Chapter

Anthropogenic Impacts as Determinants of Tropical Lake Morphology: Inferences for Strategic Conservation of Lake Wetland Biodiversity

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Abstract

Lakes as essential ecosystems for diverse life forms, including humans, have suffered altered morphology with adverse effects on biodiversity including amphibians and amphibious species. Thus, it is imperative for effective conservation strategies to simultaneously consider lake morphology, landscape variables, and the role of keystone species as ecosystem engineers for biodiversity preservation. Keystone species, particularly birds and large-bodied predators, i.e., crocodylians, play a critical role in maintaining the health of lake ecosystems as ecosystem engineers, bringing about large-scale changes in lake morphology and hydrology that determine the abundance and survival of other species in the ecosystem. Conservation strategies should, therefore, prioritize the protection of these keystone species and their habitats. To balance the needs of human society with the protection of lake ecosystems and their biodiversity, conservation practices must involve stakeholder engagement, including government agencies, local communities, traditional ecological knowledge, and scientists. A multidisciplinary approach, incorporating ecological, hydrological, and social factors, is considered necessary for effective lake conservation. This approach will encompass the preservation of lake biodiversity and consider important variables such as lake morphology, landscape variables, and the role of keystone species as ecosystem engineers in providing insights for strategic conservation practices.

Keywords: lake conservation, biodiversity, anthropogenic impacts, keystone species, multidisciplinary approach

1. Introduction

Lakes are important ecosystems that support a high level of biological diversity, making them valuable resources for conservation efforts. They provide critical habitats for many plant and animal species, including numerous rare and endemic species and are essential for the survival of many migratory birds [1]. Additionally, lakes

contribute to the regulation of global biogeochemical cycles and serve as a source of drinking water for millions of people worldwide [2, 3]. Conserving the biological diversity of lakes is, therefore, crucial for maintaining the integrity of these ecosystems and ensuring their continued provision of important ecological services.

The factors that influence lake morphology and biodiversity are complex and interconnected, making conservation efforts challenging. Some of the most significant drivers of lake biodiversity loss are anthropogenic activities, including urbanization, agriculture, and mining [1, 4]. These activities alter the natural characteristics of lake ecosystems, leading to habitat degradation, water quality degradation, and loss of biodiversity [5]. Therefore, understanding the impact of these factors is critical to developing effective conservation strategies. Keystone species are a crucial component to ensure the conservation of biological diversity in natural habitats like lakes. They play an essential role in regulating the population sizes of other species, often by controlling the availability of resources such as food or habitat. In many cases, the loss of a keystone species can have cascading effects on the rest of the ecosystem, leading to the decline of other species and ultimately compromising ecosystem health [6, 7]. Hence, the conservation of keystone species is critical for maintaining the biodiversity and ecological integrity of lake ecosystems.

1.1 Lakes ecosystems and biological diversity conservation

Lakes play a critical role in the conservation of biological diversity, as they support a diverse array of aquatic and terrestrial habitats that are home to a wide range of plant and animal species. They are recognized as one of the most important ecosystems in terms of biodiversity, and their conservation is essential for maintaining ecological balance and the provision of ecosystem services. Lakes provide optimal habitats for numerous keystone species, which are important in maintaining the balance and health of lake wetland ecosystems [8].

Human activities such as deforestation, urbanization, agriculture, and mining have resulted in significant changes in lake ecosystems, leading to loss of biodiversity and degradation of ecosystem services. Climate change also poses a significant threat to the health and functioning of lake ecosystems, as rising temperatures and changes in precipitation patterns can alter water chemistry, nutrient cycling, and ecosystem processes [9]. Climate change-related changes in the inflow water volumes of lakes may also bring about morphological changes (**Figure 1**) [10]. These threats highlight the importance of conserving lake ecosystems to maintain biodiversity and ensure the continued provision of vital ecosystem services.

Conservation efforts that focus on the protection and restoration of lake ecosystems have become increasingly important in recent years [11]. These efforts involve the implementation of policies and management practices that aim to reduce the impact of human activities on lake ecosystems, while also promoting sustainable use and the conservation of biodiversity [12]. Examples of conservation strategies include the establishment of protected areas. Implementation of sustainable fishing practices, restoration of degraded habitats, and reduction of pollution and eutrophication [13, 14].

1.2 Factors that influence lake morphology and biodiversity

Several factors influence the morphology and biodiversity of lakes, including geology, climate, water chemistry, and physical characteristics such as depth,

