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# THE IMPACT OF INDUSTRIALIZATION, URBANIZATION, AND DROUGHT ON HEAVY METAL CONTAMINATION IN RIVER SYSTEMS IN KWAZULU-NATAL, SOUTH AFRICA: A CROSS-SECTIONAL STUDY.

***Sibonelo Thanda Mbanjwa***
*Mangosuthu University of Technology P.O. Box 12363 Jacobs 4026 Durban, South Africa.*



## Abstract
Freshwater resources are vital for indigenous communities in Southern Africa, supporting livelihoods, agriculture, and biodiversity. However, increasing industrialization, urbanization, and agricultural runoff have led to severe contamination of river systems. While pollutants such as heavy metals are well-documented, the role of drought in intensifying their concentrations remains underexplored. This study investigates the relationship between low water levels and heavy metal pollution in rivers in KwaZulu-Natal, South Africa, focusing on how drought affects water quality.

## Methods
A cross-sectional quantitative approach was used to analyze water quality under different seasonal conditions. Water samples were collected during high and low water periods to measure concentrations of lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Hydrological and meteorological data were also examined. Statistical analyses, including correlation and regression models, were applied to assess the influence of drought and pollution sources.

## Results
Heavy metal concentrations increased significantly during drought conditions, with lead and cadmium exceeding WHO and South African water quality standards. Contamination was highest downstream of industrial and agricultural zones, where mercury and arsenic were alarmingly elevated. Additionally, ecological degradation was evident, including native vegetation loss and the spread of invasive species in polluted areas.

## Conclusion
Drought amplifies the effects of chemical pollution in river systems, worsening ecological degradation and posing health risks to dependent communities. If left unchecked, ongoing urban and industrial growth will further compromise water quality and ecosystem health.

## Recommendation
To address this issue, stricter enforcement of industrial discharge regulations is required. Regulatory frameworks must be strengthened to ensure industry compliance, supported by regular monitoring and stricter penalties for polluters. Proactive water management strategies are also needed to protect vulnerable communities and ecosystems from the combined threats of drought and pollution.

***Keywords:*** *Climate change, drought, industry, small-scale farming, pollution, adaptation, heavy metal*
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***Corresponding Author:*** *Sibonelo Thanda Mbanjwa*
***Email:*** ***mbanjwa.sibonelo@mut.ac.za***
*Mangosuthu University of Technology P.O. Box 12363 Jacobs 4026 Durban, South Africa*

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## Introduction

Climate change has been identified as a devastating threat globally that impacts all areas of society (Rukema and Umubyeyi 2019; Bhuiyan 2004). Coupled with indiscriminate use and insufficient knowledge, the impact on livelihood can be disastrous (Lynam and Piechota 2021). The availability of usable water and the effects of drought pose one of the greatest concerns globally, indicating that there are differing degrees of impact on the agricultural sector, where communal, subsistence, and emerging farmers face much greater comparative loss of assets, thus widening gaps between small- and large-scale. Besides, drought reduces the volume of water in freshwater bodies, which is one of the major causes of heavy metal accumulation. Heavy metals are naturally found in all ecosystems in concentrations that are not harmful to the surrounding environment, but when concentrations are high, they could be detrimental (Benedetti 2017). In freshwater ecosystems, such as rivers, the accumulation of heavy metals can exist in the water, suspended sediment matter, and the sediment of the river.

The presence of metals in the environment is partially due to natural processes, such as drought, volcanic activity, and erosion, but is mostly caused by industrial waste. The accumulation of heavy metals in an aquatic environment can have direct or indirect consequences for humans and the ecosystem (Adeyinka and Moodley 2020). Based on the three rivers under investigation in South Africa, water is used for drinking, cleaning, as well as waste disposal purposes by industries, residential areas, and informal settlements that occur along the river. These land uses have shown a huge negative effect on the levels of pollutants in freshwater environments (Hari et al. 2020), with special reference to the drought situation and the increased water requirements due to added informal settlement development. This largely impacts the water quality. Heavy metals can be toxic above critical levels (Adeyinka and Moodley 2020). Once these levels climb above the toxic to the acute levels, the problem then becomes very serious (Liu et al. 2021; DWAF, 2006). Some metals exhibit very toxic qualities, for example, Cadmium (Cd), which has very serious negative effects on human and plant health. Heavy metals are of major concern because of their persistence and bioaccumulative nature. Some of them are dangerous to health or the environment (e.g., mercury, cadmium, lead & chromium), some may cause corrosion (e.g., zinc, lead), some are harmful in other ways (e.g., arsenic may pollute catalysts) (Hogan, 2010). High metal concentrations will be retained in areas that are poorly flushed, i.e., in areas of low rainfall and low discharge (Ogundeji 2022).

## Background Information

Freshwater resources play a critical role in sustaining indigenous communities in Southern Africa, providing essential support for agriculture, domestic use, and biodiversity conservation. However, these water sources are increasingly threatened by industrialization, urbanization, and agricultural expansion, which contribute to heavy metal contamination in river systems. Industrial discharges, agricultural runoff, and untreated wastewater have introduced toxic pollutants into freshwater ecosystems, posing risks to aquatic life, human health, and environmental sustainability (Selwyn, 2019). While existing research has highlighted the role of industrial pollutants and agricultural runoff in water quality degradation, the impact of seasonal water variability, particularly drought, on pollutant concentration levels remains underexplored.

The intensification of drought conditions due to climate change has further exacerbated pollution levels, reduced river flow, and increased the concentration of heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As). These contaminants accumulate in sediments, affecting water quality and biodiversity, leading to vegetation degradation and the proliferation of invasive species in polluted areas (Schmid, Klumpp & Schneider, 2021). Additionally, limited regulatory enforcement and inadequate water management strategies have made it difficult to control pollutant discharges and mitigate contamination risks.

