PALEOLIMNOLOGICAL ASSESSMENT OF ENVIRONMENTAL CHANGE IN BUKIT MERAH RESERVOIR PERAK, MALAYSIA

SIMEON ADOLE AKOGWU

UNIVERSITI SAINS MALAYSIA

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PALEOLIMNOLOGICAL ASSESSMENT OF ENVIRONMENTAL CHANGE IN BUKIT MERAH RESERVOIR PERAK, MALAYSIA

by

SIMEON ADOLE AKOGWU

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LIST OF ABBREVIATIONS

%	Percentage
µg/ml	Microgram per millilitre
µm	Microgram
^{137}Cs	Cessium-137
^{14}C	Carbon-14
^{210}Pb	Lead-210
^{226}Ra	Radium-226
^{241}Am	Americium-241
AD	“Anno Domini”
Bq Kg^{-1}	Becquerels per kilogram
Bq m^{-2}	Becquerels per square meter
°C	Degree Celsius
C/N	Carbon-to-Nitrogen Ratio
Ca	Used to indicate an approximate value or estimation.
CHNS analyser	Carbon, hydrogen, nitrogen, and sulphur analyser
cm yr^{-1}	Centimeters per year
CRS	(Constant Rate of Supply) model
DEM	Digital Elevation Model
Diatoms	Diatoms Microfossils
g cm^{-2} yr^{-1}	Grams per square centimeters per year
g cm^{-2}	Grams per square centimeter
GPS	Global Positioning System
Kg	Kilogram
Km^2	Square kilometers

mL	Milliliter
OSL	Optically stimulated luminescence
pH	Potential hydrogen
PVC	Polyvinyl Chloride Pipe
TN	Total Organic Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
Varves	Annual sedimentary layers
XRF	X-ray fluorescence
$\delta^{15}N–NO_3–$	Delta-15 nitrogen isotope ratio of nitrate
$\delta^{18}O–NO_3–$	Delta-18 oxygen isotope ratio of nitrate
BMRI	Bukit Merah sediment core 1
BMRI	Bukit Merah sediment core 2

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PENILAIAN PALEOLIMNOLOGI PERUBAHAN ALAM SEKITAR DI EMPANGAN BUKIT MERAH, PERAK, MALAYSIA

ABSTRAK

Matlamat kajian ini adalah untuk membina semula sejarah perubahan persekitaran di Empangan Bukit Merah menggunakan proksi geokimia dan diatom. Dua teras sedimen, iaitu BMRI dan BMR2, telah dikumpulkan, dibelah pada selang 1cm, dan dianalisis untuk kronologi ^{210}Pb, logam (loid) (arsenik, kadmium, kuprum, plumbum, zink dan besi), tahap nutrien (jumlah nitrogen, jumlah organik karbon, dan jumlah fosforus), bersama dengan komposisi diatom menggunakan kaedah piawai. Model CRS (kadar malar bekalan ^{210}Pb) mencatatkan sedimen tertua pada tahun 1985 ± 34 tahun AD (22.5-24.5 cm). Analisis stratigrafi fluks pencemaran logam(loid) mendedahkan variasi dari semasa ke semasa. Pada tahun 1980-an, fluks yang lebih rendah telah dicatatkan untuk arsenik (As), kuprum (Cu), zink (Zn), dan besi (Fe) masing-masing pada 29 mg cm^{-2} thn^{-1}, 3.0 mg cm^{-2} thn^{-1}, 75 mg cm^{-2} thn^{-1}, dan 148 mg cm^{-2} thn^{-1}. Nilai ini berbeza dengan fluks yang lebih tinggi pada tahun 2000-an: 43 mg cm^{-2} thn^{-1} untuk As, 9.0 mg cm^{-2} thn^{-1} untuk Cu, 120 mg cm^{-2} thn^{-1} untuk Zn dan 2003 mg cm^{-2} thn^{-1} untuk Fe. Fluks plumbum (Pb) adalah minimum pada tahun 1980-an (33.0 mg cm^{-2} thn^{-1}), meningkat hingga 56.0 mg cm^{-2} thn^{-1} pada 1990-an, manakala kadmium (Cd) mempamerkan corak yang sama dengan fluks minimum pada tahun 1980-an (2.20 mg cm^{-2} thn^{-1}) dan meningkat pada tahun 1990-an (3.60 mg cm^{-2} thn^{-1}). Fluks pemendapan nutrien juga menunjukkan turun naik dari semasa ke semasa. Jumlah fluks fosforus (TP) adalah paling rendah antara 1985-1990 (1.56 mg cm^{-2} thn^{-1}) dan tertinggi antara 2016 dan 2018 (3.98 mg cm^{-2} thn-1). Jumlah fluks nitrogen (TN) adalah rendah pada tahun 1987 (0.26 mg cm^{-2} thn^{-1}) dan tertinggi antara 1990 dan 2010