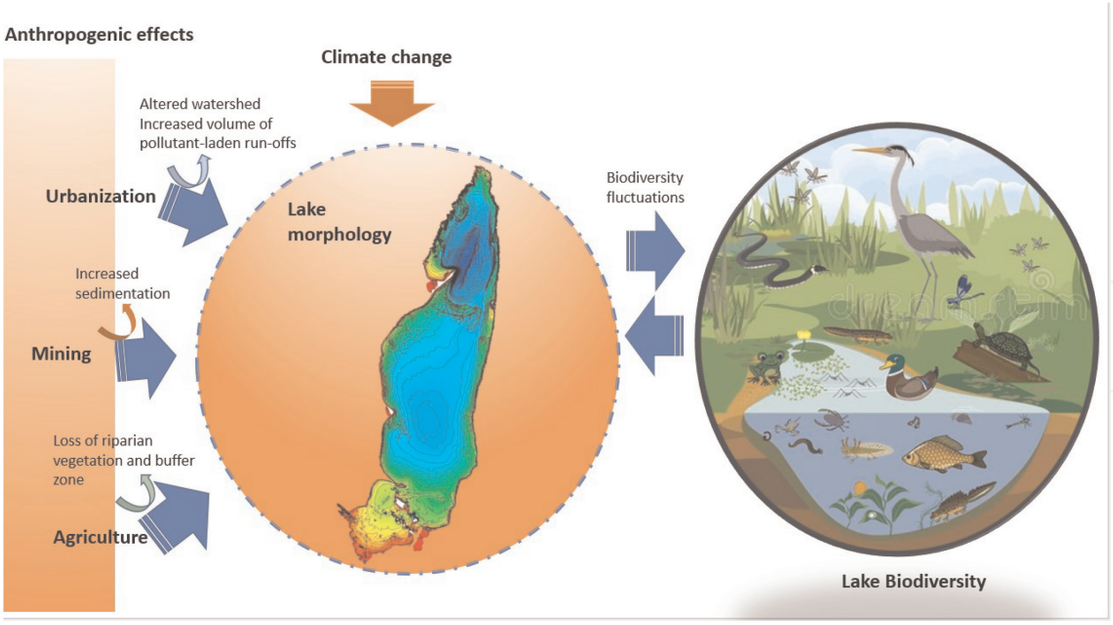

Figure 1.
Direct linkages between anthropogenic activities, lake morphology, and biodiversity occurrence.

shoreline length, and connectivity to other water bodies [15, 16]. Variations in these factors can lead to alterations in lake morphology, including changes in water depth, temperature, and nutrient availability, with significant impacts on lake biodiversity [17, 18]. For example, increased nutrient inputs from human activities such as agriculture and urbanization may lead to eutrophication and algal blooms, which can negatively affect fish populations and other aquatic organisms [19, 20]. Similarly, changes in the physical structure of lake habitats, for example, the removal of shoreline vegetation for the construction of dams, can lead to habitat loss and fragmentation, with negative impacts on the diversity and abundance of aquatic and terrestrial species [21].

In addition to the factors mentioned above, other human activities: deforestation, mining, and land use changes can also influence the morphology and biodiversity of lakes [22]. Activities like deforestation around lake watersheds may lead to increased sedimentation and nutrient runoff, altering the water chemistry of a lake and leading to decreased water clarity and dissolved oxygen levels [23]. Similarly, mining activities may introduce heavy metals and other toxic substances into lake ecosystems, which can negatively impact the health and diversity of aquatic species [24]. Land use changes, such as the conversion of wetlands to agricultural, industrial, or urban areas, can also result in the loss of crucial habitats, especially for wetland-dependent species and further contribute to biodiversity loss [25]. Thus, understanding the factors that influence lake morphology and biodiversity is crucial for effective lake conservation and management. By monitoring changes in these factors and implementing appropriate management strategies, such as nutrient reduction programs or habitat restoration efforts, it is possible to mitigate the negative impacts of human activities and promote the health and diversity of lake ecosystems [26]. Furthermore, addressing these factors can help to maintain the provision of ecosystem services that lakes offer to human society, such as drinking water, food, and recreation [27].

1.3 Keystone species and health of lake wetland ecosystems

Keystone species are essential for the maintenance of lake wetland ecosystems, and their loss can have cascading effects throughout the food web [28]. Amphibians are important in many ecosystems; however, negative large-scale effects such as climate change or massive pollution events on amphibians may have cascading effects on many other animals in the ecosystem [29]. In tropical lake wetland ecosystems, the conservation and management of keystone species, particularly amphibians and amphibious species, are vital to the regulation of food webs and nutrient cycling [30]. Amphibious species, such as mudskipper fish, birds, reptiles, and some mammals, are among the keystone species that play vital roles in nutrient cycling, predator-prey dynamics, and vegetation management [31]. Other species include amphibious fish species such as lungfish (Dipnoi), Bichir (Polypteridae), Air-breathing catfish (Claridae), and snakehead fish (Channidae). These species regulate the abundance of phytoplankton, aquatic plants, and periphyton growth in tropical lake ecosystems. While the bird, African Jacana controls the abundance of aquatic invertebrates, the mudskipper regulates the abundance of prey species, preventing overconsumption and maintaining the balance of the food web. Another example is where large-bodied apex predators like alligators undertake ecosystem roles by dam-building activities, and creating complex hydrological and ecological systems that support diverse aquatic and terrestrial species [32].

