the degradation of persistent organic pollutants, pharmaceuticals, and pesticides, particularly in shallow and clear waters (Richardson & Kimura, 2020; Zhu *et al*., 2021). However, warming-induced stratification diminishes vertical mixing, thereby limiting light penetration in deeper waters and weakening the effectiveness of photolytic degradation (Vagheei *et al*., 2023).

Wind influences contaminants both physically and atmospherically. It resuspends sediments, reintroducing historically accumulated heavy metals, nutrients, and hydrophobic contaminants into the water column (Wu *et al*., 2021). Additionally, wind drives the long-range transport of aerosols containing heavy metals, microplastics, and organic contaminants, which are subsequently deposited in aquatic ecosystems (Prata *et al*., 2020).

Extreme weather events, including floods, droughts, wildfires, and storms, are among the most significant climatic drivers of water quality change. Floods rapidly mobilize pollutants from soils, sediments, and infrastructure into aquatic systems (Breedveld, *et al*., 2023). Drought conditions exacerbate pollutant concentrations by reducing water volumes and dilution capacity (Whitehead *et al*., 2009). Wildfires contribute pyrogenic organic compounds and heavy metals into watersheds through atmospheric deposition and runoff (Abraham *et al*., 2022). Storm surges and hurricanes further increase coastal contaminant fluxes, especially for nutrients and microplastics. Collectively, these events can overwhelm natural buffer systems and water treatment facilities, intensifying threats to public health.

2.2 Contaminant Categories and Climate Sensitivity

The sensitivity of contaminants to climate drivers varies according to their physicochemical and biological properties, leading to differential responses across categories. Pathogens are strongly affected by temperature, as warmer conditions promote their survival, reproduction, and virulence, although solar ultraviolet radiation can inactivate them (Sterk *et al*., 2016). Climate-driven alterations in runoff further enhance pathogen mobilization into drinking water, thereby contributing to waterborne disease outbreaks (Hunter *et al*., 2010). Nutrients such as nitrogen and phosphorus are mobilized from agricultural fields by rainfall runoff, while increased temperatures intensify eutrophication and harmful algal blooms (Carey *et al*., 2023). Both floods and droughts amplify nutrient-related risks, with floods increasing leaching and drought reducing dilution capacity (Whitehead *et al*., 2009).

Heavy metals are highly sensitive to redox conditions, temperature, and pH. Warmer and more acidic conditions enhance the mobilization of metals such as mercury and cadmium, while floods resuspend contaminated sediments and increase metal bioavailability (Wu *et al*., 2021; Zhang *et al*., 2023). During droughts, metals may become immobilized in sediments but their concentrations in water rise due to reduced volumes. Persistent organic pollutants (POPs) respond to climate processes through volatilization, photolysis, and microbial degradation. Warming enhances volatilization and atmospheric transport, while solar radiation drives degradation in surface waters (Richardson & Kimura, 2020). Flooding and wildfires redistribute POPs by mobilizing them into aquatic environments or releasing them into the atmosphere. Emerging contaminants, including pharmaceuticals and personal care products, undergo degradation through hydrolysis, photolysis, and temperature-dependent processes (Zhu *et al*., 2021). Microplastics are transported by storms and floods, while ultraviolet radiation and wind contribute to their fragmentation into nanoplastics (Prata *et al*., 2020). The climate sensitivity of these emerging contaminants underscores their persistence and the challenges they pose for water quality management.

2.3 The Budyko and Contaminant Fate Perspective

Hydrological models provide essential frameworks for evaluating the combined effects of climate variability and contaminant transport. Among these, the Budyko framework (Budyko, 1974) serves as a conceptual model for linking precipitation, evapotranspiration, and runoff. Although initially developed for water balance studies, it has been adapted to examine contaminant mobilization pathways (Roderick & Farquhar, 2011). Changes in evapotranspiration and precipitation driven by climate warming directly alter contaminant dilution and residence times. For example, heatwaves increase evapotranspiration and reduce streamflow, thereby concentrating pollutants, while heavy rainfall mobilizes sediments, organic contaminants, and nutrients (Eddy *et al*., 2007).