(0.29 mg cm^{-2} thn^{-1}). Jumlah fluks karbon organik (TOC) berada pada tahap terendah (1.9 mg cm^{-2} thn^{-1}) antara 1985 dan 1989 dan memuncak (4.5 mg cm^{-2} thn^{-1}) antara 1993 dan 1997. Sebanyak 48 spesies diatom telah direkodkan dalam teras sedimen BMR2 dan genera yang paling banyak ialah *Aulacoseira, Cyclotella, Discostella,* dan *Eunotia*. Menggunakan analisis Pengelompokan Bray Curtis, tiga zon diatom telah dikenal pasti dan setiap satu mencerminkan kesan daripada manusia. Zon 1 (1985 hingga 1990) menunjukkan adanya gelora, aliran tinggi, dan hakisan akibat pengorekan takungan. Zon 2 (1990 hingga 2000) menunjukkan peningkatan input nutrien, pembukaan vegetasi, dan perubahan keadaan limnologi. Di zon 3 (2000 hingga 2018), spesies diatom yang rentan-pencemar meningkat, yang menandakan kesan antropogenik yang berterusan. Hasil kajian ini mendedahkan pandangan berharga tentang perubahan alam sekitar dan dinamik ekologi dalam takungan disebabkan oleh pelbagai aktiviti yang didorong oleh manusia.

PALEOLIMNOLOGICAL ASSESSMENT OF ENVIRONMENTAL CHANGE IN BUKIT MERAH RESERVOIR PERAK, MALAYSIA

ABSTRACT

The aim of this study was to reconstruct historical environmental changes in Bukit Merah Reservoir using geochemical and diatom proxies. Two sediment cores, BMRI and BMR2, were collected, sectioned at 1cm intervals, and analysed for ^{210}Pb chronology, metal(loid)s (arsenic, cadmium, copper, lead, zinc, and iron), nutrient levels (total nitrogen, total organic carbon, and total phosphorus), along with diatom composition using standard methods. The CRS (constant rate of ^{210}Pb supply) model dated the oldest sediments back to 1985 ± 34 years AD (22.5-24.5). Stratigraphic analysis of metal(loid) pollution fluxes revealed variations over time. In the 1980s, lower fluxes were observed for arsenic (As), copper (Cu), zinc (Zn), and iron (Fe) at 29 mg cm^{-2} yr^{-1}, 3.0 mg cm^{-2} yr^{-1}, 75 mg cm^{-2} yr^{-1}, and 148 mg cm^{-2} yr^{-1}, respectively, which indicated a reduced rate of deposition of these metals during this period. These values contrasted with higher fluxes in the 2000s: 43 mg cm^{-2} yr^{-1} for As, 9.0 mg cm^{-2} yr^{-1} for Cu, 120 mg cm^{-2} yr^{-1} for Zn, and 2003 mg cm^{-2} yr^{-1} for Fe. indicating a significant increase in the accumulation of these elements during this period. Lead (Pb) fluxes were minimal in the 1980s (33.0 mg cm^{-2} yr^{-1}), peaked at 56.0 mg cm^{-2} yr^{-1} in the 1990s, while cadmium (Cd) exhibited a similar pattern with minimal flux in the 1980s (2.20 mg cm^{-2} yr^{-1}) and peak flux in the 1990s (3.60 mg cm^{-2} yr^{-1}). The depositional fluxes of nutrients displayed fluctuations over time as well. Total phosphorus (TP) flux was lowest between 1985-1990 (1.56 mg cm^{-2} yr^{-1}) and highest between 2016 and 2018 (3.98 mg cm^{-2} yr^{-1}). Total nitrogen (TN) flux was low in 1987 (0.26 mg cm^{-2} yr^{-1}) and highest between 1990 and 2010 (0.29 mg cm^{-2} yr^{-1}). Total organic carbon (TOC) flux was at its lowest (1.9 mg cm^{-2} yr^{-1}) between 1985 and 1989 and peaked (4.5 mg cm^{-2} yr^{-1}) between 1993 and 1997. A total of 48 diatom species were recorded in the BMR2 sediment core and the most abundant genera were *Aulacoseira*, *Cyclotella*, *Discostella,* and *Eunotia*. Using Bray Curtis's Clustering analysis three diatoms' zones were identified, each reflecting human impacts. Zone 1(1985 to 1990) indicated turbulence, high flow, and erosion due to the reservoir dredging. Zone 2 (1990 to 2000) showed increasing nutrient input, vegetation clearance, and changing limnological conditions. In Zone 3 (2000 to 2018), pollutant-tolerant diatom species increased, signifying ongoing anthropogenic impact. The findings of this study revealed valuable insight into the environmental change and ecological dynamics within the reservoir due to diverse human-driven activities.