The loss of keystone species due to habitat destruction, pollution, and other threats may have significant impacts on the balance and health of lake ecosystems. For instance, the decline of birds due to hunting, habitat destruction, and climate change has been reported to have cascading effects throughout the food web. Similarly, the loss of amphibious species can negatively impact nutrient cycling and the regulation of phytoplankton and aquatic plant abundance in these ecosystems. The removal of top predators which constitute the amphibious group can lead to an increase in the abundance of their prey resulting in the overconsumption of aquatic vegetation and a decline in water quality [33, 34]. Developing effective conservation strategies for keystone species, (such as restoring bird habitats and conserving top predator species), is crucial for the long-term management and sustainability of tropical lake wetland ecosystems. Conservation efforts that focus on protecting and restoring keystone species, including amphibians and amphibious species, can have cascading effects that benefit multiple species and ecosystem processes [35].

2. Anthropogenic impacts on lake morphology and biodiversity

2.1 Overview

The current state of the world's lakes is indeed alarming, and people around the world will have to make a concerted effort to reverse the trend toward degradation. Human activities have been shown to have a significant impact on the morphology and biodiversity of lakes. For example, agricultural practices, deforestation, and urbanization can cause changes in land use and land cover, leading to alterations in the hydrological regime of lakes [36]. This may result in increased sedimentation and eutrophication, with negative effects on the diversity and abundance of aquatic plants and animals [37]. Pollution from domestic, industrial, and agricultural sources can also introduce toxins and excess nutrients into lakes, causing algal blooms and other

forms of ecological disturbance [38]. Furthermore, the construction of dams, canals, and other forms of water infrastructure can alter the natural flow and connectivity of rivers and lakes, and impact biodiversity and ecosystem services [39]. The fragmentation of lake habitats can lead to the isolation of populations, reducing gene flow and increasing the risk of extinction for certain species [40, 41]. Invasive species introduction, either intentionally or unintentionally, can also have a profound impact on lake biodiversity by outcompeting native species for resources and altering food webs [42]. In essence, anthropogenic activities have a significant impact on the morphology and biodiversity of lakes, and understanding these impacts along with developing strategies to mitigate them is crucial for the sustainable management of these freshwater ecosystems.

2.2 Specific anthropogenic activities and impact on Lake morphology

2.2.1 Urbanization

Urbanization refers to the process of population growth and expansion of urban areas, resulting in the conversion of natural landscapes into built-up areas. This process is accompanied by a variety of anthropogenic activities, such as land-use change, construction of buildings, and infrastructure development, that can have significant impacts on the morphology of lakes and their associated ecosystems. One of the primary impacts of urbanization on lakes is the alteration of their hydrology. The expansion of impervious surfaces, such as roads and buildings, can increase surface runoff and reduce infiltration, leading to changes in the hydrology (volume, timing, and frequency of water inputs) of the lakes [43] and resultant negative effects on lake health and its inhabitants [44]. Additionally, urbanization can lead to the destruction of natural vegetation that provides essential ecosystem services such as water purification, nutrient cycling, and erosion control, leading to reduced water quality and increased sedimentation [45]. The input of nutrients and organic matter increases the chances of eutrophication and toxic algal blooms in receiving habitats [19]. In essence, changes due to urbanization can negatively impact the diversity and abundance of aquatic species, as well as the ecosystem processes that support them. The study by Saha et al. [46] underscored the importance of considering the impacts of anthropogenic activities on lake morphology and biodiversity and the need for effective management strategies to mitigate these impacts. They found that the water quality of oxbow lake was affected by both point and non-point sources of pollution, including domestic sewage and agricultural runoff. The authors also found that the distribution of fish species within the lake was influenced by the hydrological connectivity of the lake with adjacent habitats. Fish species that were more adapted to stagnant water conditions were found in the inner parts of the oxbow lake, while species that were more adapted to flowing waters were found in the outer parts of the lake where the water was more connected to the main river channel. Urbanization also contributes to the introduction and spread of invasive species in lakes. The construction of waterways, channels, and drainage systems for urban development can facilitate the movement of non-native species, that have been observed to outcompete native species and alter the ecological balance of lake ecosystems [47]. In essence, the complex interactions between urbanization, hydrology, water quality, and biodiversity in oxbow lake ecosystems highlight the need for sustainable urban planning and management practices that minimize the negative impacts of human activities on lake ecosystems.

2.2.2 Agriculture

Agricultural practices and associated activities such as fertilizer and pesticide use, land clearing, and irrigation can result in increased sedimentation, nutrient enrichment, and water pollution in lakes [48]. These inputs may cause eutrophication, (a process whereby excessive nutrients stimulate the growth of algae and other aquatic plants), ultimately leading to oxygen depletion and fish kills [49]. In addition, irrigation practices can reduce water levels in lakes, altering lake morphology and reducing water availability for other uses [50]. Livestock grazing, crop production, and the use of fertilizers and pesticides may also have negative impacts on lake ecosystems (as runoff from agricultural lands laden with excess nutrients such as nitrogen and phosphorus), leading to eutrophication and harmful algal blooms [51]. Pesticides are a class of endocrine disrupters with reported estrogenic effects and modulated vitellogenin production in male and female aquatic species [52, 53]. Other effects resulting from vitellogenin induction in male species include kidney failure and impairment of reproductive success, increasing the risks of declines in local populations' biodiversity [54, 55].