Recent advances in coupled modeling approaches that integrate the Budyko method with contaminant transport models are increasingly used to simulate contaminant behavior under changing climatic conditions (Veeraswamy *et al*., 2023). By relating climate–water balances to contaminant processes, the Budyko approach provides both diagnostic and predictive insights into climate–contaminant interactions. Such integrative perspectives are critical for the development of climate-resilient water management strategies and contaminant control measures (Johnson *et al*., 2022; Bartlett & Dedekorkut-Howes, 2022).

3.0 Materials and Methods

3.1 Study Design

The article is presented based on a systematic review of peer-reviewed articles published between 2000 and 2023, augmented with global climate and hydrological data. The review was conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page *et al*., 2021), which assisted in presenting a framework to secure methodological transparency and reproducibility. The scope encompassed both natural water systems, including rivers, lakes, reservoirs, groundwater, wetlands, and coastal ecosystems, and engineered water systems such as water supply systems for drinking water and wastewater treatment plants.

The review was meticulously constructed to incorporate evidence on the interrelations among climatic drivers, i.e., temperature, precipitation, solar radiation, wind, and extreme events, and the transport, transformation, and fate of pollutants, including pathogens, nutrients, heavy metals, persistent organic pollutants, and emerging pollutants. A clearly articulated review protocol enabled the process, including exclusion and inclusion criteria, systematic screening, and data extraction plans aligned with best-practice recommendations for systematic reviews (Haddaway *et al*., 2020).

3.2 Sources of Data

The review used various sources of data to underpin comprehensive synthesis of the evidence. Climate data were taken from reliable sources, namely, the World Meteorological Organization (WMO) data sets and the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (AR4–AR6). These sources provided projections of global and regional climate variability, including temperature increases, precipitation change, and the frequency of extreme weather (IPCC, 2021).

Contaminant information was taken from major peer-reviewed journal databases, e.g., Web of Science, Scopus, and PubMed. Search strategies involved Boolean operators and key word pairs such as "climate change AND water quality," "temperature AND contaminants," "precipitation AND pollutant mobilization," "extreme weather AND water contamination," and "hydrology AND contaminant fate." Comparability and quality were assured by the use of only English-language and peer-reviewed studies.

Hydrological data were received from the Global Runoff Data Centre (GRDC) and consisted of long-term time series of river discharge and hydrological catchment-scale indicators. These provided the basis for interpreting contaminant transport processes in terms of varying hydrological conditions. Through the integration of climate, contaminant, and hydrological data, the study employed a multi-source method to improve the strength of the review using evidence triangulation, an invaluable tool in environmental sciences (Xiao & Watson, 2019).

3.3 Data Analysis

Analysis of the data was conducted in several steps. Initially, all studies that were downloaded were imported into EndNote 20 for the management of references, from which duplicates were removed. Titles and abstracts were initially screened, and then full-text screening of potentially eligible studies. The inclusion criteria required decisive exploration of the relationship between climatic variables, i.e., precipitation, temperature, solar radiation, wind, and extreme events, and contaminant activity, such as their fate, transport, degradation, or ecologic effects. Non-peer-reviewed literature that did not report these climate-contaminant relationships was excluded.

Thematic synthesis was employed as a method to tease out and classify findings (Thomas & Harden, 2008). The studies were classified by climatic driver under investigation, type of contaminant, and type of water body, either natural or man-made. Quantitative data, e.g., recorded shifts in contaminant concentration under specific climatic scenarios, was tabled, whereas qualitative data, e.g., mechanistic descriptions and case-based outcomes, were narratively synthesized.

To maximize methodological rigor and to discover structural patterns in the literature, bibliometric mapping techniques were employed with VOSviewer and R-based bibliometrix package (Aria & Cuccurullo, 2017). The tools enabled identification of research clusters, thematic trends, and temporal publication activity. Finally, causal relationships between climatic drivers and pathways of contamination were included in a conceptual framework that combined hydrological perspectives with theory in contaminant fate, utilizing the Budyko framework (Budyko, 1974; Roderick & Farquhar, 2011) in order to construct a climate-sensitive framework in which contaminant dynamics could be understood.