CHAPTER 1

INTRODUCTION

Worldwide, freshwater environments are being threatened by different anthropogenic activities. As global ecosystems continue to change due to expanding and intensifying human impacts, the demands and stresses on many aquatic ecosystems may increase and their integrity will eventually become degraded (Buzhdygan *et al*., 2022). These activities can also give rise to new water bodies, affecting the types, areas, and distribution of continental waters (Saulnier-Talbot & Lavoie, 2018). Freshwater environments constitute less than 2% of the earth's aquatic ecosystems (Vári *et al*., 2022), yet, the increasing demands to meet diverse human needs have constantly put freshwater ecosystems under pressure (Baggio *et al.*, 2021). Flood control, irrigation activities, land drainage, hydropower generation, recreational opportunities, navigational pathways, fisheries, and aquaculture are among the important uses of the freshwater environment for humans (Saulnier-Talbot, 2016; Kumar *et al.*, 2021).

Throughout history, humans have modified and had an impact on existing aquatic ecosystems (Gleeson *et al*., 2020). Human impacts on continental aquatic environments have been temporal and spatial, heterogenous but global in scope, and include widespread cultural eutrophication, global warming, and acidification (Tolotti *et al*., 2018; Owens, 2020). Additionally, the Anthropocene epoch, which arguably began around 1800, reflects the current time of the earth's history where human actions became the dominant forces shaping the earth to a greater degree than other natural processes (Huang *et al*., 2022). During the Anthropocene, rapid industrialization activities across Europe during the mid-20th century were known as the "Great

Acceleration" (Steffen *et al.,* 2015). The Great Acceleration epoch witnessed an unprecedented rise in global atmospheric CO_2 from the burning of fossil fuels, pollution from industries, agriculture, domestic and nuclear activities (Swindles *et al.*, 2015). The Anthropocene including the Great Acceleration are two important geological time scales implicated in the global transformation and changes observed in most aquatic environments worldwide (Steffen *et al.*, 2015; Logemann *et al.*, 2022). Regardless of the boundary officially assigned to the Anthropocene, the human imprint on earth's aquatic ecosystem will be continuous and wide-ranging including nutrient enrichment from agricultural activities (Stachelek *et al.,* 2018), rising surface temperature of freshwater bodies due to global climate change (O'Reilly *et al*., 2020), and hydrological modification from human impacts (Kominoski *et al.*, 2018)

Furthermore, freshwater ecosystems are simultaneously affected by multiple stressors resulting from natural processes and cycles, pollution, and over-use (e.g., overfishing), which often multiply the threats to lakes (Smol, 2010; Folke *et al.*, 2021). Multiple stressors may interact synergistically or antagonistically to yield amplified or diminished additive ecological responses (Folt & Burns, 1999; Okazaki *et al.*, 2017). Additionally, stressors can interact non-additively to yield complex and relatively unpredictable environmental consequences, which can be complicated and difficult to predict (Soranno *et al*., 2019; Lin *et al*., 2021). The complex and sometimes confounding effects of several stressors occurring simultaneously are not only difficult to understand but also challenging to manage (Birk *et al.*, 2020). Therefore, understanding the past changes to an aquatic ecosystem is the aim of the study of paleolimnology (Burge *et al*., 2018).