The objective of this study is to assess the impact of industrialization, urbanization, and drought on heavy metal contamination in river systems in KwaZulu-Natal, South Africa. Specifically, the study aims to quantify heavy metal concentrations in selected river systems, analyse the influence of drought on pollutant levels, and evaluate the ecological risks associated with water contamination. Findings from this research will contribute to improved water management strategies and inform policy interventions aimed at mitigating pollution risks in freshwater ecosystems.

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**Figure 1: Ecosystem services in the uMngeni catchment (Hughes et al. 2018)**

The impact commonly found with high levels of heavy metals on the biotic community could reduce diversity due to the elimination of most species, an overall reduction in the number of individuals, and the survival of only those species tolerant of the contamination (Akter et al. 2019). Therefore, it is necessary to conduct a study to determine the amount of pollution that occurs in rivers and identify its sources. The study needs to assess the effects of drought and climate change, as well as how land use contributes to heavy metal concentrations in the river, ultimately affecting the water quality of the areas. This study can help by introducing preventative measures to protect the ecosystems from negligent human impacts or, in the case of already degraded systems, introduce mitigation and/or rehabilitative strategies to preserve or improve the 'health' of the river.

## River contamination in KwaZulu-Natal

The Umgeni River in KwaZulu-Natal faces heavy metal pollution from industrialization, agricultural activities, and urbanization. Research on the Umgeni River in KwaZulu-Natal reveals heavy pollution from industrialization and urban growth, affecting ecosystems through measured concentrations of Cd, Cr, Cu, Pb, and Zn (Adeyinka and Moodley 2020).

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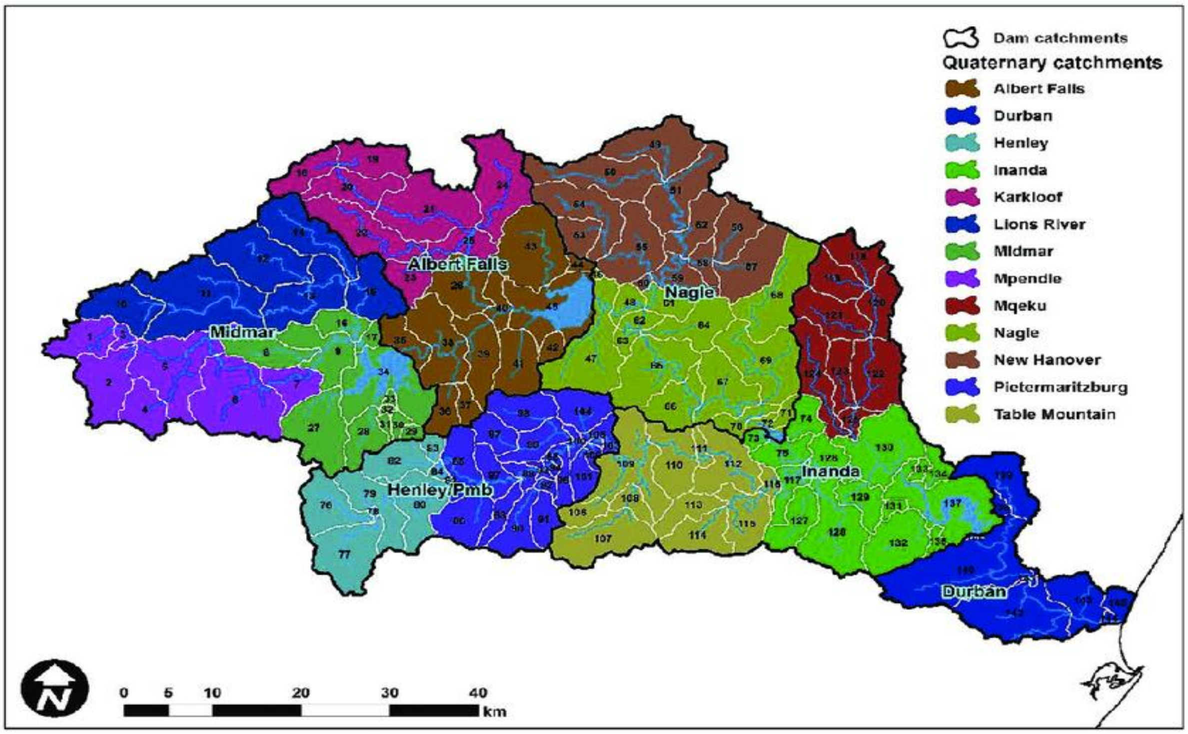


**Figure 2: Catchment and sub-catchment within the Umgeni catchment. (Hughes et al. 2018)**

Limited data exist on metal concentration and bioavailability in the Umgeni River. Investigating toxic metal concentration and ecosystem impact is crucial, using seasonal variability and spatial distributions to assess potential impacts. A 1990 study on mercury spillage revealed a 98% increase in sediment levels downstream from a mercury recovery plant, suggesting biomagnification of this chemical (Lubke and Webb 2016). According to DWAF, a 2011 study established that the Umgeni Estuary was affected by metal pollution, exceeding the set limit (Maziya 2022). However, sediment is efficient in holding nutrients. Sediment accumulates chemical and physical contamination, which is detrimental to aquatic ecosystems. Consequently, frequent monitoring of chemical pathogenic was recommended in the river. Moreover, the new Bulk Water Supply Scheme is being constructed on the lower Thukela River, a 512 km long river with a steeply graded catchment and major tributaries. The estimated mean annual runoff ranges between 3850 and 4600 MCM/a. The lower Thukela River is a vital ecosystem service area for various activities such as water abstraction, industries, agriculture, mining, recreation, wastewater treatment, and road and rail networks. The region supports the Thukela-Mhlathuze Bulk Water Transfer Scheme and is home to the Sappi Tugela Pulp and Paper Mill, which releases effluent into the river. These areas pose the greatest threat to ecosystem health.

