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Vulnerability of The Rice Milling Industry in Kenya: A Systematic Review

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Abstract

The vitality of rice as a food security and cash crop has grown over the past decades in Kenya. Rice is consumed by most households in Kenya and thus plays a strategic role in food security. This is evident in the 12 percent increase in its consumption annually. The rice milling industry acts as an engine for the entire rice value chain. However, its performance has been limited by various factors ranging from social, economic, environmental, policy, and technological. The industry's contribution to food security, poverty reduction, employment, and economic development has been greatly hampered by climate change and variability. Since the industry is dependent upon rice production, climate change impacts at the production node further affecting its value chain performance. Rice-related research in Kenya has mainly focused on climate-related effects on production and consumption nodes. Limited studies have widened their scope of climate change to demonstrate its impact on the rice milling industry. This systematic review maps the existing literature following the PRISMA protocol to synthesize the risks associated with climate change on the rice milling industry linking it with all nodes within the rice value chain. The paper further discusses possible implementable short-term solutions to under-utilization of rice mills as a result of climate change and recommends areas of future research that can provide lasting solutions to climate-related challenges in the rice value chain. Among the solutions include the need for increased investment in new irrigation infrastructure and technology, tolerant rice varieties as well as improved access to credit, inputs, and market information. Additionally, there is a need for stronger policy support to promote the growth and development of the rice milling industry,

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including measures to improve the regulatory environment, reduce taxation, and increase technical support and training for millers. Finally, promoting climate-smart agriculture practices can help mitigate the impacts of climate change on rice production and milling.

Keywords: Capacity utilization, climate change, installed capacity, milled rice, vulnerability

Introduction

The reality of climate change threatens agricultural production in Africa. The continent is particularly vulnerable to the impacts of climate change due to its reliance on rain-fed agriculture and limited access to irrigation (Terdoo & Teola, 2016). Climate change is already affecting crop yields, water availability, and food security in Africa, and these impacts are expected to intensify in the coming decades (Pereira, 2017). One of the main challenges facing agriculture in Africa is the increasing frequency and intensity of extreme weather events, such as droughts and floods (Bhargava, 2019). Kenya is not an exception to the challenges of climate change in Africa. This is exacerbated by the fact that the country's economy is heavily dependent on agriculture (Mutisya, 2022).

Rice is among the value chains that are greatly affected by climate change due to its high water-demanding nature. Irrigated rice dominates the Kenyan system consisting of 80 percent while 20 percent is rain-fed (MOA, 2008). Irrigated rice production is mainly concentrated in the Mwea Irrigation Scheme, which is the largest rice-growing area in the country (Mugalavai et al., 2018). Other rice-growing areas include Ahero and West Kano in the western region, and Bunyala in the eastern region (Mwongela et al., 2019).

As the third most significant cereal crop after maize and wheat (Obura et al., 2017), rice plays a critical role in the socioeconomic development of the Kenyan economy. Over 300,000 rice growers earn their living out of crop cultivation (Vishnu & Mukami, 2020). Rice is a staple food in Kenya, and increasing rice production helps to enhance food security in the country (Kadipo et al., 2021). In 2018, Kenya imported milled rice valued at 26 billion Kenya shillings (KNBS, 2019). Hypothetically, this is equivalent to approximately 40 percent of the 2022 national agriculture budget.

Rice milling is an important aspect of the rice value chain in Kenya (Uma, 2022a). The process involves removing the husk and bran from the rice grain to produce milled rice, which is the final product that is sold to consumers (Ndirangu & Oyange, 2019). Rice milling

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industry as used in the manuscript includes paddy drying, milling process, packaging and marketing. There are several rice mills in Kenya, with the largest milling capacity located in the Mwea Irrigation Scheme. However, the milling capacity is still relatively low compared to the country's production capacity. Rice milling in Kenya is primarily done using traditional methods (Ndirangu & Oyange, 2019). However, there is a growing trend towards the use of modern milling technologies (Watanabe et al., 2021). The vitality of the milling process is evidenced in its ability to transform paddy into nutritionally utilizable form while generating by-products husks and bran (Bodie et al., 2019). Unless irrigated and rain fed locally produced rice is milled, the efforts of those engaged in its production is rendered useless. However, it is worth noting that any hindrance to the production of rice equally impact on the activities of the rice milling.

Rice milling provides employment opportunities for thousands of Kenyans, particularly in rural areas where the industry is concentrated (Paman et al., 2016). This helps to reduce unemployment and poverty levels in these areas. Rice milling adds value to the raw rice grain by removing the husk and bran and producing milled rice that is ready for consumption. This increases the profitability of the rice value chain and benefits farmers, millers, and consumers.

Despite the efforts to increase rice production in Kenya, the sector still faces several challenges. Farmers in some areas have limited access to quality seeds, fertilizers, and pesticides, which impacts the productivity and quality of rice produced. Changing weather patterns, including droughts and floods, negatively impact on rice production. Rice pests and diseases which thrive due to climate change cause significant losses to farmers. Many smallholder farmers lack access to credit, which limit their ability to invest in their farms and cope with the impacts of climate change (Watanabe et al., 2021). These generally hamper the production volumes. Consequently, the vast majority of the installed capacity of the mills are underutilized chiefly because of absence of the paddy.

The rice milling industry in Kenya faces several challenges, including inadequate infrastructure, high production costs, and low-capacity utilization. Additionally, the industry is highly fragmented, with many small-scale millers operating with low efficiency. Due to the idleness and fast depreciation of the rice milling machines, high maintenance costs are incurred by the millers and mill owners (Ndirangu & Oyange, 2019). Other challenges facing

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rice milling industry include high foreign matter content due to poor quality milling equipment and poor storage and handling of paddy before actual milling (Atera et al., 2018). Additionally, high costs of labour, unreliable power supply, high costs of importation of raw material, inefficient transport facilities most especially within the lowland areas undermine rice production and milling efforts.

The challenges impacting rice production and milling industry in Kenya have been further compounded by climate variability. This has hampered the sector's contribution to food security, poverty reduction, employment, and economic development. Since the rice milling node is dependent upon rice production, climate change impacts at the production node which further influences the performance of rice milling activities.

Much as climate change has been fronted as a very serious contributor to agricultural related problems, research in relation to climate change has largely focused on its effects on the production node. Limited studies have widened their scope of climate change to demonstrate its impact on the rice milling industry. This systematic review is specifically designed to pinpoint the elements of climate change that directly and indirectly impact the rice milling node. The paper further discusses possible implementable short-term solutions to underutilization of rice mills as a result of climate change and recommends areas of future research that can provide lasting solutions to climate-related challenges in the rice value chain.

Theoretical Background

The vulnerability of agricultural value chains can be understood through a theoretical framework that takes into account the different factors that contribute to their instability and potential for disruption. One important framework for understanding the vulnerability of agricultural value chains is the systems theory approach. The theory was proposed by Ludwig Von Bertalanffy who fronted the idea that every system is part of a sub-system (Nicholz & Schwartz, 1998). According to Ludwig, studying individual parts of a system in isolation denies influence of the larger system thus limiting the understanding of the outside context which influences the individual part under study. Therefore, this approach recognizes that agricultural value chains are complex systems that are interconnected and interdependent. Disruptions in one part of the system can have ripple effects throughout the entire chain.

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Another framework that can be used to understand the vulnerability of agricultural value chains is the value chain analysis approach. The value chain concept was introduced to describe the full range of activities required to bring a product or service from conception through different phases from production to consumption (Porter, 1985). This approach tries to consider all economic activities within a value chain by understanding what is happening at different stages of the value chain as well as how the value chain operates as part of a system. Value chain analysis focuses on the build-up of costs and growth in value and distribution of returns along the value chain (Kaplinsky & Morris, 2000). This approach emphasizes the different stages of the value chain and the actors involved in each stage. It considers how changes in one part of the chain can affect the entire system.

A third theoretical framework that can be used to understand the vulnerability of agricultural value chains is the political ecology approach. The term political economy was first described by Wolf (1972) as a term that represents an explicit alternative to 'apolitical' ecology, which operates under common set of assumptions, and employs a reasonably consistent mode of explanation. This approach focuses on the political and social factors that influence the production and distribution of agricultural products. It considers issues such as power dynamics, social inequalities, and the impact of policies and regulations on the value chain. Overall, a comprehensive understanding of the vulnerability of agricultural value chains requires considering multiple theoretical frameworks and taking into account the diverse factors that can contribute to instability and disruption in the system.

The three theories fronted above are critical in understanding the relationship between climate change and rice milling node. However, they all have shortcomings. The systems theory approach does not offer specific tools or techniques for integration or understanding of the interdependence between an organization and its environment. This makes it difficult to use a specific methodology in applying the systems theory in understanding the relationship between rice milling node and climate change. The value chain approach largely focuses on the nitty-gritty details, and an organization may risk drifting from its overall mission and vision. Political ecology approach has a narrow definition of the environment and treats local and global environment as independent from one another which turns out to be unrealistic in climate change related studies.

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Materials and Methods

A systematic review can be conducted using **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)** guidelines according to Briner and Denyer (2012). In the application of these guidelines, a guideline checklist was developed and followed to clearly indicate and describe the stages of article identification, selection, screening, eligibility criteria and inclusion. The study used rice value chain, climate change, rice milling and rice vulnerability as key words in various combinations. The results yielded by each database were as follows: Elsevier (101); Springer Link (116); Emerald Journals (29); Wiley Online Library (56); Taylor and Francis (112); and Science Direct (142). The search was limited to studies published between 2010 and 2023.

For an article to be included in the study, three parameters were to be met. The first was to examine rice vulnerability across all contexts in terms of geographical areas. Therefore, any study on the vulnerability of other crops were discarded at this point. Studies that included aspects related to vulnerability of rice production and milling with close focus on African context were considered. Studies that largely relied on marketing, consumption and use of rice by-products were excluded. Most importantly, studies that were found related to the objective of the study with reference to the Kenyan context were included and those that were far from the Kenyan context were relegated. Overall consideration was given to studies published in English language. The overall search generated a total of 556 results out of which 54 were regarded to be satisfactory in meeting the objectives of the study.

Results and Discussions

Characteristics of Studies Considered in the Study

According to Table 1, majority (44.4%) of the studies included in the study were published between 2016 and 2020, closely followed by 2011 to 2015, and lastly beyond 2020. This implies that climate change and its impacts on the rice value chain Kenya has gained significant attention as the years go by. The average percentage of studies considered beyond 2020 is 8 percent, this implies that by the end of 2025, the number of studies conducted in relation to climate change and rice milling node will surpass the previous years. This increasing attention can be attributed to the growing importance of the rice value chain in Kenya as a staple and driver of economic development.

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Table 1: Characteristics of Studies included in the Study

Criteria	Number of papers	Percentage (%)
Year		
Between 2011 to 2015	17	31.5
Between 2016 to 2020	24	44.4
Beyond 2020	13	24.1
Value chain node		
Production	19	35.1
Rice milling	6	11.1
Marketing	3	5.6
Entire value chain	24	44.4
Production & marketing	1	1.9
Milling & marketing	1	1.9
Area of concentration		
Climate change	17	31.5
Sustainability	18	33.3
Profitability and market analysis	14	25.9
Policy and others	5	9.3
Geographic area		
Kenya	34	63.0
East Africa	2	3.7
Africa	6	11.1
Global	6	11.1
Others	6	11.1

Majority (44.4%) of the studies reviewed analysed the entire rice value chain followed by 35 percent that focused on production and 11 percent that discussed rice milling node. It is still evident that most of the studies have given much attention to the production and to a larger extent neglected the rice milling node. This overrated attention can be attributed to the increasing challenges related to production node within Kenya. This is consistent with findings from Alila and Atieno (2006), who reported that agricultural policies and development initiatives in Kenya largely focus on improving productivity and the living standards of smallholder farmers. This further expounds on why studies focus on production node since most of the studies strive towards achieving national policies and agenda.

In relation to the reviewed literature, sustainability and climate change have received enormous attention at 33 and 31 percent respectively. Just like other African countries, agriculture still remains the driver of the Kenyan economy. This calls for actions and interventions towards mitigating any disturbance that threatens the flourishing of the agricultural sector in the country. Thus, the attention that has been given to climate change and sustainability studies, and the attention they are yet to receive is not by mistake, rather it is in relation to survival for the fittest. Profitability and market analysis has equally received attention (25%) in Kenya. This is as a result the promotion of agriculture as a business by the government and different development organizations by exposing smallholder farmers to marketing skills and financial literacy.