Paleolimnology is a science that relies on the combination of physical, chemical, and biological information stored in lake and river sediments to infer past environmental changes (Smol, 2009; Reavie, 2020). Paleolimnology techniques give access to a variety of information reflecting early human activities and the corresponding aquatic ecological shifts (Tolotti *et al*., 2018). Paleolimnological methods have also been used in many studies to infer a wide variety of ecosystem changes including water quality in lakes and wetlands (Davis *et al*., 2015; Parra *et al.*, 2021), agricultural pollution (Hall, Leavitt, Quinlan, *et al.,* 1999; Nikolaidis *et al.*, 2022) changes in ice cover due to climate warming (Smol & Douglas, 2007; Cheng *et al*., 2022), and the sources and pathways of atmospheric pollutants (Leavitt *et al*., 2009; Horb *et al*., 2022).

Paleolimnological studies in tropical regions have proven useful in the assessment of human migration and colonization (Siegel *et al.*, 2015; Correa-Metrio *et al*., 2023; Zhang *et al*., 2024), climate change (Hoyos *et al.*, 2017; Okazaki *et al.*, 2017; Mackay *et al.*, 2021 ; Manciu *et al.*, 2022), biogeography of terrestrial and aquatic plants (Correa-Metrio *et al.*, 2012; Torres-Garcia *et al.*, 2022), past lake ontogeny (Wang, Chou, *et al.*, 2021; Bastos *et al.*, 2022), fire history (Behling, 1995; Caffrey & Horn, 2015; Hoyos *et al.*, 2017), domestication of agricultural plants (Johanson *et al.*, 2019; Githumbi *et al.*, 2018), pollution at various time scales (Engstrom *et al.*, 2014; Uglietti *et al.*, 2015; Engels *et al.*, 2018 ; Sari *et al*., 2021), species evolution (Elmer *et al.*, 2009; Ivory *et al.*, 2016), eutrophication (Soeprobowati *et al*., 2012; Zorzal-Almeida *et al*., 2021; Prasetyo *et al.*, 2024) human impacts and hydro-climate (Briddon *et al.*, 2020; Engels *et al.*, 2018; Soeprobowati *et al.*, 2018; Soeprobowati *et al.*, 2023). In addition, paleolimnological methods have been used in tropical regions for tracking the impacts of human activities such as mining, waste disposal, agriculture, livestock husbandry, and pollutant discharge in inland waters (Cohen *et al.*, 2016; Serna *et al.*, 2020; Kutty *et al.*, 2022; Misiko *et al*., 2024).

Lakes are accumulators of large and diverse environmental changes that involve a dynamic interaction between the geosphere, atmosphere, and hydrosphere (Monks *et al*., 2015). This prolonged interaction is driven by abiotic and biotic components of the environment that often lay the foundation for the accumulation of materials by lake sediments (Talbot, 1990; Remor *et al*., 2022). Similarly, the breakdown of nutrients and materials derived from the lake basin including watersheds (terrestrial input) and airsheds (atmospheric input), are conserved in a chronological sequence in lake sediments (Pinceel *et al*., 2013; Shu *et al*., 2021). As such, lakes are often considered sentinels of environmental change because they are sensitive and respond to environmental variables which are often recorded in the lake sediments (Smol & Douglas, 2007; Adrian *et al*., 2009; Moser *et al*., 2019); for example, one of the primary physical changes that lakes undergo because of climate change is the development of enhanced water column thermal stratification (Hondzo & Stefan, 1993). Lake stratification dynamics drive several important limnological processes, such as the distribution of oxygen (Naeher *et al*., 2013; Rabaey *et al*., 2021) and nutrients (O’Reilly *et al*., 2003; Horppila, 2019), primary productivity and habitat availability (De Stasio *et al*., 2018).

Paleolimnological indicators are valuable tools used for the study of physical, chemical, and biological changes archived in the sediments of lakes (Yang *et al*., 2018). The physical and chemical properties of lake sediments have been used in a large number of studies, these include, tracking past erosion events (Bell & Blais, 2021), and the determination of source and magnitude of metal pollution and other contaminants (Cheng *et al*., 2013; Zhao *et al*., 2015). Similarly, biological indicators (mostly microscopic) preserved in sediments have been applied for the reconstruction of past changes in both terrestrial and aquatic environments (Battarbee, 2000; Chen, Ding, *et al*., 2021). Morphological remains, for example, diatom valves and chrysophyte scales, have been used in many studies to infer past environmental conditions (Cumming *et al.*, 1993; Dixit *et al*., 1992; Slemmons *et al*., 2017; Szczerba *et al*., 2021). Consequently, biogeochemical, and organic geochemistry techniques have been employed in reconstructing biota that does not have reliable morphological remains (Cranwell, 1991; Routh *et al*., 2009; Deighton-Smith & Bell, 2017). However, in some circumstances, the preservation of indicators is compromised due to decomposition which can limit some interpretations.