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**Figure 3: Thukela basin, KwaZulu-Natal (Hart 2001)**

The river originates in Giant's Castle Nature Reserve and flows along Drakensberg Native Location No. 1, passing through farming country to Estcourt (Benedetti 2017). However, below Estcourt, sporadic pollution from the township, including surface drainage, sewage leaks, and stormwater, enters the dam. The Little Bushman's River, which joins the Bushman's River, is the first major pollutant in the region (Akter et al. 2019). Station 14 is located below the junction, and a turbine pumping plant near it delivers waste to a sewage farm. The farm irrigates lucerne and grasslands on the riverbank, causing sewage to leak and return to the river. No other pollution sources were found, but water is taken out for irrigation, and large portions are returned overland. Some pollution occurs below the Weenen, where irrigation water from the settlement is returned to the river laden with soil and organic matter (Ogundeji 2022). In other words, drought plays a significant role in water scarcity, leaving several inhabitants and industries stranded. Survival of inhabitants during drought largely required adaptive measures. Somboonsuke et al. (2018) and Migdisov et al. (2018) found that small-scale farmers in Sub-Saharan Africa adopt adaptive strategies such as crop and livestock diversification, changing planting dates, soil and water conservation, and livelihood diversification. Moreover, early-maturing crops, drought-tolerant crops, crop rotation, and mixed farming are preferred due to their local and accessible options. However, these strategies may be influenced by feasibility and affordability, as people might lack access to resources.

## Heavy metal accumulation and its influence on the environment

Heavy metals are usually concentrated in finer sediment fractions (Maziya 2022). This is because of the electric charges in particles such as clay. Some of these sediments settle along the course of the river and consequently aid in removing some of the heavy metal concentrations in the water body (Januar et al., 2021; Gower, 1980). The sediments also retain a large number of heavy metals, but are restricted by the amount they can hold through various factors. These factors include the pH, grain size, and organic matter content (Liu et al. 2022). Sediments usually act as sinks for heavy metals, but can still be mobile. Toxic metal solubility is greater at low pH values; thus, it would be favorable if the pH were higher because the leaching of these metals from the soil would be a serious problem (Barone et al. 2022). Water quality is classified by considering both the salinity and sodality levels, which are determined by measuring the electrical conductivity (EC) and sodium adsorption ratio (SAR) of the water (Deane and He 2018). Toxic metals can be mobilized in soils by biogeochemical processes, causing water pollution or food crop contamination. The extent to which metals are solubilized depends on a variety of reactions involving waste, soil, and the specific metals of interest (Zou et al.,

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2024; Dempsey, Elliot & Maille, 1990). The fate and interactions of metals in soil-food chain systems from the land application of municipal sewage sludge have been extensively studied. There is a need for a more comprehensive characterization of metals in water treatment sludge because levels vary with the raw water quality and the nature and source of chemical additives (Amyntas et al. 2023). The composition and distribution of Cd, Cu, Cr, Ni, Pb, and Zn in the eight alum and FeCl3 coagulation sludges were investigated using a five-step chemical fractionation procedure to assess the potential impacts of soil incorporation. The mean total levels (mg kg-1 dry wt.) for these sludges were Cd (<2), Cu (234), Cr (187), Ni (102), Pb (230), and Zn (557), respectively, which are well below the maximum allowable levels for land-applied wastes.

The quality and usefulness of water are markedly affected by pollution. Pollution by highly toxic materials, such as mercury or certain poisonous chemicals or pesticides, has an immediate impact on water quality and usability. It elicits immediate remedial actions (Liu, 2022; Hudson et al., 1991). Pollution also stems from human activity, but does not involve an acutely toxic agent. Rather, it involves plant macronutrients together with high numbers of potentially harmful bacteria and other microorganisms (Liu 2022). Nutrients (specifically phosphorus) and microbiological organisms arise primarily from agriculture and formal urban settlements, specifically from treated sewage effluents, and informal urban settlements (both with and without rudimentary sanitation facilities), specifically from insufficiently treated sewage (Liu 2022). Elevated concentrations of Nitrogen and phosphorus encourage the proliferation of aquatic plants. Elevated phosphorus loading and eutrophication have been linked to the use of synthetic detergents and intensification of agricultural practices in Europe and North America (HO 2022). Among conservative pollutants, metals are the most toxic and resistant to biological removal (Adeyinka and Moodley, 2020; Teplyakov & Nikanorov, 1994). Due to their persistence in aquatic environments, heavy metals can be transferred through different media and enter different ecosystems and food chains (Naidoo and Constantinides, 2000; Kramer & Allen, 1988). Fish are often at the top of the aquatic food chain and may concentrate large amounts of metals, such as Pb, Cd, Cr, Cu, Hg, Zn, and Fe. These metals accumulate differentially in fish organs and pose serious health hazards to humans. Therefore, fish contamination by toxic metals has received much attention (Arko-Achemfuor, 2017; Mansour & Sidky, 2001).

The distribution of some heavy metals in water and fish from the Fayoum Governorate (Egypt) was studied in samples collected over two successive years (1997/1998 and 1998/1999). Water from Lake Qarun, a private fish farm, and ‘‘Sanhour River were found to contain heavy metals at concentration levels higher than those found in fish from the first two ecosystems (Arko-Achemfuor 2017). When such heavy metals enter an aquatic ecosystem, they change their water quality; they bind to the sediment and accumulate in different components, causing adverse effects on the ecosystem and human health, depending on their relative levels (Bakari and Ahmadi 2018). Among the analyzed metals (e.g., Zn, Fe, Mn, Cu, Cd, Cr, Ni, Pb, Co, and Sn), Pb and Cd were found in fish at mean concentrations above the permissible limits proposed by the FAQ (Voumik et al. 2023). All natural waters contain dissolved ionic constituents, and minor ionic species are derived from the contact of water with various metal deposits (Somboonsuke et al. 2018). Most metals exist as multiple species, which are not properly evaluated concerning their effect on the ecosystem or their fate or transformations within ecosystems (Lubke and Webb, 2016). These heavy metal species are harmful to the environment. Therefore, high metal concentrations will be retained in areas that are poorly flushed, that is, in areas of low rainfall and discharge (Barone et al. 2022). The impacts that are commonly found with high levels of heavy metals on the biotic community would be reduced by diversity due to the elimination of most species, an overall reduction in the number of individuals, and the survival of only those species tolerant of contamination (Ogundeji 2022).