To mitigate the impact of agricultural practices on lake ecosystems, best management practices (BMPs) have been developed to reduce nutrient and sediment runoff from agricultural lands. These BMPs include practices such as reducing fertilizer application rates, implementing cover crops, and maintaining vegetative buffer strips along streams and lakes [56]. Additionally, the implementation of water conservation measures in agricultural practices, such as drip irrigation and precision agriculture, may reduce water use and increase water availability for other uses [57]. By implementing these practices, the negative impact of agriculture on lake morphology and biodiversity can be minimized, allowing for the sustainable use of these important ecosystems.

The agricultural sector is crucial to the economy of many African countries, and it accounts for a significant portion of their GDP, hence its widespread practice drives unregulated chemical applications, overuse of water resources for irrigation and other agricultural purposes leading to the depletion of lakes and other freshwater ecosystems. As such the negative impacts of agriculture on lake habitats may outweigh the economic benefits of agricultural production. Therefore, adopting integrated approaches that consider both the environmental and economic implications of agricultural practices are necessary to achieve sustainable agriculture and promote the protection and conservation of lake habitats.

2.2.3 Mining

Mining activities such as excavation, blasting, and sedimentation alter the physical and chemical properties of lake ecosystems [58]. The discharge of toxic chemicals and heavy metals from mining activities also has reported harmful effects on aquatic organisms and their habitats [59, 60]. For example, the gold mining industry in the Amazon basin has been linked to high levels of mercury contamination in local waterways and aquatic food webs, posing a threat to the health of human populations that rely on these resources for sustenance [61]. In addition to contaminating water bodies, mining activities can also lead to habitat destruction and fragmentation through the construction of mines and access roads, leading to the isolation of different species and populations and further reducing the biodiversity of lake ecosystems

[62]. Soil erosion caused by mining can increase sedimentation in nearby water bodies and reduce water quality, further degrading the habitat. The use of heavy machinery and chemicals like cyanide and mercury also contributes to soil and water quality degradation, leading to the loss of vegetation cover and contamination of water bodies, affecting aquatic species diversity. Mining can cause significant disturbances to the soil and subsurface habitats, altering soil structure and composition, microbial communities, and nutrient availability, resulting in a reduction in the biodiversity of lake ecosystems. The excavation of minerals leads to increased sedimentation and erosion, with negative impacts on the health of lakes and resident organisms [63]. The disposal of mining waste can also lead to the release of heavy metals and other toxic substances (organics) from subsurface sediments into the surface waters of lakes [64].

Efforts to mitigate the impacts of mining on lake ecosystems include the implementation of best management practices, such as the use of sediment traps and the reduction of chemical usage in mining operations [65]. However, the effectiveness of these measures is often limited by weak regulatory frameworks and insufficient enforcement mechanisms [66], especially in developing countries. In order to maintain the long-term health and sustainability of lake ecosystems affected by mining activities, it is important to adopt a comprehensive approach that combines sustainable mining practices with effective governance and monitoring. The negative impacts of mining activities on lake ecosystems can lead to a reduction in the diversity and abundance of aquatic species, as well as changes in ecosystem processes that support them. Therefore, management practices that minimize the impacts of these activities on lake ecosystems should be implemented to maintain their health and sustainability.

Anthropogenic activities, such as urbanization, agriculture, and mining, have been found to have significant impacts on lake morphology and biodiversity [5]. These activities can lead to changes in water quality, habitat degradation, and increased sedimentation, resulting in decreased biodiversity and harm to aquatic organisms. Additionally, climate change exacerbates the impacts of anthropogenic activities by altering water cycles, lake chemistry, and increasing water temperatures [67] (**Box 1**). Therefore, to preserve lake biodiversity, conservation efforts must consider the impacts of anthropogenic activities and their effects on habitat and food sources for aquatic organisms and other species dependent on lentic water systems, taking into account recommendations from previous studies.

1. Eutrophication: excessive nutrient enrichment of water can lead to harmful algal blooms and oxygen depletion, ultimately causing death of fish and other aquatic organisms.

2. Sedimentation: the deposition of sediment on the lake bed, which causing turbidity, alter the nutrient cycle, and reduce light penetration, affecting aquatic plants and algae.

3. Shoreline alteration: the modification of the lake's natural shoreline, leading to habitat loss, fragmentation, and changes in vegetation, which impacts wildlife diversity and abundance

4. Habitat destruction and fragmentation- the clearing of natural vegetation around the lake, impacting the distribution and abundance of species.

5. introduction of non-native species: outcompete native species and disrupt the lake's ecological balance

6. Climate change: alterations in temperature, and precipitation impacts hydrological regimes around the lake

7. Overfishing: impacts the structure and function of the food web within the lake

Box 1.
Threats to biodiversity through altered lake morphology.