Bukit Merah Reservoir (BMR) is the oldest man-made reservoir located in Peninsular Malaysia of Perak State, was built in 1902 and operated in 1906 (Najib *et al.*, 2017). The aquatic ecosystem and the surrounding catchment areas have been experiencing heavy pressure from agricultural activities, tourism, and other land-use forms. In addition, the lake is experiencing serious sedimentation problems due to increasing silts and organic matter that are filling up the lake. The human population around the catchment of the lake has also increased significantly in recent years due to expanding economic activities (Ismail & Najib, 2011). These human-induced activities may have consequences on the ecological balance of the lake. Hence, the study of the sediments from BMR will provide us with a wealth of information regarding their past environmental conditions necessary for the future management and conservation of the aquatic environment. For example, Lake Tanganyika in Africa and Lake Petén Itzá in Guatemala. Paleolimnological studies in these lakes have enhanced our understanding of historical changes in water quality, climate impacts, and human activities, providing essential data for developing sustainable conservation strategies (Cohen *et al*., 1993; Whitemore *et al.,* 1996).

1.1 Problem statement

The potential of using paleolimnology techniques for establishing restoration targets and reference conditions for freshwater ecosystems has been recognized for a long time and has received renewed attention in the past few years with the introduction of the European Union (EU) Water Framework Directive which made it mandatory for all EU member countries to restore their lakes to good status by 2015, representing a minimal deviation from the reference condition (Bennion & Battarbee, 2007; Bennion *et al*., 2011; Walton *et al.*, 2021). Restoration targets and reference conditions have been established in many lakes using paleolimnological methods (Smol, 2010; Burge *et al.*, 2018; Short *et al.*, 2022), and become a standard technique used for providing information on ecological status, timing, and magnitude of ecological change (Vincent & Laybourn-Parry, 2008; Bennike *et al*., 2021; Qin *et al*., 2022). Thus, Paleolimnological techniques can be used to Identifying a range of past environmental conditions affecting the ecological functioning of the Bukit Merah Reservoir enabling decision-makers and managers the choice of setting reference conditions on which to base restoration strategies of the lake on.

The study of lake sediment archives and the preserved microfossils and chemical constituents allow the reconstruction of environmental impacts on lake ecosystems through time, whether they are being caused by atmospheric pollutants, point source disturbance from agriculture and aquaculture, or impacts of global warming, leading to alterations in local ecology and biodiversity (Cardoso-Silva *et al*., 2021). Paleolimnological records can also provide useful insights into natural variability and baseline conditions before human-environment interactions (Dubois *et al.*, 2018). Malaysia has abundant and diverse water resources ranging from rivers, lakes, ponds, and reservoirs. These water resources have high socio-economic value for the country. They are used as a source of power generation, farming activities, tourism, and fishing (Sharip *et al.*, 2016). However, to date, there has been limited research using paleolimnology to highlight the ecological change and thresholds of the transitions of these freshwater environments due to human activities. Consequently, knowledge from paleolimnological studies on the management of critically important lakes in Malaysia is lacking.

Thus, a sediment core from BMR was studied to examine the potential impact of long-term multiple stressors on the reservoir's ecosystem. Biological sub-fossil remains of diatoms in conjunction with geochemical analysis (total carbon, total nitrogen, total phosphorus, and metals) were used to assess the paleolimnological environmental change in the BMR.

1.2 Objectives of the study

i. To determine the chronology of sediment samples from Bukit Merah Reservoir based on ^{210}Pb activity.

ii. To determine the long-term concentration of metal(loid)s (arsenic, cadmium, copper, lead, zinc, and iron) and nutrients (total nitrogen, total organic carbon, and total phosphorus) in the reservoir.

iii. To reconstruct past limnological characteristics and water quality of the lake by using biological sub-fossil remains of diatom.