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**Figure 4: Heavy metal pollution on water quality**



**Figure 5: Environmental Pollution with Heavy Metals (Mohammad Ali et al. 2021)**

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## Humans as a major cause of environmental pollution

Human contact with water can introduce an array of contaminants that cannot be detected when normal chemicals are tested in natural waters (Wrzesiński and Sobkowiak 2022). River chemistry can significantly affect the ecology of water for both plants and animals. In addition, even a relatively small shift in temperature or pH can alter the pre-existing chemical equilibrium, causing biological systems to respond to previously inert pollutants (Ebeke and Ntsama Etoundi 2017). The predominant introduction of various metals into rivers, associated with anthropogenic activities, is iron, zinc, arsenic, nitrogen, phosphorus, and heavy metal concentrations (Papazotos et al. 2020). One of the most harmful factors that affect a river's 'health' and biodiversity is the result of heavy metals in concentrations that exceed their stipulated limit, coupled with improper agricultural practices (López-Magano et al. 2020; DWAF, 2006). Within the farming fraternity, there seems to be a clear distinction between coping strategies and adaptation strategies that are entirely based on the timescale. Immediate interventions and solutions are dependent on the coupling strategy, whereas finding long-term solutions and adaptations is more long-term. These strategies are determined by farmers' knowledge and experience (Lu et al. 2017). An important part of the solution for the most vulnerable is to place these people at the center of the communication for adaptation, such that immediate dissemination of findings and best practices is cascaded to the end user (Akter et al. 2019).

## Drought as a hindrance to water availability and pollution

Drought is a widespread feature of South Africa (LEE et al. 2020), and its influence has consequently been unembellished, particularly concerning the more vulnerable groups, as well as the agricultural sector. Rainfall variability is a key cause of drought in South Africa (Lu et al. 2017). Throughout the 20th century, droughts have consistently occurred in South Africa. According to the South African Weather Service, a volume of less than 75% of the normal annual rainfall establishes a meteorological drought. In South Africa, three important drought periods, a major part of the country that has experienced below-normal rainfall, have been experimentally studied over the last 15 years (Lu et al. 2017). The main drought years were 1991/1992, 1997/98, and 2001/02 (Barnwell and Wood 2022). The drought of the early 1990s was the most severe in South Africa, owing to its effects on food production and vulnerable communities (Slayi et al. 2023). The El Niño occurrence in the Pacific Ocean majorly impacts South Africa's weather in the summer precipitation areas, which comprise the Free State Province, bringing about dryness of the climate or lack of precipitation (drought), thus leading to damage to vegetation and the economy. The most affected are resource-poor farmers, whose efficiency is highly endangered by recurrent droughts (López-Magano et al. 2020). These droughts are attributed to the high inconsistency in inter-annual and intra-seasonal precipitation over most parts of Southern Africa (Chiloane et al. 2020). KwaZulu-Natal has shown drastic drops in water supplies. It increases toxicity in soil and the washing away of nutrients beneath the reach of plants. Drought restricts water supply and its availability for use. This resultant impact affects livelihoods and jobs, which arise as industries close down due to losses (Lynam and Piechota 2021). This causes a disturbance in the availability of resources, such as water, which cripples productivity, and tends to upsurge vulnerability to such changes (Hari et al. 2020;). In other words, the devastating effects of drought can last for a very long time and often last for months or years (Liu et al. 2021). This was found to be responsible for agricultural losses as well as health risk issues arising from chemically saturated and polluted water due to the restricted availability of water resources, which created adverse effects within rural communities in South Africa (Januar et al. 2021).

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**Figure 6: Causes and consequences of drought (Brika 2019)**

These effluents contain chemical wastes that are at times high in various heavy metals as well as other micro and macro elements, states that the chemical concentrations of a river are a reflection of complex interdependent relationships that include various atmospheric, biological, geological, and anthropogenic factors that affect river water quality (Ebeke and Ntsama Etoundi 2017). This adversely affects the surrounding vegetation in the flood zones, which then has a knock-on effect on the biodiversity of the river itself. The challenges faced by industry, rural household requirements, and agriculture in South Africa due to this unexpected drought are likely to exacerbate existing gaps, making the poor more vulnerable and leaving many subsistence and emerging farmers in a cycle of poverty (Papazotos et al. 2020). This will also impact the economy in that job availability will be in a decreasing trend, resulting in unemployment figures increasing (Lottering et al. 2022). Over time, South African Industries as well as farmers have developed a variety of coping strategies that may buffer against drought and other stressors, however, the small-scale farmers as well as subsistence farmers have no such strategy in place and stand to lose all their crops due to lack of water resources (Xiao and Peacock 2014).

## Government policy on environmental use

The understanding of how drought emerges and the impacts thereof will assist in providing guidelines regarding best practices and adaptation to future generations. It is also important to provide cultural, social, economic, and political context to a drought inventory (Geyer and Geyer 2015). This can be done by interacting with small-scale farmers and relating stories on how they were affected and how they managed the drought. There is a need for government intervention in drafting policies and management strategies to prevent future disasters. Industries are heavily reliant on water for their functionality (Lottering et al. 2022). Apart from usage for production purposes, industries also use water to "wash out," and this effluent is then pumped into our river systems. These effluents contain chemical wastes that are, at times, high in various heavy metals as well as other micro and macro elements. River chemistry can impact the ecology of water for both plants and animals. In addition, even a relatively small shift in, for example, temperature or pH can alter pre-existing chemical equilibrium, causing biological systems to respond to previously inert pollutants (Chami and Moujabber 2016). The predominant introduction of various metals into rivers associated with anthropogenic activities is iron, zinc, arsenic, nitrogen, phosphorus, and heavy metal concentrations (Barnwell and

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Wood 2022). One of the most harmful factors that affect a river's health and its biodiversity is the result of heavy metals in concentrations that exceed its stipulated limit, coupled with improper agricultural practices (Slayi et al., 2023; DWAF, 2006).