Vulnerability of Rice Production to Climate Change in Kenya

Climate change has come closer to us in the current times than never before. Previously, it used to appear as though it was foreign, mostly heard and read about from a far. With the current changes in rainfall patterns, rising temperatures and intensifying solar radiation that is felt in the deepest parts of our communities, it is evident that this unfortunate circumstance is fully part of us. According to Bhargava (2018), rainfall and temperature are the most important determinants of agricultural productivity.

Across Africa, over reliance on rain-fed agriculture and poorly developed infrastructure are dominant challenges (Pereira, 2017). Since there are evident changes in these two elements, potential and grave challenges to rice production and food security can be anticipated. Extreme temperatures were found to negatively affect rice yields across all varieties in Mwea and Western Kenya (Nyang'au et al., 2014). According to Kariuki (2016), climate change has affected rice production through reduced amounts of water for irrigation, increased incidences of pests and diseases, flooding of rice fields during the rainy seasons, increased incidences of pesticide and herbicide resistance.

Many rice farmers in Kenya rely on irrigation to grow their crops (Watanabe et al., 2021). Changes in rainfall patterns and increased evapotranspiration rates due to higher temperatures has led to water shortages, making it more difficult to irrigate crops. Extreme weather events, such as floods and storms, leads to soil erosion (Wawire et al., 2021), which further reduce soil fertility and bring about lower yields.

Climate change is expected to lead to extreme weather events (Terdoo & Feola, 2016), all of which can have a negative impact on rice production. Over 80 percent of rice growers in Kenya are smallholder farmers (Atera et al., 2018). Adhikari et al. (2015) notes that these smallholder farmers are the most vulnerable to climate change and variability since they possess minimal technical and financial resources to cope with the challenges associated with climate change.

According to FAO (2021), the rising temperature in Kenya is expected to make rainfall unpredictable and increase incidences of extreme events such as drought and floods. Extreme weather events, such as storms and floods, can also damage rice crops and infrastructure, such as irrigation systems and storage facilities which can further reduce yields and increase production costs. Oort and Zwart (2019) equally report that an increase in global annual temperatures is expected which does not exclude Kenya. They note that this will result to negative impacts on rice production and yields in tropical and hotter areas such as Kenya. The expected increase in drought instances in Kenya, according to FAO (2015) and Makokha et al. (2011), is likely to further reduce the areas under rice production and the total arable land in Kenya. This will imply reduction on the area under cultivation, consequently resulting to reduced annual production volumes.

Vulnerability of Rice Milling Subsector to Climate Change

As earlier noted, climate change and other social and economic factors affect rice production which generates the raw materials for rice milling, the rice processing node becomes affected as well. Among the factors that make rice milling node vulnerable include; inadequate roads and transportation systems (Mitullah et al., 2019) which make it difficult to transport rice from the mills to the markets thus resulting in high post-harvest losses and lowering quality and prices of milled rice received by millers. Rice milling requires significant inputs, including energy, water, and labour, which is costly for small-scale millers. The proposed increase in electricity tariffs by Kenya power from KES 3 to KES 5 which was effected from 1st April 2023 is expected to further dwindle the profitability of rice mills in Kenya.

Importation of superior quality rice significantly compete with locally produced rice and affect the demand and prices for locally milled rice. Rice pests and diseases, such as rice blast and stem borers, cause significant losses to rice producers (Kihoro et al., 2013) and reduce the quality of milled rice. According to Mey and Demontt (2013), birds can cause up to 100 percent losses of rice produced by farmers. This equally affects the volume of paddy sourced by rice millers leading to low level of utilization thus recurrent losses. The rice milling industry in Kenya lacks adequate policy support (Atera et al., 2018), which can limit its growth and development.

Rice requires a lot of water to grow (KALRO, 2015), and climate change has led to unpredictable rainfall patterns in Kenya, leading to water scarcity (Nzau, 2013). This makes it difficult to maintain the required water levels in the rice paddies, which affects the growth and yield of the crop. Increase in extreme weather events such as floods and droughts has been manifested in Kenya (IFRC, 2021). This has damaged rice paddies and milling infrastructure, leading to reduced yields and increased costs of production. Rice milling requires a significant amount of energy, mainly in the form of electricity or fuel (Goyal et al., 2014). Climate change leads to disruptions in energy supply due to factors such as extreme weather events, which affects the milling process and increase the cost of production.

Development Policies and Climate Change in Kenya

This subsection discusses development policies in relation to climate change in two different ways. It recognizes the fact that development policies exacerbate impacts of climate change while at the same time can mitigate impacts of climate change. Development policies in Kenya aim to eradicate poverty, reduce inequality and achieve sustainability (Uma, 2022b). However, there are unintended downsides that come along with development policies and Kenya is not in any way exempted from such circumstances.

Development Policies that Exacerbate Climate Change

Kenya has developed many policies related to economic growth, infrastructure development, and land use that contribute to greenhouse gas emissions, deforestation, and other activities that exacerbate climate change. Transforming Kenya into an industrializing middle income country is one of the key areas of concern of Kenya Vision 2030 (Republic of Kenya, 2013). Large-scale infrastructure projects, such as roads, railways, and airports that have accompanied this initiative, have a significant impact on greenhouse gas emissions. These projects often require the use of fossil fuels for construction and operation, and they also lead to increased land use change, deforestation, and soil degradation.

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Kenya Agricultural Policy of 2021 encourages large-scale commercial agriculture (MoALF&C, 2021), which indirectly incentivizes deforestation for other purposes. Kenya still relies heavily on fossil fuels, particularly for transportation which further worsens the climate change situation in the country. The National Urban Development Policy (NUDP) of Kenya aims at promoting rapid urbanization in Kenya (Ministry of Transport, Infrastructure, Housing and Urban Development, 2016). Rapid urbanization in Kenya has led to increased demand for housing, transportation, and energy.

Development Policies that Mitigate Climate Change

Kenya has implemented a range of climate change related development policies aimed at promoting sustainable development and reducing the country's greenhouse gas emissions. Kenya's National Climate Change Action Plan sets out the country's strategy for adapting to and mitigating the impacts of climate change (Ministry of Environment and Forestry, 2021). The plan includes sustainable land use management, renewable energy development, and promotion of energy efficiency. The Green Economy Strategy and Implementation Plan aims to promote economic growth while reducing greenhouse gas emissions and improving environmental sustainability (Government of Kenya, 2016). The plan includes policies and measures aimed at promoting sustainable agriculture, sustainable forestry, renewable energy, and green infrastructure.

The National Adaptation Plan outlines Kenya's strategy for adapting to the impacts of climate change (Ministry of Environment and Natural Resources, 2016). The plan includes policies and measures aimed at promoting climate-resilient agriculture, water resource management, and disaster risk reduction. Kenya’s National Agriculture Policy includes policies and measures aimed at promoting sustainable agriculture and reducing greenhouse gas emissions from the agricultural sector (MoALF&C, 2021).

Kenya’s National Energy Policy includes policies and measures aimed at promoting the development of renewable energy sources, such as wind, solar, and geothermal power (Ministry of Energy, 2020). Kenya's Forest Conservation and Management Policy purposes to promote sustainable forest management and reduce greenhouse gas emissions from deforestation and forest degradation (Republic of Kenya, 2016). The policy includes measures aimed at promoting reforestation and afforestation, as well as measures aimed at reducing illegal logging and promoting sustainable forest management practices.

Government Efforts to Mitigate Effects of Climate Change on Agriculture

The Kenyan government has implemented several measures to mitigate the impacts of climate change in agriculture. The Kenyan government has promoted the adoption of conservation agriculture practices, such as minimum tillage, crop rotation, and intercropping (Kinyumu et al., 2021). These practices help to reduce soil erosion, improve soil fertility, and increase the water-holding capacity of soils, thereby making agriculture more resilient to the impacts of climate change. The government has promoted the adoption of drought-tolerant crop varieties, such as maize and beans, which are better adapted to the changing climate conditions (Muinga et al., 2019). The government has invested in the development of irrigation infrastructure to help farmers cope with changing rainfall patterns and water scarcity (Mati, 2023). This includes the construction of small-scale irrigation systems, such as dams, ponds, and boreholes, as well as the promotion of water harvesting techniques.

Though to a limited extent, the Kenyan government has provided farmers with weather and climate information to help them make informed decisions about planting, harvesting, and crop management (Muema, 2018). This includes the use of mobile phone apps, radio broadcasts, and community-based weather monitoring systems. The use of renewable energy sources, such as solar and wind power, in rural areas is being promoted (Takase et al., 2021). This reduces the dependence on fossil fuels and helps to reduce greenhouse gas emissions. Overall, these measures demonstrate the Kenyan government's commitment to promoting climate-resilient agriculture and mitigating the impacts of climate change.

Conclusion and Recommendation

Rice milling in Kenya is vulnerable to climate change due to its reliance on consistent water availability and temperature conditions. The production of rice in Kenya is affected by climate change through unpredictable and extreme weather patterns, including prolonged droughts and floods. Droughts have reduced the availability of water for irrigation, leading to reduced rice production. On the other hand, floods most especially from River Nyando have damaged rice paddies and milling infrastructure in Ahero, causing significant losses in the industry.

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Climate change has led to the emergence of new pests and diseases that affect rice crops, reducing the quality and quantity of rice produced. Climate change has also affected the energy sector, which is crucial for rice milling operations, leading to frequent power outages and increased costs of energy. The government has tried to combat the situation through developmental policies, however, lack of effective implementation of the policies aimed at mitigating the impacts of climate change has instead worsened the situation in Kenya.

The vulnerability of rice milling to climate change in Kenya requires urgent measures to adapt to the changing climate. These measures include the adoption of new irrigation technologies, resilient rice varieties, pest and disease management, and the development of alternative sources of energy. Furthermore, the government and other stakeholders should implement policies that support climate resilience in the rice milling industry, including access to climate information and financial support for adaptation measures.

Additionally, there is a need for stronger policy support to promote the growth and development of the rice milling industry, including measures to improve the regulatory environment, reduce taxation, and increase technical support and training for millers. Flood control dam on River Nyando may be a bigger and expensive venture but certainly a long-term viable solution to challenges that it causes in the Ahero region. Finally, promoting climate-smart agriculture practices can help mitigate the impacts of climate change on rice production and milling. Overall, a combination of these solutions can help to mitigate the vulnerability of rice milling to climate change and ensure the long-term sustainability of the rice industry.

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Amaranth Production and Consumption in Kenya: Constraints and Opportunities

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Abstract

Amaranth production and consumption have the potential to enhance the food and nutrition security in Kenya, where the overall food deficit is between 20 percent and 30 percent amidst rainfall and temperature variability. The crop is hardy and grows well under various agro ecological conditions. Its seeds and leaves are edible and nutrient-dense, providing vitamins A, C, iron, zinc, and magnesium among others. Amaranth is however, underexploited in Kenya. In order to tap the benefits derived from amaranth, several production and consumption-related challenges, including exclusive dependence on a few foods such as maize, wheat, and rice and their sifted derivatives that lack important micronutrients as well as consumers' negative perception of traditional crops need to be addressed. Traditional crops, amaranth included, are generally termed 'poor man's food'. Through a systematic literature review and observation method, this paper explores the various constraints (e.g., poor distribution of certified seeds) and opportunities (e.g., emerging niche market) of amaranth production as well as strategies of promoting consumption (e.g., sensitization) of the crop in Kenya. This paper demonstrates that amaranth has the potential to partly offer a solution to challenges of climate variability as well as food and nutrition insecurity in Kenya. Amaranth may be included in Kenya's diets directly, whether in fresh or processed form; as vegetable or grain; as an accompaniment or main dish; as a medicinal herb or fortificant; and indirectly as livestock feed. Promoting the manifold uses of amaranth through channels such as conferences, schools, and media will contribute to better livelihoods among Kenyans.

Keywords: Amaranth, climate variability, food insecurity, Kenya, under-exploited

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Introduction

Globally, the human population is projected to rise from the current 8 billion to around 8.5 billion, 9.7 billion and 10.4 billion in 2030, 2050 and 2100, respectively (United Nations Department of Economic and Social Affairs [UNDESA], Population Division, 2022). Sub-Saharan Africa (SSA) is expected to contribute more than half of the global population increase anticipated by 2050 (UNDESA, Population Division, 2022). The population increase means more food demand. For instance, global cereal and meat demand is projected to increase by 1.03 percent and 1.42 percent per year, respectively, and at 2.43 percent and 3.65 percent in SSA between 2000 and 2050 (Ringler et al., 2010). During the same period (2000 to 2050), international prices of rice, wheat, and maize are projected to increase by 48 percent, 36 percent, and 34 percent, respectively (Ringler et al., 2010).