1.3 Justification of research

Bukit Merah Reservoir is the oldest man-made lake in Malaysia. The lake and its surrounding catchment area are seriously under threat from tourism, sand mining, aquaculture practices as well as modifications from different land-use forms. However, there is no information or very little is known about the ecological response of the lake to long-term environmental changes. Also, there are few paleolimnological studies conducted in Southeast Asia (Briddon *et al*., 2020; Chawchai *et al*., 2015; Legaspi *et al.*, 2015; Yamoah *et al*., 2016). Therefore, it is hoped that the outcome of this research will provide a proof of concept for the application of paleolimnological studies to the management of ecological processes and functions needed to maintain the ecological integrity of the freshwater ecosystem. Since information on the use of paleolimnology proxies in freshwater bodies is scarce, the outcome of this research intends to provide baseline information that will be relevant to the sustainable management of freshwater ecosystems in Malaysia. The results of this research will hopefully stimulate the proliferation of more research in the field of paleolimnology in Malaysia and Southeast Asian countries.

CHAPTER 2

LITERATURE REVIEW

2.1 Environmental change and freshwater ecosystems

The magnitude of human impact on the environment has increased in recent times which has resulted in the degradation of the ecological systems worldwide (Szabó *et al.,* 2020). Notably, during the mid-20th century popularly known as the great acceleration, the global increase in human population and economic growth, as well as land-use changes, have impacted the health of the ecosystem, eventually influencing the quantity and quality of water resources (Steffen *et al.*, 2015; Saulnier-Talbot, 2016).

The freshwater ecosystem provides important natural capital for ecosystem services such as potable water, fisheries, and recreation (Downing *et al.,* 2012; Grizzetti *et al.*, 2019), yet they are the most degraded and imperiled ecosystems as they are increasingly under threat from human pressures (Carpenter *et al*., 2011; Poikane *et al*., 2020). Several inshore freshwater bodies are presently diminishing due to warmer and drier climates, mismanagement, or a combination of both (Ravilious, 2016). The availability of fresh water is also changing in response to over-use by humans and anthropogenic climate change, with continental water storage trending below previous ranges (Rodell *et al*., 2018).

More so, the net loss of freshwater ecosystem against land area throughout the earth has increased over the last 30 years, especially in Southeast Asia and Amazonia (Donchyts *et al.*, 2016; Yang *et al.*, 2019). Studies using the Aqua monitoring tool reported the emergence of 1180km^2 of water in Mayanmar between 1985 and 2010, linked with the building of dams and reservoirs (Donchyts *et al*., 2016). Similarly, Lehner *et al.* (2011) estimated that 16.7 million reservoirs larger than 0.01 ha possibly represent an area of terrestrial surface water of more than 305, 000 km^2. Anthropogenic modification of continental aquatic ecosystems affects their number, size distributions, biodiversity, physicochemical properties, and functions (Khatun *et al.*, 2021).

A large body of knowledge examining the effect of human actions on freshwater bodies exists for temperate and polar regions (Jones *et al*., 2014; Rühland *et al*., 2015) whereas, in the tropics, long-term impacts of human activities on freshwater ecosystems are poorly understood (Bannister *et al.*, 2019). This gap can be narrowed using a paleolimnological approach to understand the past, present, and future scenarios of freshwater ecosystems, thus making better decisions for sustainable management (Dearing, 2008).

2.2 Anthropogenic drivers of environmental change in lake catchment areas

2.2.1 Eutrophication

Eutrophication is a global environmental problem associated with most freshwater ecosystems (Bunting *et al.*, 2016; Carpenter *et al.*, 2020), primarily triggered by excess input of nitrogen and phosphorus (Zhang *et al*., 2018). Water bodies, including lakes, are affected by cultural eutrophication, causing algal blooms and anoxic "dead zones" (Duarte *et al*., 2009; Wang, García Molinos, *et al*., 2021). Eutrophication can also have detrimental effects on surface water quality, including reduced water clarity and increased toxicity (Schindler *et al*., 2012. Undesirable side effects such as fish kills and reductions in biodiversity have also been reported (Wagner & Erickson, 2017). Recently, the rise in agricultural development and urban land use has been associated with N inputs and increased nutrient loading (Carstensen *et al.*, 2020).