2.3 Lake morphology as a diagnostic for habitat degradation

Pressures on lakes are unevenly distributed around the world, with the most severe lake health problems across the entire continent of Africa and other densely-populated low-income countries. There is also a need for better diagnostics, in particular in low-income countries. Diagnostics include the implementation of a standardized classification system for lake health conditions. To do this we suggest focusing on a few key variables that directly reflect lake health, with empirical support and validation from The Ramsar Convention on Wetlands, an intergovernmental treaty that provides a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (**Box 2**). One of its objectives is to promote the conservation of wetlands, including lakes, through wise use and management practices that take into account ecological, social, cultural, and economic considerations. The Convention emphasizes the importance of monitoring, assessing, and reporting on the status and trends of wetlands, including their ecological character,

Lake Habitat Degradation	Altered Morphology	Landscape Variables
1 (minimal)	• No significant changes in lake morphology. • Natural shoreline with no or minimal human-made structures.	• High percentage of undisturbed natural vegetation in the surrounding landscape. • Presence of a continuous riparian buffer of at least 30 meters from the shoreline, consisting of native vegetation.
2 (slight)	• Slight alteration of lake morphology, such as minor sedimentation or nutrient enrichment. • Shoreline may have minor human-made structures, such as docks or small retaining walls.	• Moderate percentage of undisturbed natural vegetation in the surrounding landscape. • Presence of a riparian buffer of at least 20 meters from the shoreline, consisting of native vegetation.
3 (moderate)	• Moderate alteration of lake morphology, such as moderate sedimentation or nutrient enrichment.	• Low percentage of undisturbed natural vegetation in the surrounding landscape. • Presence of a riparian buffer of at least 10 meters from the shoreline, consisting of native vegetation.

	• Shoreline may have significant human-made structures, such as bulkheads or seawalls.	
4 (severe)	• Severe alteration of lake morphology, such as significant sedimentation or nutrient enrichment. • Shoreline may have extensive human-made structures, such as large marinas or commercial development.	• Minimal percentage of undisturbed natural vegetation in the surrounding landscape. • Presence of a narrow or intermittent riparian buffer, consisting of non-native or disturbed vegetation.
5 (critical)	• Critical alteration of lake morphology, such as complete loss of natural shoreline or severe pollution.	• Absence of natural vegetation in the surrounding landscape. • Absence of a riparian buffer, or presence of a degraded buffer consisting of non-native or disturbed vegetation.

Box 2.
Lake health diagnostics.

functions, and services. The Convention also guides the development of management plans and the implementation of conservation measures for wetlands, including lakes.

In addition, the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 on clean water and sanitation, provided additional empirical support and validation for the suggested diagnostics. SDG 6 aims to ensure the availability and sustainable management of water and sanitation for all, including the protection and restoration of water-related ecosystems, such as lakes. The SDGs provide a framework for countries to set targets and indicators for measuring progress toward sustainable development, including the conservation and management of lakes and their biodiversity.

2.4 Lake morphology change and biodiversity loss: Focus on bird diversity

The link between changes in lake morphology and biodiversity loss is well established, with numerous studies highlighting the negative impacts of anthropogenic activities on biodiversity in lake ecosystems. For example, Chukwuka et al. [1] observed that urbanization, agriculture, and mining activities all have significant impacts on the morphology of tropical lakes and wetlands, which may have cascading effects on the biodiversity of these ecosystems. Bird diversity is one aspect of biodiversity that has been particularly affected by changes in lake morphology. Birds are important keystone species in lake ecosystems and play a crucial role in maintaining ecosystem processes such as nutrient cycling and food webs. However, urbanization and other anthropogenic activities have led to habitat loss and fragmentation, as well as changes in water quality and hydrology, with negative impacts on bird populations [68].

For example, the construction of dams and reservoirs for hydroelectric power generation and irrigation has resulted in the fragmentation of bird habitats and reduced the availability of suitable nesting sites, leading to declines in bird populations in some areas [69, 70]. Similarly, the conversion of wetlands to

agricultural land or urban areas could result in the loss of important feeding and breeding grounds for birds, which also contribute to declines in bird diversity [71]. In addition to habitat loss and fragmentation, changes in water quality and hydrology also have negative impacts on bird populations. For example, the discharge of pollutants such as nutrients, pesticides, and heavy metals into lakes and wetlands can lead to eutrophication and toxic algal blooms, which can directly or indirectly impact bird populations [72]. Changes in hydrology such as altered water flow and water level fluctuations can also impact bird populations by altering the availability of suitable foraging and breeding habitats [73]. Therefore, it is important to recognize the link between changes in lake morphology and bird diversity loss and to develop effective conservation strategies that focus on preserving and restoring bird habitats and populations in lake ecosystems.

3. Lake morphology and landscape co-factors affecting biodiversity

The morphology of a lake is a key factor in determining the biodiversity of the aquatic ecosystem. Physical characteristics such as water depth, shoreline complexity, and substrate composition have a significant impact on the distribution, abundance, and diversity of species in lakes [74]. Changes in lake morphology, particularly those caused by anthropogenic activities, can have significant impacts on biodiversity. One of the most significant impacts of changes in lake morphology is the loss of shoreline habitats such as wetlands and riparian zones. These habitats are important for supporting a diverse array of aquatic and terrestrial species, including birds [75]. Wetlands offer critical nesting, foraging, and roosting areas for various bird species, particularly those that rely on shallow water habitats. Riparian zones are equally essential for bird diversity, serving as significant sources of food and habitats for various bird species, including migratory species that use them as stopover sites [76, 77].