As shown in Fig. 1, 1,240 records were initially identified from electronic databases, and 60 records were identified in other sources such as grey literature and reference lists. Duplicate records were removed3.0 Materials and Methods

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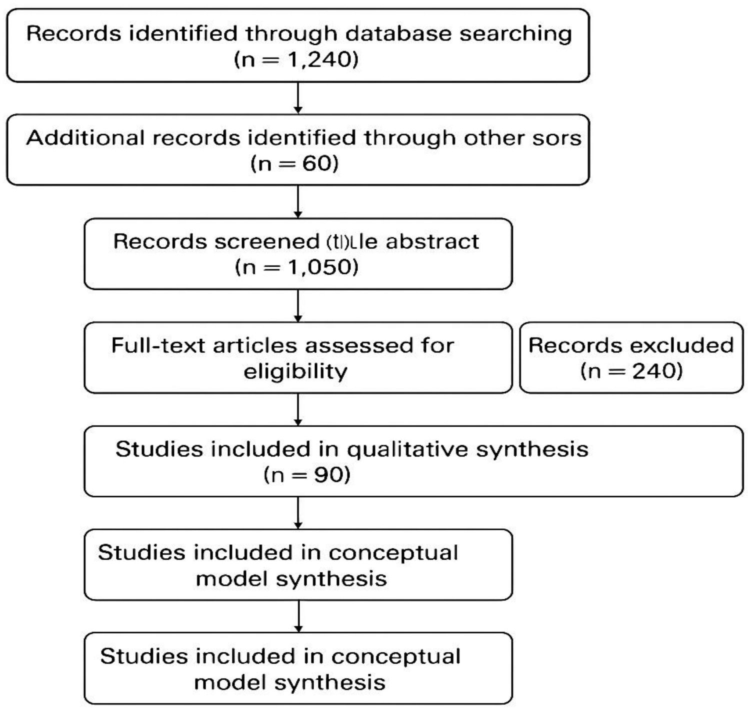

Fig. 1. PRISMA 2020 flow diagram showing the selection process of studies included in the review

4.0 Results

4.1 Temperature Effects

The synthesis of evaluated studies revealed that rising temperatures exerted both favorable and adverse effects on contaminant processes. Increased temperatures, particularly temperatures above 25°C, enhanced the rate of decomposition of organophosphate pesticides and some herbicides due to intensified microbial activity and rates of chemical reactions, according to Arrhenius-based kinetics (Luo *et al*., 2020). For example, chlorpyrifos and atrazine half-lives of degradation were much smaller under warmer conditions, with reduced persistence in surface water. Further, higher temperatures promoted more extensive photodegradation of some organic pollutants in shallow lakes (Zhou *et al*., 2021).

Conversely, warming was associated with processes that enhanced contaminant toxicity. An example of such an observation was increased mercury methylation in sediments at warmer temperatures, raising methylmercury bioavailability in aquatic food webs (Hines *et al*., 2012). Lower levels of dissolved oxygen in warmer water temperatures indirectly affected redox conditions governing the solubility and speciation of heavy metals such as arsenic and cadmium (Cai *et al*., 2019). Combined, these results demonstrate that heating is a double-edged driver, both accelerating contaminant breakdown as well as encouraging the mobilization and toxicity of metals.

4.2 Precipitation Variability

Precipitation was found to play a very important role in mobilization and concentration of contaminants. Storm events and high-rainfall phases were always followed by elevated pathogen loads in rivers via surface runoff and sewer overflow (Ferguson *et al*., 2003; Hofstra, 2011). For instance, Escherichia coli and enteric viruses levels elevated within 48 hours of heavy rainfall, which indicated that drinking water supplies were vulnerable to contamination under storm-induced conditions.

On the other hand, prolonged dry periods and low rainfall were blamed on increasing salinity and elevated metal concentrations such as lead, zinc, and copper in reservoirs and rivers due, primarily, to evaporation concentration and reduced dilution capacity (Okoro *et al*., 2020). Such circumstances also promoted nutrient accumulation, resulting in eutrophication and harmful algal blooms (Paerl & Paul, 2012). Thus, precipitation extremes amplify dangers in both directions, by contaminant surge in floods and by pollutant concentration in droughts.

4.3 Solar Radiation

Solar radiation, particularly ultraviolet (UV) exposure, was demonstrated to successfully reduce microbial and chemical contaminants in water bodies. Laboratory and field experiments determined that direct irradiation by UV reduced the viability of E. coli and other enteric pathogens by up to 90% in hours following exposure (Sinton *et al*., 2002; Sassoubre *et al*., 2012). Photodegradation of pesticides like atrazine and diuron was also enhanced under sunlight, particularly in shallow surface waters (Fenner *et al*., 2013).