High nutrient concentrations in lakes may be caused by runoff containing synthetic fertilizers, P-containing laundry detergents, and waste from humans and animals (Dodds & Smith, 2016; Mushtaq *et al.*, 2020). Nonetheless, eutrophication can be controlled by regulating nutrient input (N or P) into the water body (Andersen *et al*., 2017). In addition, better restoration success can be achieved with sound knowledge of the biological, chemical, and physical processes in the aquatic ecosystem during eutrophication (Lewtas *et al*., 2015; Stager *et al*., 2020).

Studies on lake eutrophication have been well-documented over the last six decades in temperate regions (Schindler *et al*., 2016; Sun *et al*., 2022). For example, Lake Erie, one of the largest lakes in North America, is known for its rich nutrients and productivity (Reutter, 2019). The International Lake Environment Committee (ILEC) examined the trophic states of selected lakes worldwide between 1988 to 1993. Findings showed that 54% of lakes in the Asia Pacific were eutrophic; Africa 28%, South America 41%, North America 48%, and Europe 53% respectively (Bhagowati & Ahamad, 2019). Yang *et al.*, (2008) investigated lakes in China province. Sixty-seven lakes representing 51.2% of the total lakes examined were rich in nutrients. Water quality deterioration in the freshwater ecosystem is a major challenge in India (Kumar *et al.,* 2021). In Malaysia, a study showed that 62% out of the 90 lakes studied are eutrophic (Sharip & Jusoh, 2010). Agricultural activities, and widespread forest clearance coupled with unplanned development activities in the catchment areas, cause the erosion of sediments and nutrient-rich materials into lakes and are mainly responsible for lake eutrophication in Malaysia (Sharip & Jusoh, 2010). Therefore, historical studies are needed to track, understand, and manage eutrophication in lakes and reservoirs of Malaysia.

2.2.2 Climate change

Globally, climatic change is one of the most challenging environmental issues affecting both the freshwater environment and its resources (MacAlister & Subramanyam, 2018). More than 93% of the impacts associated with climate change are transforming aquatic habitats (Döll *et al.*, 2014), and negatively affecting their overall health status (Hoegh-Guldberg *et al.*, 2017). Amongst several markers of climate change are intensifying high temperature, acidification, deoxygenation, and warming up of the aquatic environment (Maxwell *et al*., 2019). Acidification triggers physiological stress amongst vulnerable aquatic water species (Pörtner, 2008; Thomas *et al*., 2022). Consequently, deoxygenation and hypoxia conditions in an aquatic environment can change the distribution, aerobic scope, and survival of aquatic organisms (Baldissera *et al.*, 2018; Diaz & Rosenberg, 2008), and with persistent anthropogenic forcing, these stressors will further increase, thereby altering the structure and functioning of freshwater environments (Doney *et al*., 2012; He & Silliman, 2019)

Furthermore, climate change can alter the distribution and intensity of additional stressors within aquatic freshwater ecosystems (Engels *et al.*, 2018; Parra *et al.*, 2021; Cheng *et al*., 2022). For example, rising temperatures are projected to impact the occurrence and intensity of diseases in the aquatic environment (Burge *et al.*, 2014), habitat loss (Drouineau *et al*., 2018; Friedland *et al*., 2020), and an increase in a variety of environmental pollutants (Kibria *et al*., 2021). Additionally, climate change stressors co-occur with other stressors, leading to complex interactive impacts on the aquatic environment (Griffith & Gobler, 2020).

Studies on freshwater responses to climate change have received significant attention over the last few decades with a focus on the impact on species and communities (Huang, Ding, *et al*., 2021), climate warming (Berghuijs *et al*., 2017), and precipitations (Felton *et al.,* 2021). In Malaysia, lakes and reservoirs have experienced the impacts of climate change, leading to fluctuations in water levels and changes in flow patterns within these bodies of water (Islam & Elfithri, 2018). Furthermore, the increasing frequency of extreme weather events such as floods and droughts may disrupt the delicate ecological balance of freshwater ecosystems in Malaysia (Ching *et al*., 2015). Also, the rise in sea levels and temperatures may contribute to more frequent occurrences of floods, water scarcity issues, and challenges related to food security (Alam *et al*., 2013; Tang, 2019). In addition, human climate change-induced activities including logging, deforestation for agriculture, particularly for the establishment of oil palm plantations (Lee & Baharuddin, 2018), and industrial activities have continued to exert pressure on Malaysia's freshwater ecosystems (Amin *et al.*, 2018).