Agriculture will continue as the leading supplier of the increasing food demand. As such, global crop production should double by 2050 to satisfy the demand for food (Ray et al., 2013). Increasing crop production is, nevertheless, being undertaken in an environment constrained by variability in rainfall and temperature associated with climate change, posing major challenges to the venture particularly in countries such as Kenya that mainly rely on rain-fed agriculture (Pathak et al., 2018). Variability in temperature and change of onset, intensity, duration and frequency of rain positively or negatively influence the optimal crop production (Patrick et al., 2020). For instance, projections point to low yields of wheat, sweet potato and maize while that of millet and sorghum will be high in SSA (Porter et al., 2014). Generally, there have been low yields of staple crops (maize, wheat, rice, and potatoes) in Kenya (Patrick et al., 2020).

Reduced staple crop yields partly contribute to food and nutrition insecurity in Kenya. Ten million, four million, and 1.5 million people in the country are food insecure, chronically food insecure, and continuously require food aid, respectively while 29 percent of children five years and below are stunted (Njora & Yilmaz, 2021). Kenya's overall food deficit which is between 20 percent and 30 percent increases annually (Republic of Kenya, 2019). Besides, overreliance on maize, wheat, rice, and potatoes increases micronutrient deficiencies and related diseases because they lack vitamin A and zinc (Aworh, 2018; Zhao et al., 2022). Moreover, reliance on a narrow spectrum of foods poses the risk of losing agricultural biodiversity, which is helpful in countering malnutrition (Hunter et al., 2019).

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Low cereal production in SSA and Kenya in particular implies more food imports at higher prices to make up for the deficits. World trade in cereals is projected to increase in almost threefold from 253 million metric tonnes in 2000 to 646 million metric tonnes by 2050 (Ringler et al., 2010). SSA is expected to have a net cereal imports increase by a factor of 5 within 50 years (2000 to 2050) (Ringler et al., 2010). In Kenya, average cereal imports in Kcal/day per capita are projected to rise to 1103 in 2050 from 403 between 2001 and 2010 (Chouchane et al., 2018). Higher food prices will depress food demand on final buyers in the longer term, with a decline of 1.5 percent expected in SSA by 2050 (Ringler et al., 2010). The decline in food demand will increase malnutrition rates in an already food-insecure region (FAO & ECA, 2018).

Malnutrition in SSA is further compounded by low intake of vegetables and fruits (Brückner & Caglar, 2016; Muyonga et al., 2020). Worldwide, 3.9 million deaths in 2017 were attributed to low consumption of fruits and vegetables (WHO, 2019). World Health Organization and FAO recommend that at least 400 grams or five servings of 80 grams of fruits and vegetables be eaten daily to benefit from their vitamins, minerals, essential micronutrients, fibre, and proteins (Aworh, 2018). However, the consumption of fruits and vegetables in SSA is a third of the WHO/FAO recommendation (FAO, 2020). In Kenya, the mean daily consumption of fruits and vegetables among young adults (aged 19–30 years) is 3.6 servings (Nyanchoka et al., 2022). Of the vegetables eaten in Kenya, exotic types (e.g., cabbages) are famous compared to amaranth even though their nutrient composition is lower (Table 1) (Muthoni & Nyamongo, 2010; Muyonga et al., 2020). Inadequate consumption of fruits and vegetables exposes Kenyans to non-communicable diseases (Wekesah et al., 2018).

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Table 1: Mean Nutrient Composition (per 100g) of Amaranth Vegetables Compared to Cabbages and Spinach

Nutrient Composition	Amaranth	Cabbage	Spinach
Potassium (mg)	411	-	470
Iron (mg)	8.9	0.7	3.1
Protein (g)	4.6	1.7	3.2
Calories	42	26	-
Carbohydrates (g)	8.2	6.0	4.3
Fiber (g)	1.8	1.0	0.6
Ascorbic acid (Vitamin C) (mg)	64	54	51
Calcium (mg)	410	47	93
Phosphorus (mg)	103	40	-
Carotenoids (Vitamin A) (IU)	6,100	100	8,100
Thiamine (Vitamin B1) (mg)	0.05	0.04	-
Riboflavin (Vitamin B2) (mg)	0.42	0.1	-

Source: Extracted from Muthoni and Nyamongo (2010); Rastogi and Shukla (2013).

Note. – represents missing data

Climate variability, food and nutrition insecurity are a concern in Kenya. As such, the government of Kenya is actively involved in addressing these concerns through increasing large-scale production of maize, potatoes and rice in 700,000 new acres via irrigation (Republic of Kenya, 2019; Republic of Kenya, 2020). Besides irrigation, several adaptation measures that can reduce adverse effects of climate variability including crop diversification, intercropping, planting drought-resistant or tolerant varieties, water harvesting techniques, and food biofortification among others have been documented (Ochieng et al., 2016; Patrick et al., 2020).

This review focuses on one of the climate variability adaptation measures, amaranth production and consumption, yet an underexploited indigenous crop (Chepkoech et al., 2019, 2020; Krause et al., 2019). Amaranth exists in more than 70 species and 400 varieties and grow wildly worldwide, with only a few cultivated in various countries (Aderibigbe et al., 2022). The crop is a C_4 plant, making it efficient in using CO_2 under a wide range of temperatures (from 25 to 40°C), higher light intensity, and moisture stress environments (Mlakar et al., 2010). Therefore, while amaranth thrives at 25°C, it tolerates low (15°C) and high (40°C) temperatures (Ebert, et al., 2011). Although actual data on global production and consumption of amaranth is not available, the contribution of neglected, underexploited and

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underutilized domesticated and undomesticated crops to global food production is approximated to be between 115-120 billion US$ per annum (Singh et al., 2019). Amaranth is a resilient multifunctional plant providing cereals and leafy vegetables with high essential nutritional value (Riggins et al., 2021).

The study contributes to the achievement of Sustainable Development Goal (SDG) number two: End hunger, achieve food security and improved nutrition and promote sustainable agriculture amidst the challenges of low cereal production, high food prices and low intake of vegetables. This review documents the common amaranth varieties in several parts of Kenya, their inherent features, and their uses. It also explores the emerging opportunities and constraints of amaranth production and strategies for promoting sustainable production and consumption of the crop in the country. It then highlights some recommendations in an attempt to make a case for intensified promotion of the inclusion of amaranth in Kenya's diets.

Method and Materials

This study involved a review of published literature on climate variability and amaranth production. The observation method (photographs were taken by author) was also used to enhance information on amaranth farming. The Google Scholar search engine was mainly used to access online literature. The search was limited to a time span ranging from 2010 to 2023 to give the researcher a historical perspective of amaranth production, consumption, constraints, and opportunities in Kenya. Using selected keywords, including 'amaranth production', 'amaranth consumption', and 'climate variability and agriculture', to confine the internet search to the topic at hand, literature that was open access was reviewed. Data collected through observation was incorporated in this paper to provide current information on what is happening in some parts of the country where amaranth is cultivated. A detailed review of rainfall and temperature variability effects on crops as well as amaranth production and consumption with more focus on Kenya is described systematically in the following sections.

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Results and Discussions

Production of Amaranth in Kenya

In Kenya, amaranth grows well under a wide range of agroecological conditions (Alemayehu et al., 2014). The crop grows in poor soils but is best in fertile ones (Ebert, et al., 2011; Kariithi et al., 2018). As such, amaranth is grown in various regions in Kenya, including Kisumu, Vihiga, Nyamira, Bomet, Bungoma, Kakamega, Kisii, Kiambu, Nakuru, Kajiado and Kilifi (Kinyuru et al., 2012; Krause et al., 2019; Ochieng et al., 2019; Nyonje et al., 2022). Although amaranth can thrive on large farms (Patrick et al., 2020), its cultivation in Kenya is mainly by small-scale farmers on small parcels such as kitchen gardens (Plate 1). Besides being cultivated, amaranth grows wildly as a weed (Dizyee et al., 2020; Nyonje et al., 2022).

Fig. 1: Amaranth Growing as a Weed in a Kitchen Garden

Source: Author, April 2023

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Although the total number of amaranth species world over is still unknown (Aderibigbe et al., 2022), a few species (Figure 2) are common in Kenya (Muriuki et al., 2014). The species include *A. dubius*, *A. blitum*, *A. spinosus* (spiked) and *A. hybridus* (red amaranth) mainly grown as vegetables; *A. Cruentus* as grain; and *A. hypochondriacus* as grain and vegetable (Muriuki et al., 2014; Muthoni & Nyamongo, 2010). The varieties go by the following names in Kenya; *Mchicha* (Swahili), *Terere* (Kikuyu), *Ododo/Soisoi* (Luo), *Tsimboga/Livogoi* (Luhya), *Emboga/Emboga Nyerere/Dodo* (Kisii), *Chelwanda/Mborochik* (Kalenjin), and *Logatsi* (Mijikenda) among others (Nyonje et al., 2022). Muthoni and Nyamongo (2010) note that *A. hybridus and A. graecizans* are widespread in the country; *A. dubius* is dominant in the coastal region; *A. sparganiocephalus* in regions occupied by nomadic pastoralists *(*Maasai, Turkana, Samburu, Pokot); *A. lividus* in Kisii, Nyanza and western while A. *spinosus* mainly thrive at the Coast and Western Kenya.

Fig.2: Three Types of Amaranths Common in Kenya
Note: From right to left *A. dubius*, *A. blitum* and *A. hybridus*.
Source: Author, April 2023

Inherent Features of Amaranth

Generally, amaranth has intrinsic features including resistance to drought, tolerance to heavy rainfall and pests and diseases (Chepkoech et al., 2019, 2020). Amaranth can produce a crop

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of edible leaves within two weeks and can mature within 60 days of planting (Aderibigbe et al., 2022). The crop is mainly grown by smallholder farmers for family food and income needs (Kinyuru et al., 2012; Krause et al., 2019). It is cultivated solely or intercropped (Malaba et al., 2018). However, the inherent features vary across the various varieties of amaranth (Muriuki et al., 2014). For instance, compared to other varieties, *A. Cruentus* and *A. blitum* better adapt to poor soil conditions and low soil moisture levels while *A. dubius* is less susceptible to wet/stem rot (Ebert, et al., 2011; Rastogi & Shukla, 2013). The inherent features of amaranth and the rising market demand are attracting more farmers to venture into its production (Krause et al., 2019).

Amaranth is a nutrient-dense crop providing vitamin A, C, iron, calcium, zinc and magnesium, protein, dietary fibre, lipids, unsaturated fatty acids and bioactive compounds such as phytosterols, squalene, fagopyritols, saponins and polyphenols necessary for health body development (Uusiku et al., 2010; Chivenge et al., 2015; Mbhenyane, 2017; Kambabazi et al., 2021). It is, however, important to note that the composition of nutrients varies in different species (Muriuki et al., 2014). For instance, *A. dubius* is a superior source of calcium and iron, while *A. cruentus* has high protein and phytochemicals (Muriuki et al., 2014). *A. dubius* has higher zinc content than *A. cruentus* and *A. hypochondriacus* – making it essential breeding material for amaranth breeders, best preferred by farmers (Fekadu et al., 2020).

The protein found in amaranth is high in the amino acid lysine, which is the key component found in insufficient amounts in maize, wheat, and rice (Alemayehu et al., 2014). This implies that amaranth would act as a suitable complement in the diets of Kenyans. However, it should be noted that the nutrient levels in amaranth are influenced by the ecological environment (Croft et al., 2017; Fekadu et al., 2020).

Consumption of Amaranth in Kenya

Both amaranth leaves and grains are eaten in Kenya (Nampeera et al., 2019). There is a notable increase in the consumption of amaranth in Kenya currently than was the case two decades ago (Fekadu et al., 2020; Krause et al., 2019; Macharia-Mutie et al., 2011; Uusiku et al., 2010). Amaranth is commonly eaten by most rural communities due to its being inexpensive and easy availability rather than the nutritional value (Gido et al., 2017). In addition, positive beliefs concerning the crop such as amaranth boosting blood in the body and milk production for nursing mothers, enhancing eyesight, eliminating marasmus in children, being an appetizer, detoxifying, and relieving constipation and menstrual pain, do promote its consumption (Nyonje et al., 2022).