Lake morphology can have a significant impact on the biodiversity of aquatic and terrestrial species. For example, shallow lakes may support higher plant and fish diversity than deep lakes [21]. Furthermore, surrounding landscape variables such as land use, vegetation cover, and water quality can influence biodiversity in lakes. For example, agricultural land use surrounding lakes has been linked to decreased amphibian diversity, while forested land use has been associated with increased amphibian diversity [78].

Changes in water depth and substrate composition can also have significant impacts on bird diversity in lakes. For example, shallow water habitats such as marshes and wetlands are important for supporting many bird species, particularly waterfowl and wading birds. Changes in water depth due to dredging or filling can result in the loss of these important habitats, leading to declines in bird diversity [79]. Similarly, changes in substrate composition due to sedimentation or erosion can impact bird diversity by altering the availability of food and nesting materials. Overall, changes in lake morphology can have significant impacts on bird diversity and the broader aquatic ecosystem. Conservation efforts that focus on maintaining and restoring important shoreline habitats, preserving water depth and substrate composition, and reducing the impacts of anthropogenic activities can help to maintain the health and resilience of lakes and their associated ecosystems.

3.1 Loss of riparian vegetation and lake morphology

Loss of riparian vegetation and alterations in lake morphology due to human activities may have significant impacts on lake ecosystems and their biodiversity. Riparian vegetation plays a crucial role in maintaining the physical, chemical, and biological integrity of lakes by reducing erosion, filtering pollutants, and providing habitat and food for aquatic and terrestrial organisms [80]. However, land use changes such as deforestation, urbanization, and agriculture have resulted in the loss and degradation of riparian vegetation around many lakes, leading to reduced water quality, altered hydrological regimes, and changes in the structure and function of lake ecosystems [81]. Anthropogenic alterations to lake morphology, such as shoreline modification, dredging, and damming, can also affect the physical and chemical characteristics of lakes and alter available habitats for aquatic organisms [82]. These changes can ultimately lead to a decline in lake biodiversity and ecosystem services.

Studies have demonstrated the negative impacts of riparian vegetation loss and alterations in lake morphology on lake biodiversity and ecosystem functioning [83]. Lewin et al. [84] documented that the development of residential areas along lake shores often leads to the conversion of natural littoral habitats to various structures such as riprap, sheet piles, beaches, parks, or marinas, driving the loss of littoral vegetation, which negatively affects the structural diversity and fish communities in the littoral zone. Litterfall from riparian vegetation is a significant source of organic matter for benthic and pelagic habitats in lakes [85]. The impact of this input depends on various factors such as the riparian habitat's characteristics, shoreline complexity, and the overall productivity of the aquatic ecosystem. While most organic inputs come from litterfall, terrestrial insects sustained by riparian areas can also provide a substantial source of prey for aquatic predators and contribute tothe lake nutrient cycle in some cases [86, 87]. Furthermore, Saha et al. [46] and Chukwuka et al. [1] demonstrated the role of hydrological connectivity, water quality, and landscape structure in shaping the distribution and abundance of fish and bird communities in urban oxbow lakes and wetlands. In this light, it is imperative that conservation and restoration plans for lake ecosystems should acknowledge the importance of riparian vegetation and lake morphology and account for the complex interplay between physical, chemical, and biological factors affecting lake biodiversity and ecosystem services.

3.2 Adjacent landscape variables and lake biodiversity

The surrounding landscape variables of a lake can also have a significant impact on the biodiversity of the lake ecosystem. The composition and structure of surrounding vegetation, as well as the presence of nearby habitats such as forests, wetlands, and agricultural lands, can influence the diversity and abundance of species in the lake [21]. For example, studies have shown that lakes surrounded by diverse and extensive vegetation have higher species diversity than lakes surrounded by sparse vegetation [88, 89]. This is attributable to surrounding vegetation that provides food and shelter for lake species and contributes to the regulation of water quality and temperature. Similarly, adjacent wetlands and forests also sustain bird species, providing nesting sites and foraging areas [90]. The loss or degradation of these habitats due to land-use changes portends negative effects on the diversity and abundance of bird species within lake ecosystems [91].