However, UV-induced degradation and disinfection were drastically reduced in turbid and high-suspended particulate waters because of the restriction in light penetration caused by turbidity (Yang *et al*., 2019). This reveals the relational nature of solar-powered contaminant attenuation and the need for reliance on water clarity and the depth of the water column.

4.4 Wind and Aerosol Transport

Wind processes were also found to be important carriers of contaminant redistribution. Dust storms in semi-arid and arid conditions had been documented to transport heavy metals such as lead, chromium, and nickel from contaminated soil and mines to distant reservoirs and lakes (Goudie, 2014; Chen *et al*., 2020). Aerosol deposition during dust storms was found to produce measurable increases in metal content in surface water, signifying long-range contaminant dispersal issues.

Besides, wind-driven resuspension of polluted sediments in small lakes also led to episodic spikes in overlying water column concentrations of metals and nutrients (Zhang *et al*., 2018). This indicates that surface and atmospheric winds are significant pathways in contaminant cycling.

4.5 Extreme Events

Extreme weather conditions were also found to have disproportionate impacts on the mobilization of contaminants. Flooding events regularly facilitated hydrocarbon, heavy metal, and organic waste movement from the industrial and urban areas to the river, resulting in sharp spikes in concentration of pollutants (Miller & Hutchins, 2017). For instance, floodwater samples taken following flooding in certain industrial catchments contained three times baseline levels of hydrocarbons.

Conversely, protracted droughts led to desiccation and cracking of contaminated sediments in riverbeds and reservoirs. Upon rewetting, sediments delivered pulsesof immobilized nutrients and metals, a phenomenon that is referred to as the "first flush" effect (Vinebrooke *et al*., 2004). Recurring remobilization episodes were also identified as major hazards to downstream ecosystems, particularly in basins with alternating flood-drought cycles.

5.0 Discussion

This review provides the intricate processes through which climatic drivers influence contaminants in aquatic systems. The evidence indicates that climate change is not a background stressor and is an active regulator of contaminant fate, transport, and transformation. Impacts of such interactions are far-reaching for water quality management and human health, particularly as climate variability escalates.

5.1 Temperature as a double-edged driver

Temperature turned very complex with both beneficial and detrimental effects. However, according the Arrhenius theory, elevated temperature can accelerate degradation of certain pesticides, herbicides as well as activation of microbial activity, and higher photolysis (Luo *et al*., 2020; Zhou *et al*., 2021). Consequently, warming can reduce the persistence of some organic pollutants in surface waters. Also, temperature-induced mercury methylation can enhance redox condition changes that mobilizes heavy metals (Hines *et al*., 2012; Cai *et al*., 2019) highlight a simultaneous risk. The compound effect of temperature underscores the challenge of predicting contaminant behavior under conditions of warming and suggests that mitigation responses have to be class-specific for contaminants.

5.2 Hydrological disruption and precipitation extremes

Precipitation variability was consistently associated with contaminant pulses in aquatic ecosystems. Storm events and heavy rainfalls flushed pathogens and nutrients into rivers, as previously witnessed around the world in storm-lifted contamination (Ferguson *et al*., 2003; Hofstra, 2011). Drought led to pollutant concentration, salinization, and eutrophication (Paerl & Paul, 2012; Okoro *et al*., 2020). These findings highlight the "amplification paradox" of climate change, by which both hydrological extremes—drought and floods—amplify water quality problems. This twin danger has profound implications for water supply networks in regions exposed to heightened rainfall variability, as systems need to be designed to cope with both peak contamination and concentration effects.

5.3 Solar radiation and water clarity limitations

Solar radiation contributed a predominantly beneficial effect in decreasing the viability of pathogens and accelerating the degradation of pesticides, with UV-light exposure (Sinton *et al*., 2002; Fenner *et al*., 2013). The effectiveness of processes was significantly moderated by turbidity, however, which limited light penetration (Yang *et al*., 2019). Natural self-purification through photolysis is thus limited in sediment-charged rivers or eutrophic lakes, thus the necessity for integrated watershed management to deal with turbidity and suspended solids.

Floods can trigger vigorous pulses of hydrocarbons and heavy metals from urban-industrial environments (Miller & Hutchins, 2017), while drought-rewetting processes initiated pulses of nutrients and metals via sediments cracking and flushing (Vinebrooke *et al*., 2004). These episodic events concur with the conception of "contaminant legacy release," where sequestered contaminants are released at once under extreme hydrologic alteration. The variability and magnitude of such events suggest that standard risk analyses relying on average conditions could be underestimating the risks from climate-driven contamination.