Amaranth is mainly cooked before eating through boiling, frying or both (Nyonje et al., 2022). The vegetables are prepared either on their own or in combination with other foods such as kale, beans, and meat. Mbhenyane (2017) observes that amaranth is mixed with other vegetables to act as a tenderizer, reduce bitterness, improve flavour, save time for cooking, and increase the food quantity. Amaranth is mainly eaten as an accompaniment for other foods such as rice, but in rare circumstances, it is taken as a main dish (Macharia-Mutie et al., 2011). Including amaranth in diets caters for diversification, essential in achieving nutrient demands in body development. While cooking amaranth vegetables enhances their palatability and digestibility, it destroys microorganisms, minimizes their antinutrient content, it may denature the nutrients (Aderibigbe et al., 2022; Lee et al., 2018). This calls for further research on the best cooking methods.

Despite the improved consumption, some impediments remain to amaranth's full acceptability in Kenya (Okoth et al., 2017) (Figure 3). Several factors work in synergy to inhibit the consumption and, by extension, the cultivation of amaranth. The factors include the consumption of exotic vegetables such as kales, sensory attributes of amaranth, its seasonal availability, consumer's awareness of its nutritional and medicinal benefits, etc. (Gido et al., 2017; Nyonje et al., 2022).

Pests and diseases, poor distribution of quality seed in various parts of the country, uprooting as a harvest technique, and low yields during dry seasons reduce the quality and quantity of the amaranth (Ochieng et al., 2019; Nampeera et al., 2019). During rainy seasons when vegetables are abundant, there are meagre sales coupled with very low prices (Nyonje et al., 2022). Because amaranth vegetables are highly perishable and farmers do not preserve them, they incur postharvest losses.

Emerging Opportunities

With Kenya becoming more vulnerable to climate variability, an increasing population size and transformation of agricultural land to built-up areas, crops that can withstand harsh climatic conditions, produce relatively high yields and thrive in small parcels of land such as

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amaranth (Figure 2) may be the feasible complements or alternatives (Bharucha & Pretty, 2010; Kariithi et al., 2018; Patrick et al., 2020; Onyango et al., 2013). Grain amaranth, being high yielding, fast growing, resistant to drought, and nutrient-dense has the potential to complement staple food crops in Kenya (Alemayehu et al., 2014). Furthermore, amaranth thrives with minimal effort even as weeds and can be intercropped with such crops as kales (Fig. 3) thus optimizing on land use as well as ensuring diet diversification (Malaba et al., 2018).

Fig. 3: Amaranth Growing as Weeds among Kales in a Kitchen Garden

Note. 'Amaranth weeds' are harvested as vegetables before weeding while a few are allowed to continue growing among the kales.

Source: Author, April 2023.

Four (i.e., *A. dubius*, *A. hybridus*, *A. blitum* and *A. cruentus*) of the amaranth varieties found in Kenya have been improved (Ochieng et al., 2019). The improved varieties have large leaves, enhanced palatability, and are more drought-tolerant (Ochieng et al., 2019). Improved amaranth seeds are mainly supplied by Kenya Seed Company (KSC) Ltd, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya Agricultural and Livestock Research Organization (KALRO) and East Africa Seed Company (Ochieng et al., 2019). Availability of improved amaranth seeds presents an opportunity for farmers to grow high-yielding and drought-resistant varieties.

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There is an emerging market niche of consumers who prioritize the nutritional value and safety of their foods in Kenya and beyond (Aderibigbe et al., 2022; Rojas-Rivas et al., 2019; Singh et al., 2019). In Kenya, the niche market comprises high-performance athletes, malnourished children, HIV/AIDS and diabetic patients, people suffering from coeliac disease and those allergic to gluten (Alemayehu et al., 2014; Kinyuru et al., 2012; Muyonga et al., 2014; Nyonje et al., 2022). Besides, there is a rise in demand by urban residents (Krause et al., 2019; Ngenoh et al., 2018). Internationally, developed nations such as Germany import amaranth grains for use in food industries (Aderibigbe et al., 2022). These markets present an opportunity for farmers to exploit.

Amaranth is a feasible fortificant due to its inherent features. Fortification of staple foods has the potential to alleviate micronutrient deficiency and malnutrition problems in Kenya (De Groote et al., 2020; Olson et al., 2021). Amaranth flour has been suggested as a fortificant for foods such as maize (Okoth et al., 2017; Singh & Punia, 2021). Amaranth as a fortificant may be appropriate for financially struggling farmers in Kenya who may find it expensive to buy fortified planting materials or mineral fertilizers (Chadare et al., 2019; Olson et al., 2021). Moreover, poor farmers may neither afford industrial fortified foods for their consumption nor point-of-use fortification which targets specific groups, usually a small percentage, leaving out many in the society (Chadare et al., 2019; Olson et al., 2021). The use of amaranth to fortify foods could enhance the food and nutrient security of lots of people, enhance the utilization of traditional diets as well as promote Kenyan-based food systems and biodiversity.

The manifold uses of amaranth need to be exploited (Figure 4). In an attempt to shed more light on the multiple uses of amaranth, this review was guided by multifunctionality theory. The theory determines the role of agriculture and its structural elements in the modern economy (O'Farrell, 2005). It purports that an economic activity may have multiple outputs including intended and unintended ones (O'Farrell, 2005; Zhichkin et al., 2022). The theory has been widely applied in the study of agriculture and rural development of developed nations such as Russia in advocating for government support of agriculture (Robinson, 2018; Zhichkin et al., 2022).

Although multifunctionality theory may not be wholly replicated in developing countries such as Kenya, it provides a basis for the ideas presented in Figure 4 on amaranth

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farming. Apart from being human food, it is also emerging that amaranth has medicinal value, is an important fodder for livestock, their stalks are used for firewood, it is part of greening the environment, and preserves biodiversity and cultures of Kenyan communities (Muriuki et al., 2014; Nyonje et al., 2022). However, more research is required in order to scientifically establish the medicinal value of amaranth.

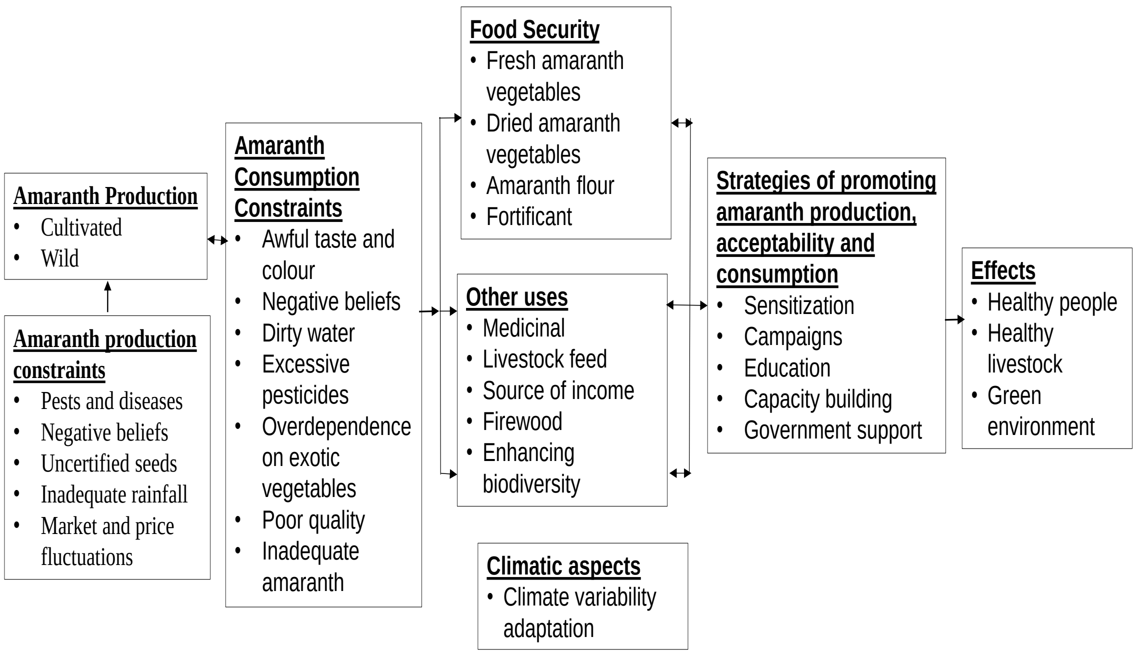

Fig. 4: A Conceptual Model Depicting the Manifold Uses, Production and Consumption Constraints, Strategies of Promoting Production, Acceptability and Consumption, and Effects of Amaranth

Note. A conceptual model developed by author from reviewed literature

Strategies for Promoting Acceptability of Amaranth

Acceptability of amaranth may be shaped by sensitization, education and capacity building. Activities (e.g., circulation of brochures, integrating awareness programmes on local or ethnic radio and television stations, well-coordinated market supply chains) geared towards raising awareness about the nutrient value of amaranth where producers, traders and consumers participate may be beneficial (Gido et al., 2017). Research indicate that such activities have in the past born fruits where ten years after such activities, almost half (45.2%) of participating households in Kenya had increased consumption of traditional leafy vegetables (Gotor & Irungu, 2010).

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Schools are avenues of creating awareness or application of interventions related to enhancing health diets (Hardcastle & Blake, 2016). School eating programmes do incorporate locally available foods in their diets (Bioversity International, 2019). Given the new Competent Based Curriculum (CBC), school-based interventions promoting the diverse importance of amaranth may be undertaken.

In order to achieve sustainability of what is learnt in school, the knowledge or skill should be transmitted to the parents or caregivers (Hardcastle & Blake, 2016). After all, some parents and caregivers are also the producers, buyers, and cooks of food at home. Besides, parents' dietary behaviour partly influences children's food intake (Mahmood et al., 2021; Monterrosa & Pelto, 2017; Scaglioni et al., 2018). Hardcastle and Blake (2016) and Mahmood et al. (2021) note that people seem to be socialized into particular types of eating when they are children and their childhood experiences may continue into adulthood. This observation implies that matters of health diets must go beyond production to encompass socio-psychological aspects.

Conclusion and Recommendations

The review demonstrates that amaranth has the potential to partly offer a solution to challenges of climate variability as well as food and nutrition insecurity in Kenya. Availability of amaranth in fresh or processed form, as vegetable or grain, as accompaniment or main dish, as medicinal herb or fortificant, as human food or livestock feed present opportunities of directly or indirectly having more of it on Kenyans' plates. However, Kenyans need to be incentivized to overcome common prejudices about amaranth and include it in their diets. Kenyans need to transition from production and consumption of a few staple crops and exotic vegetables to the underutilized nutrient-dense foods such as amaranth that thrive with minimal effort within a non-predictable climate variability environment making them readily available in most seasons of the year in many parts of the country. This will help transform Kenya into a greener and healthier country, contributing to the attainment of the SDG number two.

The study recommends an awareness campaign to all the stakeholders in the amaranth value chain including; farmers, traders, consumers, nutritionists, environmentalists, scientists, and policy makers, on the nutritional and biodiversity values of the crop. Concerted effort by all stakeholders in the amaranth value chain to implement the transition from a few staple foods and exotic vegetables to amaranth is encouraged.

The study also advocates for training on appropriate preparation and flavour promoting cooking methods of amaranth that minimally denature nutrients. There is also need to train farmers on the appropriate conservation techniques of surplus amaranth to reduce postharvest losses and ensure its availability during low production seasons.

This paper is mainly based on secondary data. An empirical study to determine the actual servings of amaranth consumed by Kenyans in both rural and urban areas is recommended.