3.3 Keystone species as ecological engineers

Like other animals, amphibians (salamanders, frogs, toads, and caecilians) are affected by numerous environmental stressors that often act in complex ways [92]. However, in at least some regions, amphibian losses appear to be more severe than losses in other vertebrate taxa [93, 94]. Amphibious species, on the other hand, include lungfishes, mudskippers, newts, otters, herons, crocodilians, and alligators. It is important to note that the large-bodied predators among amphibious species are highly recognized as both keystone species (which contribute to nutrient and energy translocation across ecosystems) and highlighted as ecosystem engineers. Keystone species that function as ecosystem engineers are relevant to the concept of lake morphology dynamics. This is because, these organisms have the ability to create, modify, and maintain physical attributes of habitats in ways that can affect the distribution, life histories, behaviors, and abundance of other species within that ecosystem [95]. Crocodilians (alligators and crocodiles) perform the keystone function of maintaining ecosystem balance by controlling the population growth of prey species, maintaining residual waterholes during dry periods, and inhibiting encroachment of aquatic plants. However, they can modify habitats in ways that can influence the distribution and abundance of other species. They excavate open holes, dens, and tunnels that serve as refuges from environmental extremes and predation and can also store fresh water. Mound-nesting species can build elevated structures or construct nests on floating vegetation, creating elevated "islands" [32]. These modifications can have a significant impact on lake morphology, such as shaping shorelines and affecting water flow patterns. The excavation of large holes, tunnels, and the construction of mound nests by crocodylians can result in significant modifications to the landscape. The holes can be more than 20 meters in diameter and have depths greater than 1 meter, while tunnels can reach over 50 meters in length [32]. Mound nests can be as large as 7 meters in diameter and 1 meter in height. The pathways used by crocodylians between these features can also create depressions that can retain water during dry periods. These modifications have the potential to strongly influence topographic heterogeneity within the landscape due to the substantial size of the habitat features and the total area of physical modifications created by crocodylians [32].

Considering the role of crocodylians in habitat modification, we can infer that population dynamics for fluctuations of nesting crocodylians for instance can amplify their effects on the landscape and lake morphology by extension. While both amphibians and amphibious vertebrates play a crucial role as keystone species in the biodiversity of lakes and wetlands, [96] the morphological characteristics of lakes, such as size, depth, and shoreline complexity, as well as surrounding landscape variables, are driven and largely determined by the large-bodied amphibious species [97]. This brings to bear the concept of "keystone structures" which refers to the significance of habitat heterogeneity in creating areas of high species richness. This concept has been extensively studied in terrestrial environments but has received less attention in freshwater systems. Keystone structures can concentrate species activity and thus influence density and biodiversity. For instance, the presence of complex shorelines, which provide a variety of niches and microhabitats for amphibians, is positively correlated with their abundance and diversity [98]. In addition, larger and deeper lakes are associated with higher amphibian species richness [99]. The importance of habitat complexity is further seen in the presence of other keystone structures in freshwater systems including weed beds, patches of gravel or rock outcrops, and deep pools in lotic systems, which provide refuges to different sizes of crayfish and their predators [100].

While the loss of amphibious keystone species in lakes and wetlands may have far reaching ecological consequences, the decline of amphibian populations could also impact the structure and function of food webs in these ecosystems via an unregulated abundance of invertebrate species [101]. In addition, the loss of amphibians can have negative impacts on nutrient cycling, as they play a critical role in the regulation of organic matter decomposition and nutrient release [102]. Thus, incorporating measures to protect and enhance these species can contribute to the sustainability of these ecosystems and the provision of essential ecosystem services.

4. Lake conservation and multidisciplinary approaches

4.1 Importance of a multidisciplinary approach to lake conservation

Managing a lake as an environmental indicator poses significant challenges due to the need to address complex technological, financial, and institutional issues. It requires support from both the public and industry, which may prioritize short-term economic gains over long-term environmental sustainability. Effective lake management requires careful consideration of various factors, including monitoring and assessment of water quality, management of surrounding land use, and regulation of pollutant discharge into the lake. In addition, stakeholder involvement and collaboration are crucial for developing effective management plans that balance economic and environmental concerns. A multidisciplinary approach to lake conservation is critical to addressing the complex challenges facing these ecosystems. The management of lakes requires collaboration between various fields, including ecology, hydrology, limnology, geography, and social sciences. The integration of these disciplines allows for a comprehensive understanding of the environmental, social, and economic factors that affect lake ecosystems. Studies have highlighted the importance of considering the social context of lake management and found that the attitudes and perceptions of residents toward lake management influenced the success of conservation efforts [103, 104]. Aside from aiding in the development of sustainable and adaptive management strategies, integrating ecological and social knowledge, lake management can be tailored to address the unique challenges and goals of each ecosystem [105]. This approach has accounted for the interconnectedness of social and ecological systems and identified trade-offs between conservation and human well-being [106]. Furthermore, a multidisciplinary approach can help address the uncertainties and complexities associated with lake ecosystems. The integration of multiple perspectives and data sources can also improve the accuracy and robustness of predictions and models used in management decisions. By working together, scientists, managers, and stakeholders can develop effective and sustainable strategies that balance the conservation of biodiversity with the needs of local communities.

4.2 Ecological, hydrological, and social factors in conservation strategies

Effective management of lake health requires a holistic approach, recognizing the interconnectedness of ecological, hydrological, and social factors. Ecological factors, such as the physical and biological characteristics of a lake and its surrounding landscape, and hydrological factors (referring to the water cycle and human impacts on water quality and quantity) must be considered alongside social factors, including the

cultural, economic, and political context in which the lake exists. To address the complex interactions that affect lake ecosystems, a multidisciplinary approach is necessary.