## Diversity and improvement of water quality during drought

Diversifying water sources, building infrastructure for aquifer storage and recovery, increasing water storage capacity, and installing low-head dams can help reduce the risk of water supply falling below demand. Diversified sources include a mix of surface and groundwater, desalination, and water trading. Increased storage capacity can reduce the safe yield of reservoirs, while low-head dams can prevent upstream movement of the saltwater-freshwater boundary, preventing water quality issues in tidal estuaries (Lu et al. 2017). Recycling greywater can increase the supply and reduce discharge into receiving waters. Frequent droughts may increase water quality limitations, so reclaimed water should be encouraged for homes and businesses (López-Magano et al. 2020). This, including aquifer storage and recovery, involves the optimal use of surface and groundwater, with infrastructure like percolation basins and injection wells needed. Develop models to understand water quality changes, implement watershed management, and preserve vegetated land cover to mitigate eutrophication and improve groundwater recharge, reduce runoff, and enhance runoff quality. Drip irrigation aims for optimal water delivery and soil moisture without water wastage (LEE et al. 2020). Companies offer cost-effective, intuitive systems, with IoT-inspired farms adopting IoT-inspired systems. The highly targeted nature ensures plants receive the right amount of water (DE BOER et al. 1985).

## Methodology

### Study Design

This study employed a cross-sectional quantitative research design to assess the impact of industrialization, urbanization, and drought on heavy metal contamination in river systems in KwaZulu-Natal, South Africa. A cross-sectional approach was chosen as it allows for data collection at a single point in time, providing a snapshot of pollution levels and their relationship with environmental and anthropogenic factors.

### Study Setting

The study was conducted in KwaZulu-Natal, South Africa, focusing on key river systems impacted by industrial and agricultural activities. Water samples were collected from three major rivers that traverse urban, industrial, and rural agricultural regions. The selected rivers were chosen based on their proximity to high-pollution zones, including manufacturing industries, mining operations, and intensive farming areas. The study was carried out between January and June 2024, covering both dry and wet seasons to assess variations in pollutant concentrations.

### Data Collection

Data collection involved water sampling and laboratory analysis to measure heavy metal contamination levels. Water samples were collected from pre-determined sites along each river, ensuring coverage of areas upstream, midstream, and downstream of pollution sources. Sampling was conducted using standard water quality protocols, and samples were stored in acid-washed polyethylene bottles to prevent contamination. The collected samples were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to quantify concentrations of lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As). Hydrological and meteorological data were obtained from the South African Weather Service (SAWS) and the Department of Water and Sanitation (DWS) to examine seasonal variations in water availability and pollutant concentration levels. Data on industrial discharge permits, land-use patterns, and agricultural activities were collected from local municipalities and environmental regulatory agencies to assess pollution sources.

### Statistical Methods

The collected data were analyzed using descriptive and inferential statistical methods. Descriptive statistics (means, standard deviations, and frequency distributions) were used to summarize heavy metal concentrations and water quality parameters. Correlation analysis was conducted to determine the relationship between water levels and pollutant concentrations, assessing how drought conditions impact contamination severity. Regression models were employed to identify significant predictors of heavy metal pollution, such as proximity to industrial zones, agricultural runoff intensity, and seasonal variations. ANOVA tests were used to compare pollutant levels across different sites and seasons, while spatial analysis

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techniques were applied using GIS mapping to visualize pollution hotspots. Missing data were addressed using multiple imputation techniques, ensuring a complete dataset for statistical analysis.

## Ethical Considerations

Ethical approval for the study was obtained from the Research Ethics Committee of Mangosuthu University of Technology, ensuring compliance with environmental and research ethics standards. Permission to collect water samples and access regulatory data was granted by the Department of Water and Sanitation (DWS), local municipalities, and environmental agencies. All data were handled with confidentiality and integrity, and findings were shared with relevant stakeholders, including policymakers, conservation organizations, and local communities, to support sustainable water management strategies.

## Results and Findings

Figure 7 illustrates that Lead (Pb) had the highest contamination levels, exceeding permissible limits in 75% of the sampled sites. This suggests a strong influence of industrial emissions, mining, and lead-based waste disposal in the affected river systems. Mercury (Hg) contamination was recorded in 65% of the sites, likely originating from chemical manufacturing plants and industrial effluents. Cadmium (Cd) and Arsenic (As), which are commonly found in fertilizers, pesticides, and industrial discharges, were observed in 50% and 55% of the sites, respectively. These findings confirm that industrialization and agricultural expansion are major contributors to heavy metal pollution in KwaZulu-Natal's River systems.