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Exploring the Impact of Climate Change on Metals in Water: A Case Study of Artisanal Gold Mines in Kenya's Lake Victoria Basin

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Abstract

The emissions from fossil fuels, power plants, vehicles, and mining activities have contributed to increased atmospheric carbon levels associated with climate change threat. Carbon enrichment in aquatic habitats impacts pH, salinity, and the mobility of toxic metals like Cu, Cd, Zn, and As. Climate change poses significant challenges for hydrologists, as water resource management systems historically focused on climatic stability. Maintaining the quality of river water, which constitutes a major source of drinking water, is vital for environmental health as well as for the well-being of humans and animals. Consequently, a study was undertaken to examine the presence of potentially harmful metals in water prior to and following the El Nino event of 2020. A total of forty-eight samples of drinking water were collected in triplicate using Van Dorn water bottles from twenty randomly selected sites. The sampling sites, all located in Migori County, included River Kucha and River Migori, both of which discharge into Lake Victoria and pass through the Migori artisanal mining sites. The samples were processed, packed, and sent to Bureau Veritas, Vancouver, Canada, for heavy metal analysis using inductively coupled plasma-mass spectrometry (ICP-MS). The analysed heavy metals included mercury (Hg), chromium (Cr), copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), and arsenic (As). Water mercury levels were found to be elevated both before October, 2016 and after El Nino in October, 2021. The study indicated that mean metal concentrations in water samples decreased in the following order: Zn >Pb >Cu >Cr >As >Cd >Hg. The analysed metals exhibited concentrations higher than the permissible limits by WHO for drinking water. The results of the ecological risk assessment indicated that there is an urgent need to prioritize the control and management of heavy metal contamination and the associated risks in the studied rivers and water sources. Additionally, it is crucial to

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maintain ongoing monitoring of potentially harmful metal levels in order to mitigate the unnecessary risks associated with their toxic effects. Importantly, the analysis revealed that the levels of heavy metals, in general, were elevated after the El Nino event compared to the period prior to it.

Keywords: Ecological risk estimation, EL Nino, heavy metals, ICP-MS, water pollution

Introduction

The presence of potentially harmful metals in the environment is a matter of global concern. When the concentration of metals exceeds acceptable levels, they are regarded as pollutants and pose significant risks to the environment (Kim et al., 2019; Zhang et al., 2020). Heavy metal pollution is attributed to various human activities, and multiple studies have demonstrated the significant contribution of industrial operations in intensifying metal concentrations. Consequently, this amplification of metal levels due to mining activities leads to severe environmental issues (Sharma et al., 2020). Heavy metals can easily aggregate in the water and sediment and may create lethal effects on aquatic organisms as well as on human expanded by food chains (Chen & Luo, 2019; Khan et al., 2019).

Climate change can have a significant impact on heavy metal concentration in drinking water in gold mining regions, such as Migori County in Kenya. Climate change-induced changes in rainfall patterns and temperatures can affect the concentration, speciation, mobilization and transport of heavy metals in water bodies, leading to increased levels of heavy metal contamination in the environment (Jarsjö et al., 2020), and thereafter in humans through the food chain. The possible increased threats of flooding caused by climate change has ramifications for the inundation of polluted land, increasing the likelihood of pollutants being remobilized in flood water and contaminated sediment and water reaching the freshwater and marine environment.

According to a study conducted by Crawford et al. (2022), the occurrence of intense flood events brings about significant threats to human and environmental well-being due to the re-release of pollutants. One study conducted in Migori County found that climate change has contributed to increased heavy metal contamination in water resources in the area, with mining activities exacerbating the problem (Odhiambo et al., 2020). The study found high

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levels of heavy metals such as lead, cadmium, and mercury in water samples taken from the area, which pose a significant risk to human health and the environment.

Another study conducted in neighbouring Tanzania also found that climate change has contributed to increased heavy metal contamination in water resources in gold mining regions in the country (Mwakalobo et al., 2018). The study found that changes in rainfall patterns and temperatures have led to increased erosion and transport of heavy metals from mining sites to nearby water bodies, leading to elevated levels of heavy metal contamination in drinking water sources. Furthermore, a study conducted in Ghana found that climate change can affect the quality of groundwater resources in gold mining regions, with increased temperatures and reduced rainfall leading to increased levels of heavy metal contamination in groundwater (Asumadu-Sarkodie et al., 2018).

Migori County in Kenya is a region rich in gold deposits, and the mining activities in this region have been associated with the release of heavy metals into the environment. This has led to concerns about the potential impact of heavy metal contamination on human health and the environment. In recent years, there have been indications that the region is experiencing changes in climate, including increases in temperature and changes in precipitation patterns (MoALFC, 2021). This has led to concerns about the potential impact of climate change on heavy metal concentration in water in the region. Therefore, this study aimed to evaluate the metal concentrations (Hg, Cd, Cr, Cu, Zn, As and Pb) in water in Migori gold mines in the Lake Victoria basin, Kenya and to assess the intensity of contamination.

Materials and Methods

Study Area

This study focused on the gold mines situated in Migori County, which is located in the southwestern part of Kenya's Lake Victoria basin. The study area, approximately 309 km away from Kenya’s capital city Nairobi, possesses geographical coordinates of latitude -1.070698 and longitude 34.475272 (Table 1) Migori, Kenya, is positioned approximately 262.1 kilometres west of Nairobi. The region experiences an average annual temperature of 25.0°C, along with an annual precipitation of approximately 1521 mm. The study location is characterized by artisanal gold mining activities and subsistence agricultural practices. The sampling took place in the years; 2016, 2017, 2019, 2020 and 2021.

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Figure 1 depicts the map showcasing the position of Migori County within Kenya, as well as the sampling sites. The study employed a systematic approach to ensure the uniformity of sampling points throughout a five-year period. Utilizing GPS technology, precise coordinates for each sampling site were determined, establishing it as the primary method for accurate location. Furthermore, a centralized digital database was established to meticulously store essential information about each site, including GPS coordinates, unique identifiers, details regarding physical markers, and other relevant data. This methodological framework not only facilitated consistent sampling across the study duration but also provided a reliable foundation for data management and analysis.

Table 1: Global Positioning System (GPS) of Sampling Points in the Study Area, Migori, Kenya

Sampling Points	Longitudes	Latitudes
	34.2268	-1.0115
	34.2271	-1.0137
	34.2382	-1.0147
	34.2584	-1.0123
	34.2739	-1.0218
	34.2882	-1.0290
	34.2889	-1.0301
	34.3215	-1.0314
	34.3453	-1.0468
	34.3003	-1.0069
	34.2901	-0.9882
	34.2928	-0.9889
	34.2904	-0.9887
	34.2780	-0.9813
	34.2791	-0.9820
	34.2669	-0.9806
	34.2605	-0.9823
	34.2559	-0.9903
	34.2421	-0.9934
	34.2728	-1.0086

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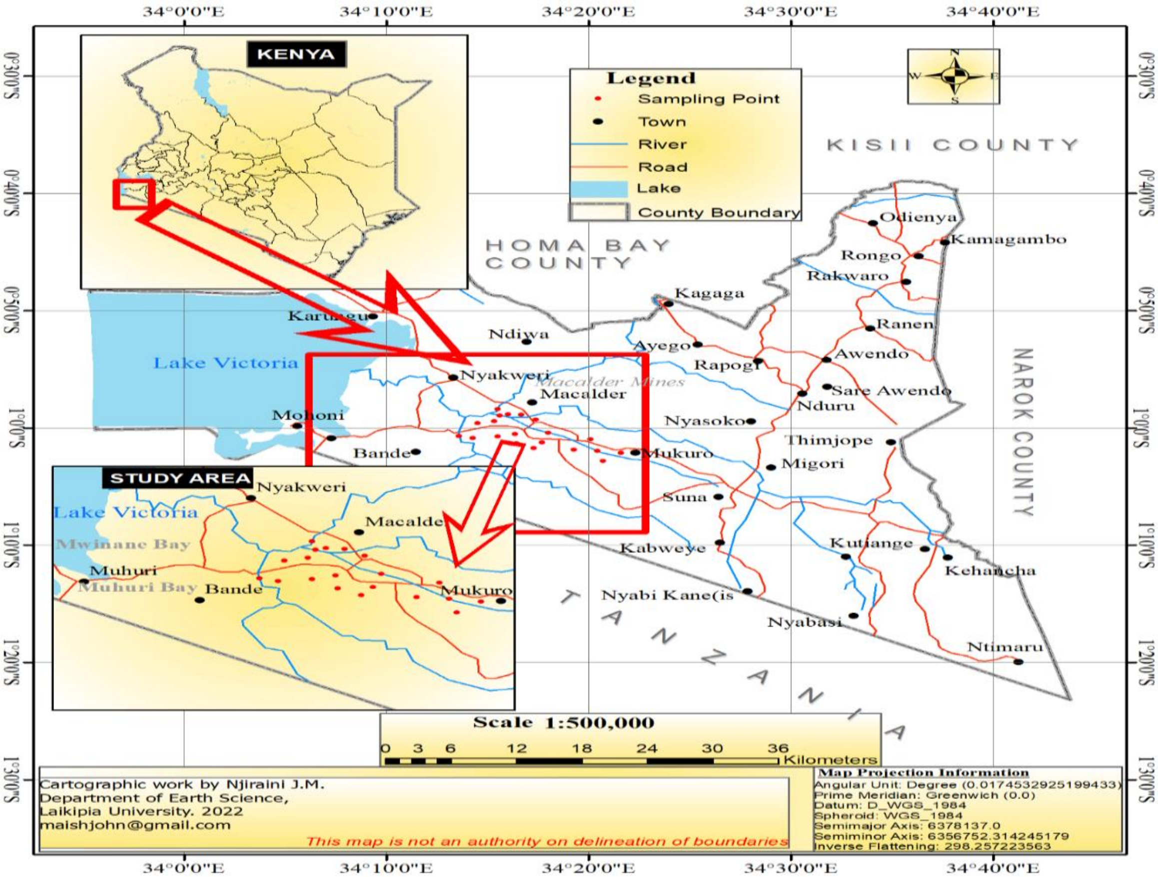

Fig. 1: Map of Kenya Depicting the Geographical Location of Migori County and the Sampling Sites

Sample Collection and Analysis

Field observations were conducted to document changes in the climate (Rainfall, pH, salinity, and temperature) and identify potential changes in heavy metal concentration in water. Water samples were collected from different sampling sites in the artisanal mining sites in Migori County in October of each year (2016, 2017, 2019, 2020 and 2021), to analyse them for heavy metal concentration variation. Use of statistical tools such as ANOVA was employed to analyse the data obtained from water samples and identify any significant changes in heavy metal concentration that can be linked to climate change events such as rainfall, pH, salinity, and temperature. Laboratory analysis was done on water samples to determine the composition or species of the heavy metals.

A total of 48 water samples were collected from 20 sites in 2016, 2017, 2019, 2020 (El-Nino) and 2021. About 100 ml of water samples were collected in triplicates using a Van Dorn water sampler at a depth of 20cm. To preserve the samples, 2 ml of 100 percent

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concentrated HNO_3 was added to each sample, acidifying them. The acidified samples were then stored in the laboratory at 4°C. The metal concentrations in the water samples were determined using inductively coupled plasma-mass spectrometry (ICP-MS)- ICPMS-2030 series at Bureau Veritas Laboratory in Canada.

Statistical Analysis

Statistical tools were used to analyse the data collected from laboratory analysis and identify any significant changes in the concentration of the heavy metals that can be linked to climate change events. Additionally, a historical analysis of heavy metal concentration in water in the study area over a five years' period of time was assessed to provide insights into how heavy metal concentration has changed over time. Descriptive analysis was conducted using SPSS 23 software. Furthermore, a one-way ANOVA was performed to examine the significant differences among the metal concentrations in water samples for the selected seasons, with a significance level set at $p < 0.05$. The normality test for the elements was conducted using the Kolmogorov-Smirnov and Shapiro-Wilk tests (Razali & Wah, 2011), while the homogeneity of data was evaluated using Levene tests (Pardo-Fernández, et al., 2020). In cases where the data variables did not exhibit normality or homogeneity, the Kruskal-Wallis test was utilized (Huang & Pei, 2020).

Degree of Contamination (Cd) with Metals in Drinking Water

The degree of contamination (Cd) of heavy metals in the environment is a critical concern due to their potential harmful effects. Numerous studies have investigated the levels of heavy metal contamination in various environmental compartments, such as water, soil, and biota. For instance, a study by Li et al. (2021) assessed the contamination of heavy metals in urban soils and found elevated concentrations of lead (Pb), cadmium (Cd), and other metals exceeding the recommended limits. Similarly, research conducted by Wang et al. (2020) focused on the contamination of heavy metals in aquatic ecosystems, revealing significant accumulations of mercury (Hg), arsenic (As), and other metals in water bodies, indicating a potential risk to aquatic organisms and human health. These findings underscore the importance of monitoring and mitigating heavy metal contamination to safeguard environmental and human well-being.

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In this study, degree of contamination (Cd) of studied metals was calculated using the following equation: (i) (Sharifi et al., 2016).

$$Cd = \frac{C_i sample}{Cref} \quad (i)$$

Where,

C_i is the heavy metal concentration in water samples; C_{ref} is the reference value of the element (WHO, 2017a).