A multidisciplinary approach recognizes that lake ecosystems are complex and interconnected systems that require a holistic understanding of the interactions between biotic and abiotic factors, human activities, and their impacts on lake ecosystems [107]. Therefore, ecological studies that assess the physical and biological features of a lake should be complemented by hydrological studies that examine water flow dynamics and quality, as well as social studies that identify the attitudes, perceptions, and behaviors of local communities toward a lake and its resources [108]. Understanding the hydrological aspects including water availability, flow, and quality, and how these are affected by changes in land use and climate are crucial factors for developing strategies to mitigate the negative impact of human activities on lakes. These may include reducing the use of synthetic fertilizers in agriculture to prevent nutrient pollution or designing stormwater management systems to minimize runoff into lakes. On the other hand, ecological research can help identify the key drivers of ecological change and determine the appropriate conservation interventions needed to maintain or restore healthy lake ecosystems.

According to de Bisthoven et al. [109] study on the socio-ecological assessment of the Lake Manyara basin in Tanzania, they observed that improved water governance through a multi-actor approach (with a focus on distributing benefits and rights and assigning specific roles to water authorities) should be a priority for future integrated management strategies. Additionally, they highlighted the need to raise awareness among decision-makers, scientists, and local communities about the advantages of an integrated approach. Elsewhere, a lake management strategy based on both bio-physical and socio-economic aspects which also adopts a watershed/ecosystem approach at the policy level, integrates income generation in conservation activities, sharing responsibility and benefits among local stakeholders, and enhancing management capacity development and institutional strengthening for sustainable development was recommended [110]. In essence, a participatory approach involving multidisciplinary stakeholders could assist in ensuring successful lake conservation and management.

4.3 The importance of keystone species in lake conservation efforts

Lake conservation efforts have traditionally focused on preserving individual species and maintaining biodiversity. However, an approach that considers the role of keystone species in maintaining ecosystem health is becoming increasingly important [111]. Keystone species have a disproportionately large impact on the structure and function of an ecosystem relative to their abundance. They often play a critical role in maintaining ecosystem processes such as nutrient cycling, pollination, and predation [112]. In the context of lake ecosystems, amphibians and amphibious vertebrates (including birds, turtles, and crocodylia) control the flow of trophic resources including phytoplankton and aquatic plants, and also stimulates the growth of periphyton [113].

Conserving keystone species is essential for maintaining the health and resilience of lake ecosystems. Loss of keystone species can have cascading effects throughout the ecosystem, leading to declines in biodiversity and the disruption of ecosystem services [111]. For example, the loss of fish species in lakes can lead to an increase in the abundance of phytoplankton and algae, which can result in eutrophication and oxygen depletion, ultimately leading to a decline in biodiversity [114]. In addition, amphibians such as frogs and salamanders are sensitive indicators of environmental health and can provide early warning signals of changes in ecosystem function [115]. To

effectively conserve keystone species in lakes, a multidisciplinary approach is necessary. This approach involves collaboration among ecologists, hydrologists, social scientists, and policymakers to develop conservation strategies that consider the ecological, hydrological, and social factors that influence the health and resilience of lake ecosystems [111]. For example, conservation efforts may involve regulating land use practices such as urbanization, agriculture, and mining that can negatively impact lake ecosystems and their keystone species. Additionally, monitoring and research programs to identify and track changes in keystone species populations and their roles in ecosystem function can inform conservation planning and management toward enhancing the resilience and sustainability of lake ecosystems [115].

5. Conclusion

Lakes are crucial ecosystems that are pivotal in conserving biological diversity. A plethora of factors influence their morphology and biodiversity, including human activities like urbanization, agriculture, and mining, as well as lake morphology and landscape features. These activities lead to changes in water quality, vegetation cover, and habitat structure, all of which affect the survival of various species in the lake. Moreover, changes in lake morphology affect the distribution and abundance of keystone species, such as fish and amphibians, which are essential for maintaining the ecosystem's functioning and health. Such species also play an important role in maintaining the balance of lake wetland ecosystems. To ensure the effective protection of lake ecosystems and their biodiversity, a multidisciplinary approach that integrates ecological, hydrological, and social factors in conservation strategies is essential. In addition, keystone species must be prioritized in conservation strategies since their decline can have cascading effects throughout the ecosystem. The overall health of lake ecosystems is critical for human well-being, as these ecosystems provide numerous services, such as water supply, fisheries, and recreation. Therefore, sustainable management practices that prioritize and strike a balance between biodiversity conservation in lake ecosystems while meeting human needs should be implemented.

Given the complex interactions between lake morphology, landscape variables, and anthropogenic impacts on biodiversity, a multidisciplinary approach is crucial for effective lake conservation. Ecological, hydrological, and social factors should all be considered when designing conservation strategies, while anthropogenic activities such as urbanization, agriculture, and mining should also be taken into account. Keystone species, such as amphibians and amphibious vertebrates, are important for maintaining lake ecosystem health and should be a top priority for conservation efforts, which must involve not only ecologists and biologists but also social scientists and policymakers. To ensure the success of conservation practices, it is also essential to engage local communities and incorporate indigenous knowledge and perspectives. Strategic conservation practices that prioritize the protection of keystone species and their habitats while balancing human needs and environmental sustainability are necessary to ensure the long-term health and sustainability of lakes as vital resources.

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