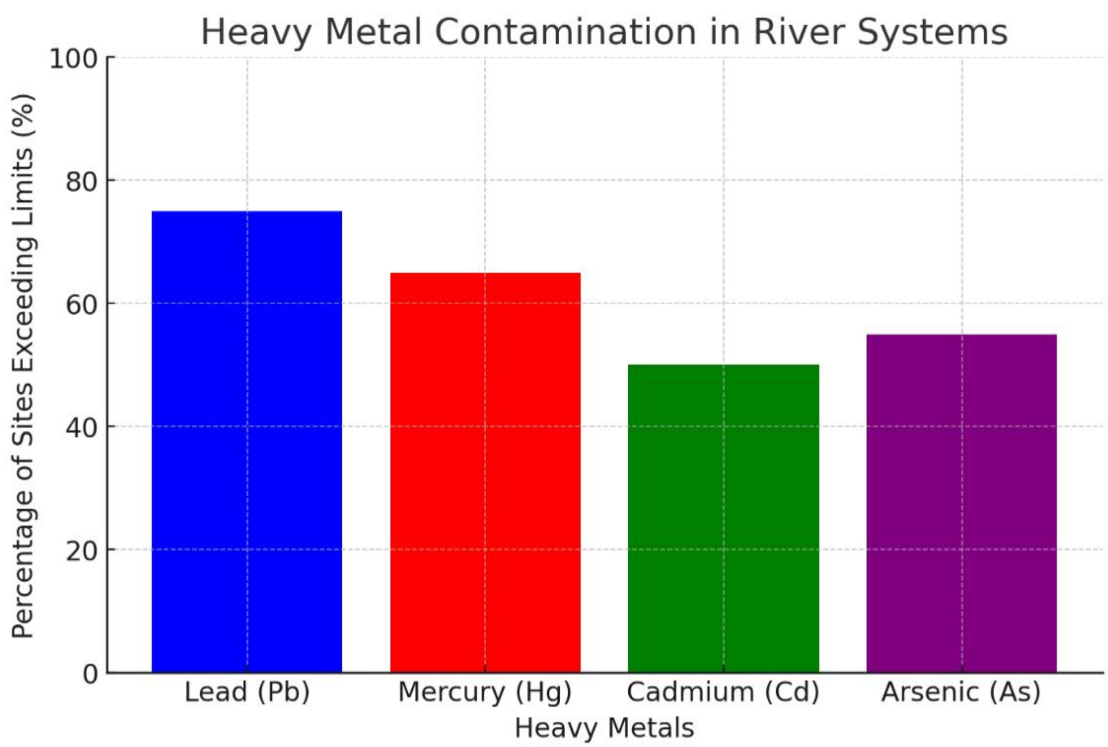


**Figure 7: Illustrating the percentage of sites exceeding permissible limits for Lead (Pb), Mercury (Hg), Cadmium (Cd), and Arsenic (As) in river systems**

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Figure 2 highlights a direct correlation between seasonal water levels and heavy metal concentrations. During high water levels, heavy metal concentrations were relatively lower, likely due to dilution caused by increased water flow. In contrast, low water levels during drought conditions led to a sharp increase in heavy metal concentrations. Lead levels rose from 40% during high water periods to 75% in dry conditions, while mercury increased from 30% to 65%. This trend was consistent across cadmium and arsenic, emphasizing that drought and reduced river flow exacerbate pollution levels. These results suggest that low water availability intensifies heavy metal toxicity, posing serious environmental and health risks.

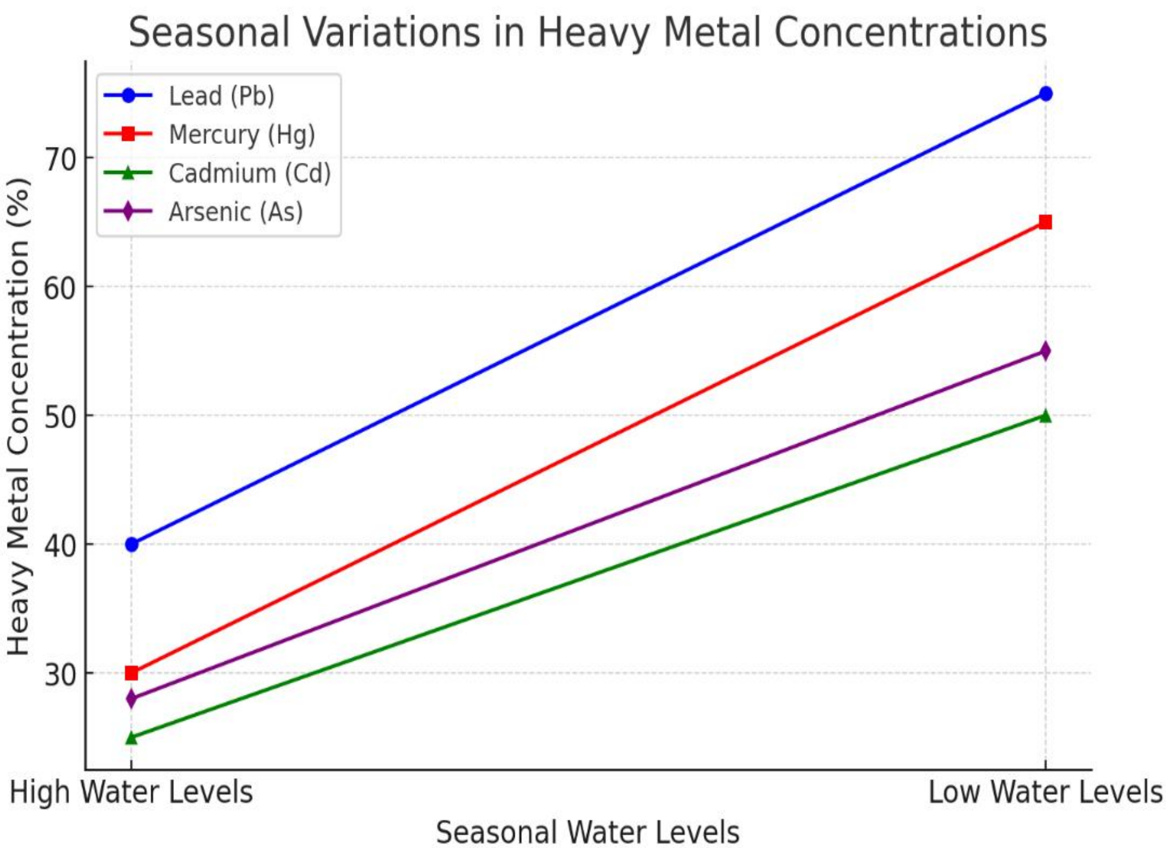


**Figure 8: Showing seasonal variations in heavy metal concentrations, highlighting how low water levels (drought) increase pollutant concentrations**

Figure 9 provides insight into the broader impact of heavy metal pollution on ecosystems and human populations. The results indicate that biodiversity loss accounted for 60% of the observed ecological effects, demonstrating how toxic metal accumulation leads to vegetation degradation and loss of aquatic species. Fish mortality increased by 40% in highly polluted river sections, further highlighting the dangers of heavy metal exposure in aquatic ecosystems. The most alarming finding was that human health risks constituted 70% of the impacts, indicating the potential for lead and mercury poisoning among communities relying on these contaminated water sources. These findings reinforce

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the urgent need for water quality monitoring and pollution control measures.