Estimated Daily Intake (EDI) of Metals through Drinking Water

The estimated daily intake of metals in drinking water is a critical factor in assessing health risks. It helps determine if metal levels are within acceptable limits and guides the development of guidelines for safe water quality. Monitoring and managing this intake allow authorities to mitigate risks and protect public health. Overall, it provides a quantitative assessment for decision-making in water quality management.

To calculate the estimated daily intake, factors such as the concentration of metals in drinking water, daily water consumption rates, and body weight were considered. The estimated intake was compared to established regulatory limits or reference doses to evaluate the potential health risks associated with metal exposure. The risk assessment of specific elements aims to evaluate their exposure and potential for accumulation in the human body as described in ATSDR (2019).

In the context of water samples collected, two distinct pathways were considered for element exposure; ingestion, which occurs through the intake of water (Rodríguez-Seijo et al., 2021); and dermal contact, which happens through skin contact (Kwon & Yang, 2020). To assess the potential health hazards associated with these exposure pathways, the US Environmental Agency has established specific formulas. Equations (ii) and (iii) in the ATSDR (2019) report represent the calculation methods utilized for determining the human health hazard related to ingestion and dermal contact absorption, respectively.

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$$\text{EDI (ingestion)} = \frac{CM \times EF \times ED \times IR}{BWt \times AT} \quad \text{(ii)}$$

$$\text{EDI (dermal)} = \frac{CM \times SA \times KC \times EF \times ED \times ET \times ABS}{BWt \times AT \times 10^6} \quad \text{(iii)}$$

where,

CM denotes metal concentration (mg/kg); EF represents exposure frequency: 365 days per year; and ED indicates exposure duration: 70 (adult) and 6 (child). The ingestion rate (IR) is 30 L/d, and the body weight is 70 for adults and 15 for children. AT is the element's average time: 365 x ED d for non-carcinogenic elements and 365 x 70 for carcinogenic elements. SA is the skin surface area for interaction with the environment: 5700 cm^2/d (adult) and 2800 $cm^{2/}$d (child); The permeability factor for dermal contact is KC: 0.001cm/hour; the exposure duration/time is ET which is 24 g/d; the proportion of dermal absorption presented as ABS is 0.03 (for As) and 0.001 (for the other metals studied) while the conversion factor is 10^6 (USEPA, 2011, ATSDR, 2019).

Results and Discussion

Mean Concentrations of Heavy Metals in Drinking Water Samples

The ICP-MS technique was employed to analyse the heavy metal levels in the water samples obtained, and the average metal concentrations in the samples are provided in Table 2. The findings of this investigation demonstrated a decline in metal concentrations in the following sequence: zinc (Zn) > lead (Pb) > copper (Cu) > chromium (Cr) > arsenic (As)>cadmium (Cd) > mercury (Hg) for the year 2020. According to Table 2, the average concentrations of all the studied metals exceeded the recommended drinking water standards set by the World Health Organization (WHO, 2017a).

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Table 2: Comparison of Mean Concentrations (mg/L) of Heavy Metal in Water Samples

Elements	Mean (mg/L) 2020 El-Nino event	Maximum allowable concentration (WHO, 2017a)
Hg	0.19±0,015	0.002
Cr	16.8±0.011	0.005
Zn	279±0.002	3.00
Cu	30.3±0.013	2.00
Pb	108.7±0.022	0.005
Cd	5.18±0.031	0.001
As	13.1±0.011	0.001

Heavy Metal Concentration and Climate Change (Temperature and Precipitation)

The findings of the study revealed a possible relationship between rising temperatures, declining precipitation, and an upward trend in heavy metal concentrations in drinking water samples from the Migori gold mining area. The results are shown in Table 3, which presents the average concentrations of heavy metals before and after the El Niño event in 2020 with a descending order of magnitude as Zn >Pb >Cu >Cr >As >Cd >Hg.

Table 3: Mean of Heavy Metal Concentrations in Water Samples Collected through the 2016-2021(El-Nino Event Year 2020)

Elements	**Mean (mg/L): of the years 2016, 2017, 2019, 2020, and 2021**							Rank	MAC (WHO, 2017)
	2016	2017	2019	**Mean 2016-19**	2020	2021	**Mean (2020-21)**		
Hg	0.01	0.11	0.16	**0.093**	0.19	0.18	**0.25**	7	0.002
Cr	14.0	12.6	15.6	**14.06**	16.8	19.3	**18.05**	4	0.005
Zn	178.2	212	272	**220.7**	279	393.7	**336.35**	1	3.00
Cu	3.3	9.1	20.6	**11.0**	30.3	70.8	**37.06**	3	2.00
Pb	4.7	8.3	103.7	**38.9**	108.7	143.0	**125.85**	2	0.005
Cd	0.12	0.38	0.58	**0.36**	5.18	3.36	**4.27**	6	0.001
As	2.4	2.8	2.9	**2.07**	13.1	12.9	**13.0**	5	0.001
MAC		Maximum allowable concentration							

The metal historical data was collected by the researcher in the indicated years. Secondary data on temperature and rainfall in the months of October collected in 2016, 2017, 2019, 2020 and 2021 are indicated in appendices 1-5 (Grosell, 2011). The data was compared to the recorded observed values of the studied heavy metals. The findings revealed that there

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are observable increases in heavy metal concentrations which can be attributed to changes in temperatures and precipitation in the study area for the period 2016-2021.

This is consistent with findings from other studies that have shown that increases in temperature and changes in precipitation patterns lead to increased leaching of heavy metals from soils into water sources (Wijngaard et al., 2017). The researchers observed that increasing warmth and decreased precipitation were related with greater amounts of heavy metals in water samples, which is similar with the finding by Adhikari and Khanal (2019).

This shows that climate change is increasing the region's heavy metal pollution. In addition to variations in heavy metal concentrations, the study revealed substantial changes in the composition of heavy metals in water. Some metals, such as Zn, Pb and Cu., increased in concentration more than others, such as Hg and Cr (Table 3). This is consistent with prior research, which has demonstrated that various heavy metals have distinct mobilities and are influenced differently by changes in climatic factors (Ponting et al., 2021). These findings are significant since heavy metal poisoning can have detrimental effects on human health and the ecosystem, as well as contribute to long-term environmental deterioration (Briffa et al., 2020).

Changes in Heavy Metal Composition

In addition to alterations in the levels of heavy metals, the research unveiled that climate change has also influenced the composition of heavy metals present in water. The study revealed that certain metals; namely Pb, Zn and Hg experienced a more pronounced elevation in concentration compared to others such as chromium and copper (see tables 2 & 3). Similar observations were reported by Adhikari and Khanal (2019) and Obasi and Akudinobi (2020). These findings suggest that different heavy metals are influenced disparately by shifts in climate variables, such as temperature increases and decreased precipitation.

The observed increase in concentrations of Pb, Zn and Hg may be attributed to various factors influenced by climate change. For instance, rising temperatures can accelerate the weathering of geological formations, leading to the release of these metals into water sources (Xing et al., 2022). Further, Xing et al. (2022) observed that reduced precipitation can result in a higher concentration of heavy metals in water due to decreased dilution effects. Additionally, changes in the pH and redox conditions of water bodies influenced by climate change can also contribute to the altered composition of heavy metals in the study area.

Understanding these differential responses of heavy metals to climate change is crucial for assessing and mitigating potential risks to aquatic ecosystems and human health. By identifying the metals that are most affected, appropriate management strategies can be implemented to minimize their impact and ensure the safety of water resources. Future research should continue to explore the intricate relationships between climate change, heavy metal concentrations, and their ecological consequences.

Implications of Climate Change on Studied Heavy Metal Toxicity

While the study did not directly investigate the influence of climate change on the toxicity of metals in water within Migori County, the findings regarding the elevated concentrations of heavy metals carry significant health implications, particularly in light of the observed rise in temperatures and decrease in precipitation indicated by secondary data for the region. The study area has experienced a general pattern of increasing temperatures and reduced rainfall over the years, except for the year 2020. Climate projections indicate that Migori County (Figure 1) will remain susceptible to drought and heat stress, both of which can negatively affect agricultural and livestock production. The average duration of dry periods between 1985 and 2015 was 10 days, and this is projected to increase to 13 days by 2050, according to the Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALFC, 2021).

Additionally, considering the observed concentrations of heavy metals in the water samples, the combination of increasing temperatures and low precipitation could potentially exacerbate the toxicity of these metals. Elevated temperatures can enhance the transformation of certain metals into more toxic forms, increasing their potential impact on ecosystems and human health. Moreover, the reduced precipitation can lead to decreased water volume and increased concentrations of heavy metals in water bodies, intensifying their potential adverse effects (Xing et al., 2022). The limited availability of water resources during dry periods may also result in the consumption of contaminated water, further increasing the risk of exposure to toxic metals (WHO, 2017b).

It is important to note that the specific interactions between climate change, heavy metal concentrations, and their toxicity are complex and may vary depending on the characteristics of each metal, as observed by Amanullah et al. (2020). Further research is needed to fully understand the combined effects of climate change and heavy metal

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contamination in order to implement effective mitigation strategies and safeguard the well-being of both ecosystems and human populations in Migori gold mines.

The toxicity of Hg can be modulated by various factors such as pH, salinity, and temperature. Increased temperature can potentiate the conversion of inorganic mercury to the more toxic form, methylmercury (Briffa et al., 2020). However, the impact of pH and salinity on Hg toxicity can vary depending on the specific environmental conditions (Rebolledo et al., 2021). Similarly, the toxicity of Cr can be shaped by pH, although the response to changes in salinity and temperature is less definitive. According to Ferreira et al. (2020), Cr(VI) species generally exhibit greater toxicity than Cr(III), and the prevalence of each species can be contingent upon pH.

Copper toxicity can be influenced by pH and salinity, while the significance of temperature is comparatively lesser. Acidification (lower pH) can amplify the bioavailability and toxicity of copper, whereas elevated salinity levels can ameliorate its toxicity, as indicated by Rebolledo et al. (2021). The toxicity of Cd is known to be influenced by pH and salinity. Acidic conditions (lower pH) can heighten the solubility and bioavailability of Cd, thereby augmenting its toxicity, while increased salinity can mitigate its toxic effects to some extent (Costa et al., 2020).

Zinc toxicity is generally not substantially altered by changes in pH, salinity, or temperature within typical environmental ranges. However, extreme pH conditions or exceedingly high temperatures can exert an impact on its toxicity (Rebolledo et al., 2021). Lead toxicity can be impacted by pH and salinity. Acidification (lower pH) and reduced salinity can escalate the solubility and bioavailability of lead, consequently intensifying its toxicity (Costa et al., 2020). The toxicity of As can be shaped by pH, although the response to changes in salinity and temperature is less definitive. Under alkaline conditions (higher pH), the solubility and bioavailability of arsenic can escalate, thereby rendering it more toxic (Rebolledo et al., 2021).

According to published literature, it has been observed that certain heavy metals can exhibit increased toxicity under specific climate conditions (Kumar et al., 2018). Moreover, available evidence suggests that climate change has influenced the toxicity of heavy metals in water, leading to alterations in their bioavailability and toxicity (Fang et al., 2019). Although pH, salinity and conductivity of the water samples was not determined in this study,

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published literature show that these parameters have an impact on the toxicity, distribution and concentration of heavy metals in water (Senze et al., 2023). Parameters such as pH, salinity and conductivity of the water are influenced by climate changes which in turn has an impact on the concentrations of heavy metals in water (Frogner-Kockum et al., 2020). These changes in climate variables have the potential, therefore, to elevate the toxicity, mobility, and availability of heavy metals in the food chain, posing risks of heavy metal poisoning to the environment, animals, and humans.

Ecological Risk Calculation

The Risk Quotient (RQ) formula was used to estimate the ecological risk. The RQ compares the exposure concentration of the contaminant to an effect threshold (Zhang et al., 2017). The following equation was used:

RQ = Exposure Concentration (EC) / Effects Threshold (ET)

Where:

1) Exposure Concentration (EC) represents the concentration of the contaminant in the water sample.
2) Effects Threshold (ET) refers to the concentration below which adverse effects on aquatic organisms are not expected to occur. This threshold can be derived from toxicity data or established guideline values.

The resulting RQ value indicated the potential risk level. If RQ is less than 1, it suggests that the contaminant concentration is below the effects threshold and is considered low risk. On the other hand, an RQ greater than 1 indicates a potential risk, suggesting that adverse effects may occur.