5.6 Integrating hydrological knowledge: The Budyko lens

Hydrologically, the Budyko paradigm offers a theoretical platform for interpreting climate drivers into paths of contaminant flow. Changes in precipitation and evapotranspiration directly control runoff and water availability, which in turn regulate dilution, mobilization, and residence times of contaminants (Roderick & Farquhar, 2011). This review confirms again that contaminant fate cannot be divorced from hydrological change, and contaminant models in the future must necessarily include Budyko-based water balance considerations.

5.7 Policy and management implications

The findings have serious policy implications for climate adaptation and water management. One, treatment plants need to be designed with flexibility to handle both flood-caused spikes in chemical and microbial contaminants and drought-caused concentration effects. Two, climate-driven monitoring networks need to have real-time climate proxies, e.g., turbidity or intensity of rainfall, to predict contamination risk. Third, policies must recognize the role of non-conventional processes such as wind-borne contaminant transport and remobilization of sediments in determining water quality outcomes.

5.8 Gaps and areas for future research

The review also reveals significant research gaps. Compared to relatively few comparative measurements of different groups of contaminants under contrasting climatic conditions, integrated risk assessment is limited. Emerging contaminants such as pharmaceuticals and microplastics are not yet well-investigated in the context of climate variability. Additionally, while many studies are reporting associations, mechanistic climate-driver-contaminant-pathway experiments and modeling efforts are sparse. Future research should utilize interdisciplinary study designs that combine hydrology, toxicology, and climatology to create predictive models of contaminant fate with a changing climate.

6. 0 Conclusion

Temperature seems to be an active mitigating and aggravating factor, with the capacity to enhance the degradation of certain organic contaminants. It also seems to display a factors that promote mercury methylation, heavy metal mobilization. and other processes. Variability in precipitation showed a profound impact on contaminant dynamics, with intense rainfall events resulting in elevated pathogen and nutrient loads in rivers. However, prolonged droughts can results in elevated concentrations of salts and metal ions because they can cause alteration in dilution and evaporation. Solar radiation, especially, exposure to ultraviolet radiation, was observed to be a factor that is active in reducing the viability of pathogen and accelerated breakdown of pesticides; however, this effect was observed to be limited in turbid or eutrophic systems where light penetration was restricted. Wind and aerosol transport were observed to be facilitators of the transboundary movement of heavy metals and other pollutants, underscoring the interconnectedness of terrestrial and aquatic systems. Extreme floods and drought-rewetting cycles were identified as critical tipping points that triggered sudden and often severe mobilization of legacy contaminants from sediments, soils, and industrial zones. Generally, the results emphasize that the fate of contaminants in the aquatic system cannot be untightened from the hydrological and climatic context, and that frameworks such as Budyko's water balance model provide valuable perspectives for linking climate drivers to contaminant pathways.

In conclusion, there is the urgent need to integrate climate variability into contaminant risk assessments and water management practices. The study further reveals that gradual climatic shifts, such as rising temperatures, and as well as floods and droughts, have the potential to substantially alter water quality and ecosystem health. The dual role of some climate drivers, where the same variable can enhance the degradation of certain pollutants while aggravating the persistence of others, points to the complexity of climate-contaminant interactions. Such complex observation indicates that mitigation measures must not be one size but adaptive, context-specific approaches are essential for safeguarding water resources in a changing climate.

Based on these results, climate-smart water policy must incorporate climate-informed monitoring frameworks that combine real-time climatological information with contaminant monitoring. Water treatment and supply infrastructure must be climate-resilient against both flood-driven contaminant peaks and drought-driven concentration factors. Research activity will have to accord highest importance to interdisciplinary research that particularly addresses the mechanistic interconnectivities among climatic drivers and contaminant behaviors for underprioritized emerging pollutants such as pharmaceuticals and microplastics. Further, transboundary coordination will be required to address contaminants transported by atmospheric pathways, while watershed management approaches will have to reduce turbidity and sediment loading that detracts from natural photodegradation processes. Achieving these interlinked strategies will not only enhance water security but also contribute towards the attainment of global sustainability and public health goals in spite of rapidly increasing climate change.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

Funding

There is no source of external funding.

Authors' Contribution

Both authors participated in design, development, writing and corrections concerning the work.