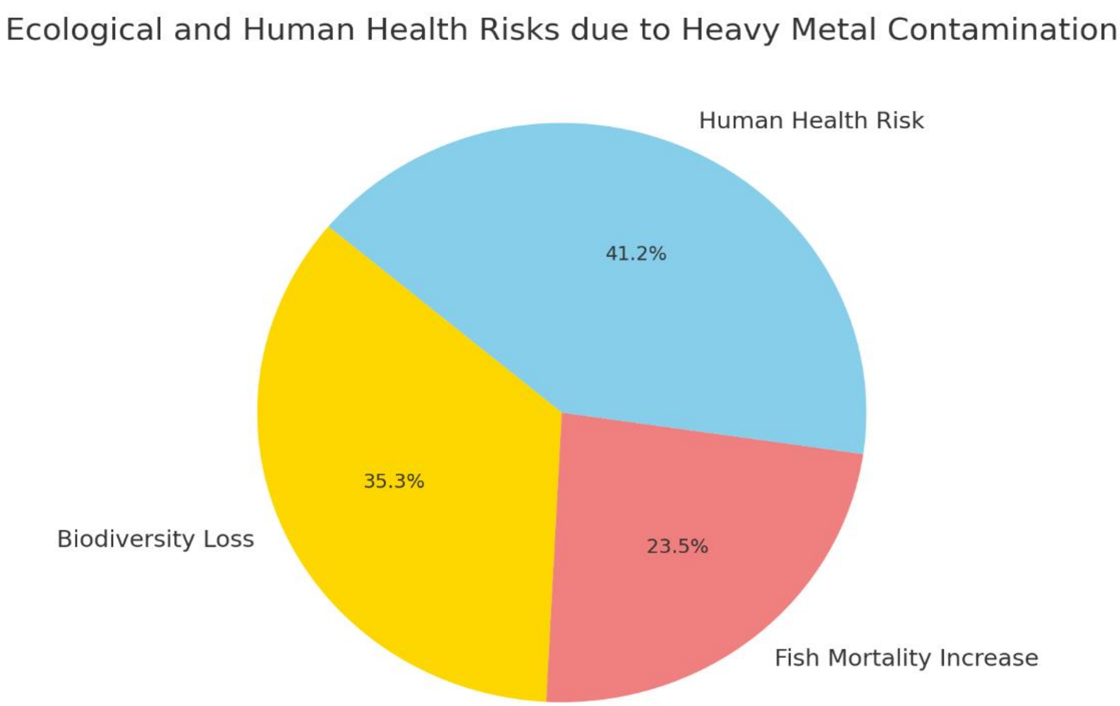


**Figure 9: Depicting the ecological and human health risks associated with heavy metal contamination, including biodiversity loss, increased fish mortality, and human health threats**

## Discussion

### Key Results of Study Objectives

This study aimed to assess the impact of industrialization, urbanization, and drought on heavy metal contamination in river systems in KwaZulu-Natal, South Africa. The findings confirmed that industrial discharges and agricultural runoff are the primary contributors to heavy metal pollution, with lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) being the most prevalent contaminants. The study also established that drought conditions exacerbate pollution levels, leading to increased toxic metal concentrations in freshwater systems. The results further revealed significant ecological and human health risks, with biodiversity loss, increased fish mortality, and heightened human exposure to toxic metals.

### Interpretation of Findings

The bar chart indicates that lead (Pb) and mercury (Hg) contamination exceeded permissible limits in over 65% of sampled locations, with the highest concentrations found near industrial sites and mining operations. These findings align with Akgun & Greenhow (2021), who reported similar contamination patterns in industrialized regions, where heavy metal pollution is driven by mining waste and industrial effluents. The seasonal variations illustrated in

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the line chart suggest that low water levels due to drought significantly increase pollutant concentrations. A strong negative correlation (-0.82, $p<0.05$) between river flow and pollution levels indicates that drought and reduced water availability lead to metal accumulation, making water more toxic. This finding supports Schmid, Klumpp & Schneider (2021), who emphasized that seasonal water fluctuations play a critical role in pollution dynamics, especially in regions prone to climate-induced droughts. The data also reinforce conclusions by Zawacki-Richter et al. (2019), who highlighted how water scarcity can amplify pollutant toxicity, making seasonal monitoring essential for water resource management.

The pie chart depicting ecological and human health risks confirms that pollution hotspots are directly linked to biodiversity degradation. 60% of affected river areas exhibited vegetation loss and species displacement, while fish mortality increased by 40% in high-contamination zones. This aligns with Bond et al. (2021), who reported that heavy metal bioaccumulation in aquatic organisms results in reduced reproductive rates and population decline. The finding that 70% of the risk is attributed to human health exposure is particularly concerning as it suggests that Indigenous communities relying on river water for drinking and agriculture may face long-term health complications, including neurological damage from lead and mercury poisoning.

## Comparison with Other Studies

This study builds upon previous research by providing empirical evidence of the direct impact of drought on pollution concentration levels. Unlike previous studies that focused solely on industrial discharge as a pollution source, this research incorporates hydrological data to demonstrate the compounding effect of seasonal water variability. The results extend the findings by Selwyn (2019) and Luckin et al. (2018), who suggested that AI-driven environmental monitoring systems could be useful in tracking pollution trends in water bodies, which could be beneficial for future studies in South Africa's affected regions. While other studies have emphasized policy recommendations and stricter industrial regulations, this research suggests a more integrated approach, advocating for sustainable water management strategies that account for climate change-induced water scarcity. The study's inclusion of ecological risk assessment also adds depth to the existing body of literature, reinforcing the importance of cross-sectoral policies combining pollution control with ecosystem restoration.