In this study, the ecological risk calculation for water samples indicated that the levels of heavy metal contamination and associated ecological risks were relatively high compared to the reference values provided in environmental guidelines (WHO, 2017b). The calculated ecological risk was found to be one to a hundred fold orders of magnitude higher than the established low reference values. This implies that heavy metal contamination and ecological risks is a highly significant concern in this study area now as well as for future pollution

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control and management plans for the drinking water sources including the rivers. It is important to note that continued monitoring of heavy metals is necessary to prevent the potential risks that arise and to ensure the ongoing protection of the environment and associated ecosystems as recommended by Li et al. (2019) and Yu et al. (2018).

Degree of Contamination (Cd)

Degree of contamination was done to assess the degree of pollution by metals and is reported as contamination factor (CF). Among the studied metals, Cr, Cd, Pb, As were shown to have very high contamination in the study area (Table 4).

Table 4: Contamination Factor of Heavy Metals in Water Categorized for Aquatic Life (CCME, 2007)

Elements	Average conc (mg/L)	ERA	Aquatic life permissible limits (mg/L)	WHO, 2017a MAC	Aquatic life		Calculated EDI
					CF	Degree of contamination	
Hg	0.13	65	0.002	0.002	65	High	**3.9**
Cr	18.46	9.3	2	0.005	3692	Very high	**55.3.8**
Zn	266.98	8.899	30	3.00	88.99	High	**80.09**
Cu	26.82	6.705	4	2.00	13.41	Moderate	**60.8**
Pb	73.68	10.52	7	0.005	14736	Very high	**78.9**
Cd	1.924	1.069	1.8	0.001	1924	Very high	**26.9**
As	6.82	6820	0.001	0.001	6820	Very high	**18.45**
ERA	Ecological risk assessment= Risk Quotient						
EDI	Estimated dietary intake						
MAC	Maximum allowable concentration						

Estimation of Daily Intake (EDI)

In accordance with the description provided by Kasozi et al. (2019), this study employed equations (ii) and (iii) to estimate the daily intake (EDI) for the selected pathways. The findings of the study demonstrated that the daily intakes of heavy metals followed the following descending order: Zn > Pb>Cu> Cr> Cd> As> Hg (see table 4). These findings indicate that Zn had the highest intake value through the ingestion route for all consumers. The significance of the ingestion pathway in terms of metal intake aligns with previous literature findings (Proshad et al., 2020; Dash & Kalamdhad, 2021). These studies have also highlighted the importance of the ingestion route as a major contributor to heavy metal intake.

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The daily intake of heavy metals through the ingestion pathway is of significant concern due to the potential health risks associated with chronic exposure. Elevated levels of Hg, Zn, Cr, Zn, Cu, As and Cd in water sources can lead to various health issues, including gastrointestinal problems, organ damage, and increased susceptibility to certain diseases (Teschke, 2022). Understanding the relative intake of heavy metals through different pathways, such as ingestion, is crucial for assessing human exposure and managing health risks. It allows for the development of targeted strategies to minimize exposure and safeguard public health. Further research and continuous monitoring are warranted to assess the potential health risks posed by heavy metal intake through the ingestion pathway and to ensure the implementation of appropriate control measures.

Conclusion and Recommendations

The study findings provide valuable insights into the contamination characteristics of heavy metals in drinking water from various water sources that drain into Lake Victoria within the Migori gold mining areas. It was observed that the mean concentrations of all detected heavy metals in the research locations exceeded the acceptable limits set by the World Health Organization (WHO, 2017a). The mean concentrations of heavy metals under study exhibited a noticeable decline before the El Niño period in comparison to the post-El Niño period (2021). This variance can be attributed to an increase in temperatures and an overall decrease in precipitation during the post-El Niño period. These climatic changes may have facilitated the mobilization of heavy metal concentrations into water systems, providing a plausible explanation for the observed shift in metal levels. Water ecological risk analyses revealed that the predicted hazards were 1 to more than 100 times higher than the recommended limit values or reference values. Additionally, the study underscored the significance of ingestion pathways in determining the daily intake of heavy metals (EDI) in the human body.

While the study successfully explored the impact of climate change on heavy metals concentration in artisanal gold mining areas in Migori, Kenya, it is recommended that future research endeavours to delve into the specific influence of temperature variations and rainfall amounts on the raised concentration of heavy metals in these regions. This targeted investigation would provide a more nuanced understanding of the climatic factors contributing to heavy metal contamination in the context of artisanal gold mining.

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Furthermore, assessing the interplay between climatic conditions and mining practices can inform adaptive strategies and sustainable environmental management approaches for these areas. To complement this research, it is also suggested to consider studying the effectiveness of regulatory policies in mitigating heavy metal pollution from gold mining activities to ensure a comprehensive and actionable approach to environmental sustainability.

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Appendices

Appendix 1: Temperature and Rainfall for Year 2016

Temperature	Max	Average	Min
Max Temperature	28.0°C (82.4°F)	26.23°C (79.21°F)	23.0°C (73.4°F)
Avg Temperature	23.0°C (73.4°F)	22.29°C (72.12°F)	20.0°C (68.0°F)
Min Temperature	17.0°C (62.6°F)	15.39°C (59.7°F)	13.0°C (55.4°F)
Dew Point	Max	Average	Min
Dew Point	16.0°C (60.8°F)	13.68°C (56.62°F)	12.0°C (53.6°F)
Precipitation	25.8mm | 1.02in	7.61mm | 0.3in	0.2mm | 0.01in

Appendix 2: Temperature and Rainfall for Year 2017

Temperature	Max	Average	Min
Max Temperature	31.0°C (87.8°F)	27.68°C (81.82°F)	20.0°C (68.0°F)
Avg Temperature	25.0°C (77.0°F)	22.45°C (72.41°F)	19.0°C (66.2°F)
Min Temperature	18.0°C (64.4°F)	16.45°C (61.61°F)	14.0°C (57.2°F)
Dew Point	Max	Average	Min
Dew Point	17.0°C (62.6°F)	14.32°C (57.78°F)	10.0°C (50.0°F)
Precipitation	32.9mm | 1.3in	8.15mm | 0.32in	0.0mm | 0in

Appendix 3: Temperature and Rainfall for Year 2019

Temperature	Max	Average	Min
Max Temperature	27.0°C (80.6°F)	25.23°C (77.41°F)	22.0°C (71.6°F)
Avg Temperature	22.0°C (71.6°F)	21.19°C (70.14°F)	20.0°C (68.0°F)
Min Temperature	18.0°C (64.4°F)	15.58°C (60.04°F)	14.0°C (57.2°F)
Dew Point	Max	Average	Min
Dew Point	17.0°C (62.6°F)	15.06°C (59.11°F)	12.0°C (53.6°F)
Precipitation	19.8mm | 0.78in	5.28mm | 0.21in	0.0mm | 0in

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Appendix 4: Temperature and Rainfall for Year 2020

Temperature	Max	Average	Min
Max Temperature	30.0°C (86.0°F)	27.13°C (80.83°F)	20.0°C (68.0°F)
Avg Temperature	24.0°C (75.2°F)	21.74°C (71.13°F)	19.0°C (66.2°F)
Min Temperature	18.0°C (64.4°F)	15.58°C (60.04°F)	14.0°C (57.2°F)
Dew Point	Max	Average	Min
Dew Point	17.0°C (62.6°F)	15.06°C (59.11°F)	12.0°C (53.6°F)
Precipitation	27.6mm | 1.09in	5.5mm | 0.22in	0.0mm | 0in

Appendix 5: Temperature and Rainfall for October, Year 2021

Temperature	Max	Average	Min
Max Temperature	30.0°C (86.0°F)	27.68°C (78.22°F)	24. 3.0°C (73.4°F)
Avg Temperature	25.0°C (77.0°F)	22.26°C (72.07°F)	20.0°C (68.0°F)
Min Temperature	19.0°C (66.2°F)	16.61°C (61.9°F)	15.0°C (59.0°F)
Dew Point	Max	Average	Min
Dew Point	17.0°C (62.6°F)	14.71°C (58.48°F)	10.0°C (50.0°F)
Precipitation	33.5mm | 1.32in	12.49mm | 0.49in	0.0mm | 0in

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Optimizing a Hybrid Round-Bottom Triangular Open-Channel For Storms

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Abstract

According to the Fluid Flow Equation, the mass flow rate of a fluid is the product of its density, area and velocity. Fast flowing storm water could therefore cause a sudden increase in fluid velocity and flooding, an increasingly common challenge as the effects of global warming become more pronounced. These might overshoot certain desirable thresholds and damage the channel or canal, by scouring. Similarly, the Continuity Equation guarantees that the velocity of a fluid decreases the closer a location is from the bottom. This implies a converse danger of siltation when the speed of flow is too sluggish. For that reason, channel designers carefully choose shapes with dimensions which maximize discharge, while keeping siltation in check. They also seek to slow down the velocity of the channel's flow by making it dissipate much of its load in case of an overflow. This can be partially achieved by an appropriate design of the area above the channel. Meta-heuristic, nondominated sorting genetic algorithms, ant-colony optimisation, differential evolution algorithm (DEA), sequential quadratic programming (SQP) and Lagrange multipliers are some of the methods deployed in minimising the cost function subject to the cross-section of a channel. In practice, channel design hydrodynamics and engineering will involve more parameters than those that this paper covers, including the type of construction materials used to line the channel. Several studies have shown that for a given discharge value and for all slopes, the total cost of construction of a compound triangular cross-section with a rounded bottom is always less than the cost of trapezoidal cross-sections. This paper assumes other factors optimum and applies a purely mathematical approach to determine the best round bottomed triangular open channel design which additionally decreases velocity fluctuations during storms.

Keywords: Discharge, hydraulic radius, Manning equation, open channel, wetted perimeter

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Introduction

The main difference between fluid flowing in a closed pipe (*full-bore*) and the other type of flow categorised as *open-channel* is that the latter has a free and exposed surface that is subject to atmospheric pressure, while in the former, the flow is determined entirely by solid boundaries. Wahome (2014) gives a more detailed comparison of the two flows. Familiar open-channels flows include rivers and streams which are *natural*, while canals, flumes, spillways are examples of *artificial* channels.

The *hydraulic efficiency* of a channel depends on its shape. Therefore, the channel shape which provides maximum discharge for a fixed bed slope, roughnes and fixed area is the most efficient. According to Massey and Smith (2006), the formulae of Manning and Chezy among others predict that for a uniform flow with a given bed gradient, the hydraulic mean depth m affects the factors which influence channel efficiency such as discharge (Q), mean velocity, roughness and cross-sectional area. The hydraulic mean depth, m, is defined as the ratio of the flow area A to the wetted perimeter, P. The less the wetted perimeter, the greater the m and the discharge, and the less the cost of lining materials.

It has been established in open-channel flow studies that the semi-circular bottom gives the maximum hydraulic mean depth according to Douglas et al. (2001), but in practice this shape is useful only for small channels since some other factors such as the need for a reasonable angle of repose for granular banking material, relative ease of construction and cost excavation often override. Trapezoidal channels, which include the triangular and rectangular shapes, are more widely used. These are the ones encountered in practice, especially where the digging is done manually by shovels. For any shape adopted for a channel, different bases and angles will give different efficiencies, so that there is a particular configuration which gives the most discharge per a certain amount of excavation.

This paper assumes the fluid flow which is irrotational, inviscid, steady and incompressible neglets surface tension and viscosity, and considers only mathematical hydraulic efficiency to highlight the most economical dimensional characteristics that minimise velocity flunctuations, scouring and siltation for the round-bottomed triangular open channel. An appropriate extension of the section above the free surface to ameliorate the effects of overflow due to storms is also proposed.

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Mathematical Principles

Application of Manning's Equation in Treatment of Common Channel Shapes

In the context of open channel flow, Marriott and Uddin (2009) treat the terms *best hydraulic section* and *most economic section* as synonymous. The more a channel gives *the maximum discharge for a given amount of excavation*, the more economical it is said to be (Rajput, 2006). At the heart of most open channel flow computations lies the Manning's equation,

$$\boldsymbol{Q} = \frac{\sqrt{(S_0)}\ m^{\frac{2}{3}} A}{n} \qquad (2.1)$$

in which **Q** represents the flow rate in the channel, $\mathbf{S_0}$ the slope of the channel, A the cross-sectional area of the channel and *m* is the hydraulic radius of the channel, defined as the ratio of cross-sectional area to the wetted perimeter, P. The equation (2.1) above may also be reformulated as,

$$\boldsymbol{A} = (\boldsymbol{P})^{\frac{2}{5}} \left(\frac{n\,Q}{\sqrt{S_0}}\right)^{\frac{3}{5}} \qquad (2.2)$$

The equation (2.2) demonstrates that if $\boldsymbol{S_0}$, **Q** and n held constantly, A and P are directly proportional, and that gives a way of minimising the flow area (and thus maximising the efficiency of the channel).

In a way, the round-cornered triangular channel is a special case of a simple trapezoidal channel which is the reason this paper uses the latter to demonstrate the application of Manning's equation in determining the optimum dimensions of a channel.

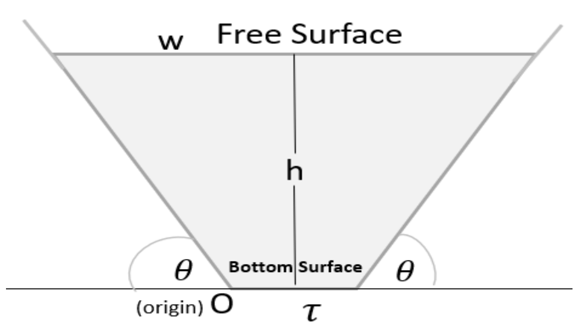

Fig. 1: The Trapezoidal Open Channel

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The wetted area and wetted perimeter of the trapezoidal channel illustrated in the Figure 1 are,

$$\boldsymbol{A = \int_0^h \int_{y cot(\pi-\theta)}^{y cot(\theta)+\tau} dxdy = \tau\, h + h^2\, cot\theta} \quad (2.3)$$

$$\boldsymbol{P = \tau + 2\, h\, cosec\theta} \quad (2.4)$$

$$\boldsymbol{m = \frac{A}{P} = \frac{A}{\tau+2\, h\, cosec\theta} = \frac{A}{\frac{A}{h} - h\, cot\theta + 2h\, cosec\,\theta},\ \left(since\ \tau = \frac{A}{h} - \ h\, cot\theta\right)} \quad (2.5)$$

This means that $m = \frac{A}{\frac{A}{h} - \ h\, cot\theta + 2h\, cosec\,\theta}$, which is greatest when the denominator is minimised with respect to h. Furthermore,

$$\frac{\partial}{\partial h}\left(\frac{A}{h} \ - \ \ h\, cot\theta + 2h\, cosec\,\theta\right) = -h(-cosec^2\theta) + 2h(-cosec\theta cot\theta) = 0 \quad (2.6)$$

Thus,

$$\frac{1}{sin\theta}(1 - 2cos\theta) = 0 \ \Longrightarrow \theta = \frac{\pi}{3} \quad (2.7)$$

This means that the trapezoidal channel is most efficient when $\theta = \frac{\pi}{3}$, $i.e.\ 60^0$, which is the half of a hexagon.

Additionally, with $\theta \ = \frac{\pi}{3}$, we also infer a relationship between the sides; i.e.,

$$\tau = \frac{2}{\sqrt{3}}\, h \quad (2.8)$$

The other relationships such as wetted perimeter, *P,* and cross-sectional area, *A,* for the trapezoidal channel are similarly derived; that is,

$$P = h\, 2\sqrt{3}, A = h^2\, \sqrt{3}, P = 3\tau, surface\ width\, w = \frac{4}{\sqrt{3}}\, h\ and\ bottom\text{-}width\ to\ depth\ ratio,\ \frac{\tau}{h} = 2(cosec^2\theta - \ cot\theta) \quad (2.9)$$

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Table 1and Figure 2 compare the efficiencies of channels having number of sides near the six of the hexagonal one. It was generated using Microsoft Excel.

Table 1: Efficiency Values for Polygons Around the Hexagon with A = 100 and η = 50

Trapezoidal Channel Slope (radians)	No. of sides	Wetted Perimeter	Efficiency
1.571	4	102	0.01
1.257	5	90.9	0.011
1.0472	6	88.6	0.01129
0.897598	7	90.03112933	0.011107
0.78539825	8	93.42135265	0.010704

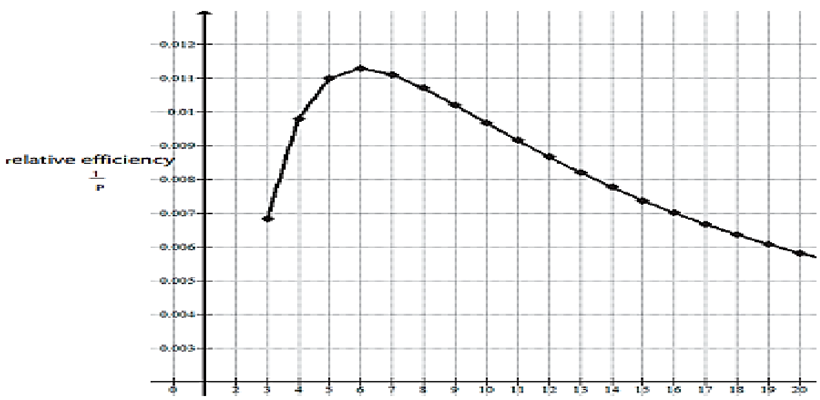

Fig. 2: The relative efficiencies of channels near the hexagonal one, with A = 100 and h = 50

The graph peaks at $n = 6$ therefore supporting the result that the hexagon is the most efficient trapezoidal design. It also reveals that a 7-sided (heptagonal) cross-section at 0.011107269 is more efficient than a 5-sided (pentagonal) one at 0.011001071.

The Hybrid Triangular Channel With Rounded Bottom

Although the semi-circular channel is the most efficient, it has limited practical usability. This creates need for hybrid channels which are trapezoidal but with rounded bottoms. Froehlich (2008), Chahar and Basu (2009), Hameed (2010) and several others have applied different techniques to specify the optimum dimensions of various types of hybrid round-bottom

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channels. This paper has focused on the round-bottomed channel shown in Figure 3, which will be treated as a special case of the trapezoidal one with round corners.

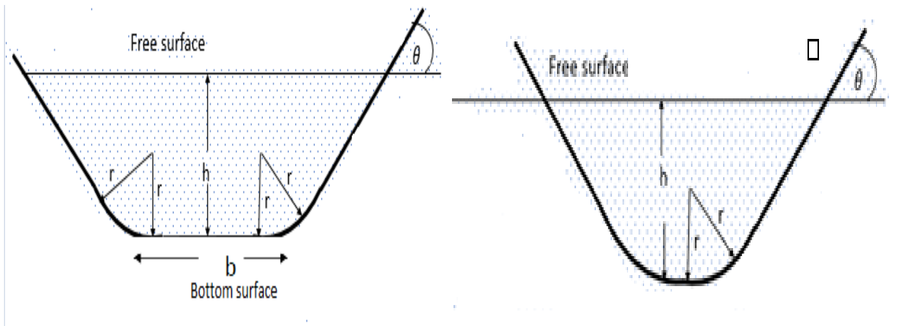

Fig. 3: A round-cornered triangular channel as a special case of Figure 3, with *b = 0*

In Figure 3, r is a scalar multiple of h, so that $r = \zeta h, \quad 0 \leq \zeta \leq 1$
(2.11)

The expressions for the wetted perimeter, P, and the channel cross-sectional area, A, may respectively be expressed as

$$P = b + 2\zeta h\left(\frac{\pi\theta}{180}\right) + 2h\, cosec^2\theta \, - 2\zeta h(cosec^2\theta - cot\theta) \quad (2.12)$$

And

$$A = bh + 2\zeta h^2(cosec^2\theta - cot\theta) + h^2 cot\theta - 2\zeta^2 h^2\,(cosec^2\theta - cot\theta) + \zeta^2 h^2\left(\frac{\pi\theta}{180}\right)$$

(2.13) (Fattouh & Yousif (2020). Setting $\lim_{b\to 0} A$ and $\lim_{b\to 0} P$ makes the equations (2.12) and (2.13) reflect the situation represented by Figure 4. Subsequent optimisation based on Manning's formula and the criterion of minimal wet-perimeter yields the most efficient radius r as

$$r = \frac{2^{\frac{1}{4}}\, Q_n}{\left(cot\,\theta + \frac{\theta\pi}{180}\right)^{\frac{3}{8}}\ \sqrt{S_f}} \quad (2.14)$$

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Where Q is the discharge for a given Manning's roughness coefficient, n, and S_f is the longitudinal slope. Furthermore, the other optimal conditions for radius r, top width W, cross-sectional area A, wetted perimeter, P, as summarised by Experto en Ingenieria (2022), in an informative online video narration,

$$r{=}h,\ W = 2r cosec^2\theta,\ A = \frac{W}{4cot\theta} - \frac{r^2}{cot\theta}\left(1 - \left(\frac{\theta\pi}{180}\right) cot\theta\right), \quad (2.15)$$

and $P = \frac{W}{cot\theta} cosec^2\theta - \frac{2r}{cot\theta}\left(1 - \left(\frac{\theta\pi}{180}\right) cot\theta\right)$ (2.16)

Minimising the fluctuation of velocity above the free surface of the optimised channel

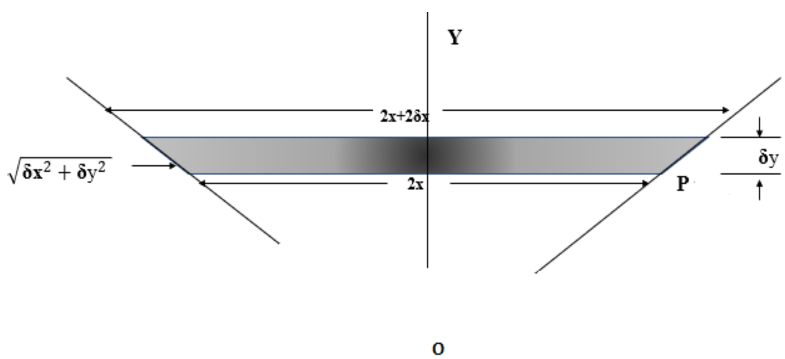

Fig. 4: An element cross-sectional area above the open surface of the channel

Figure 4 shows the top surface of a compound round-bottomed channel with constant hydraulic radius $m = \frac{A}{P}$, which is the only requirement according to Manning and Chezy formulae to keep velocity constant. The shaded section is a trapezoidal area element with horizontal sides equal to $2x$ and $2x + 2\delta x$,and a thickness δy.

The element area is $A = \frac{((2x+2\delta x)+2x)}{2}(\delta y) = 2x\delta y + \delta x\, \delta y$, while the wetted perimeter, $P = 2\sqrt{\delta x^2 + \delta y^2}$ Therefore, the hydraulic radius $m = \lim_{n\to\delta x=0,\delta y=0} \frac{2x\,\delta y + \delta x\,\delta y}{2\sqrt{\delta x^2+\delta y^2}}$, that is $m = \frac{x\,dy}{\sqrt{dx^2+dy^2}} \Rightarrow m^2 = \frac{x^2\,dy^2}{dx^2+dy^2}$ and $m^2(1 + \left(\frac{dy}{dx}\right)^2) = x^2\left(\frac{dy}{dx}\right)^2 \Rightarrow \int dy = \int \frac{m}{\sqrt{x-m^2}} dx$, which yields $y = m\, ln\left(x + (\sqrt{x^2 - R^2})\right) + k$ (3.1)

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In view of Figure 4, where the equation of the slant side of the channel is $y = x\ tan\ \theta$ i.e. (choosing the origin, O appropriately), the value of the arbitrary constant k may be determined whenever x is known (Rajput, 2006). The channel equation (3.1) is applicable in designing the top sections of any regularly shaped channels for minimal velocity fluctuations during overflow.

Conclusion

This paper has used a purely analytical approach to explore the efficiency of the hybrid round-bottom triangular open channel with minimum velocity fluctuation above the free surface. The motivation for exploring hybrid shapes is the fact that the semi-circular channel, known to rank highest in efficiency unfortunately falls short in utility due to propensity for scouring, and difficulty in layering. The optimum dimensions of the round-bottom triangular channel with minimum velocity fluctuation in stormy conditions were explored and established to be $y = m\ ln\left(x + (\sqrt{x^2 - R^2})\right) + k$ with the significance of each symbol as elaborated in section 3 above.

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