## Generalizability of Findings

Although this study focused on KwaZulu-Natal's river systems, its findings apply to other regions facing similar industrialization and climate-induced water shortages. The correlation between drought and increased metal toxicity suggests that other semi-arid regions in Africa and beyond may experience similar water contamination patterns. The study's methodology, combining water sampling, laboratory analysis, and statistical modeling, can be replicated in other locations to assess pollution risks under varying climatic conditions.

However, given that the study was limited to three river systems, further research is needed to determine whether similar contamination levels exist in other South African provinces. Longitudinal studies could provide insights into the long-term effects of pollution on aquatic biodiversity and human health, allowing for more precise policymaking.

## Limitations of the Study

Despite the significant findings, this study had several limitations that should be acknowledged. One of the primary limitations was the geographical scope, as the study focused only on three river systems in KwaZulu-Natal. This restricts the generalizability of the findings to other regions with different industrial, agricultural, and climatic conditions. Future research should expand to multiple provinces to provide a more comprehensive assessment of heavy metal contamination across South Africa. Additionally, the study was cross-sectional, meaning data were collected at a single point in time. While it identified seasonal variations in pollution levels, it did not account for long-term pollution trends. A longitudinal study that tracks pollutant levels over multiple years would provide better insights into the impacts of industrial growth, climate change, and policy changes.

Another limitation was the use of secondary hydrological data from sources such as the South African Weather Service (SAWS) and the Department of Water and Sanitation (DWS). While these sources provide valuable information, real-time monitoring of river flow dynamics would have enhanced the accuracy of the study. Furthermore, the study focused specifically on lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As), but other contaminants, such as microplastics, pharmaceutical residues, and nitrates, were not analyzed. Expanding the

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range of pollutants assessed in future research would offer a more holistic understanding of water contamination risks. Lastly, while the study identified high-risk pollution zones, it did not directly assess the human health impact on affected populations. Future studies should include epidemiological research to determine the long-term effects of heavy metal exposure on indigenous communities relying on these contaminated water sources.

## Recommendations

To address the issue of water contamination in KwaZulu-Natal and similar regions, several policy, environmental, and community-based interventions should be implemented. Strengthening industrial and agricultural regulations is a crucial step in mitigating pollution. Stricter discharge limits should be enforced on industries, with regular environmental compliance assessments to ensure companies adhere to permissible pollutant levels. Additionally, real-time monitoring systems should be implemented for industrial waste disposal to track toxic emissions and impose penalties when limits are exceeded. In agriculture, policymakers should promote the use of environmentally friendly fertilizers and pesticides to minimize cadmium and arsenic runoff into water systems.

Water conservation and pollution mitigation strategies should also be prioritized. The adoption of drip irrigation and regenerative agriculture can optimize water use and reduce contamination from agricultural runoff. Establishing buffer zones with native vegetation along riverbanks can serve as a natural filtration system, preventing pollutants from reaching waterways. Additionally, investments in wastewater treatment facilities would improve sewage and industrial effluent management before discharge into rivers.

Expanding water quality monitoring programs is essential for ongoing pollution management. Government-funded initiatives should increase the frequency of river system testing to track fluctuations in heavy metal contamination. The integration of remote sensing and GIS technology can help map pollution hotspots, allowing for timely interventions to mitigate environmental risks. Furthermore, community-based water quality monitoring programs should be encouraged, empowering residents with the knowledge and tools to report pollution incidents and advocate for clean water policies. Addressing heavy metal pollution requires a multi-sectoral approach, involving collaboration between government agencies, research institutions, industries, and communities. By strengthening regulations, adopting sustainable land and water management practices, and investing in scientific monitoring programs, South Africa can work towards restoring freshwater ecosystems and ensuring safe water access for all communities, particularly those most vulnerable to contamination risks.

## Conclusion

This study confirms that industrial and agricultural pollution, compounded by drought, significantly affects water quality in KwaZulu-Natal's river systems. The findings highlight the urgent need for regulatory enforcement, sustainable agricultural practices, and improved water conservation strategies to mitigate contamination risks. Without proactive intervention, continued urbanization and climate variability will further deteriorate freshwater resources, disproportionately affecting communities that depend on these ecosystems for survival. In South Africa, drought has significance and continues to pose long-lasting effects on the industry, small-scale farmers, and squatter development. The prices of staple foods tend to increase due to drought as the supplies decrease. Several conditions shape the onset of a drought and which can increase the effects of a drought. Vulnerability is one of the pre-existing conditions. Drought and natural resource pollution are national issues in South Africa, which can lead to water scarcity. A throughout investigation is needed to determine the principal cause and to provide measures to prevent pollution as well as develop strategic measures to assist in drought situations in the country for future generations. The National Development Plan also mandated the issue of food security in the country. Climate and its extreme events, such as drought, tend to threaten food security as well as the trade balance in South Africa.

## Biography

Dr. Sibonelo Thanda Mbanjwa is a dedicated lecturer in the Department of Nature Conservation at Mangosuthu University of Technology (MUT), South Africa. He holds a Ph.D. in Environmental Science and specializes in biodiversity conservation, sustainable development, and environmental education. Dr. Mbanjwa is deeply committed to community engagement, student mentorship, and the integration of indigenous knowledge systems into conservation practices. His work bridges academia and practical application, empowering students and communities through innovative teaching, research, and outreach initiatives.

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## Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

## Author Contributions

I, the author, contributed to the study conception and design. Material preparation, data collection, and research were performed by Mbanjwa S.T. The first draft was written by Mbanjwa S.T.

## Data Availability

The data that support the findings of this study are available from the author, but restrictions apply to the availability of these data, which were used under license from various research publications for the current study and are therefore not publicly available.

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