Thus, there is a need to conduct paleolimnology study to understand trends and the historical impacts of climate change on the freshwater ecosystems of Malaysia.

2.2.3 Vegetation clearance

Vegetation removal is one of the several lines of evidence concerning early human activities recorded in lake sediment through evidence from pollen and charcoal analyses (Dubois *et al*., 2018). Changes in ecosystems in the catchment of a freshwater ecosystem affect structure and processes within the freshwater environment (Molina *et al*., 2017; Espel *et al*., 2020), for example, vegetation removal from a lake watershed may increase light penetration and sediment load, which may alter microhabitat abundance (Majdi *et al*., 2015; Roth *et al*., 2021) and chemical composition of aquatic sediment (Benson *et al.*, 2018). Vegetation also influences freshwater processes by acting as a sink and/or source of matter and energy, which are attributed to allochthonous sources of organic deposits in lake sediment (Bonetti *et al*., 2021).

2.2.4 Soil erosion

The process where materials are removed from the soil surface by water or wind and transported to another location is referred to as soil erosion (Aygün *et al*., 2021). Soil erosion is crucial for the soil formation processes under natural conditions through geological time (Liu, Xie, *et al*., 2020; Duan *et al.*, 2021). Erosion processes are influenced by anthropogenic and natural factors but are controlled by climate and tectonic cycles (Peizhen *et al*., 2001). Erosion comprises three main steps: detachment, transportation, and deposition, and the resulting soil particles are transported by rolling, floating, splashing, and translocation to the river or site (Baffaut *et al*., 2020).

The anthropogenic modification of freshwater catchments, involving burning, vegetation removal, urbanization, and agricultural practices often leads to variations in soil erosion rates (Dubois *et al*., 2018). Increasing soil erosion rate impacts the freshwater environment through the external loading of sediment, pollutants, and nutrients which can result in flooding, turbidity, and eutrophication (Boardman, 2013). High accumulation of soil in an aquatic ecosystem can also lead to aquatic habitat damage, water deterioration, and a decrease in water storage capacity within the catchment area (Ling *et al*., 2016; Ahilan *et al*., 2019). These fluctuations are often captured in lake records as variations in sediment accumulation rates (SAR) (Foucher, Evrard, *et al.*, 2021) or geochemical profiles (Wen *et al.*, 2020). SAR in high latitude and temperate regions has shown a general decline as soils started to stabilize due to increasing vegetation cover (Holtgrave *et al*., 2020). Gradual changes in SAR are attributed to climate forcing, whereas large perturbations are often linked to anthropogenic activities (Issaka & Ashraf, 2017).

The early recording of disturbance linked to soil erosion is largely determined by the geology and morphology of the river basin (Dubois *et al*., 2018). Other factors such as lake depth (Chiverrell, 2006; Milan *et al*., 2015), catchments ratio (Dearing & Jones, 2003), and erosive tendency of the catchments are also important (Koinig *et al*., 2003). Studies linked to soil erosion in the catchment are often linked to a rise in agriculture (Foucher, Chaboche, *et al.,* 2021). Small upland basins have often eroded in temperate Europe (Flessa *et al*., 2013). In America and Oceania, agricultural intensification associated with industrialization has a wide-scale impact on catchment erosion (Humane *et al*., 2018). Strong evidence of soil erosion in river catchments owing to industrialisation has been reported in China (Wang *et al.*, 2008; Wu *et al*., 2020).

In Malaysia, sediment transportation and soil erosion are the main cause of pollution and siltation in most freshwater ecosystems (Harun *et al*., 2020). It is also one of the major triggers of flash floods in the cities and towns in Malaysia (Chan, 1995). It has been estimated that about 27,000 sq. km of the total land area is impacted by flooding every year affecting more than 4.82 million individuals (Chan, 1995), and an estimated RM 1.06 billion worth of agricultural and public property losses yearly (Liu & Chan, 2003). Some important examples of uncontrolled sedimentation-aided flood events in the country include the Cameroon Highlands floods in 2013 and 2014 and the Kelantan flood in 2014 (Omran *et al*., 2018), with an estimated RM2.9 billion worth of public infrastructure damaged (Chan *et al*., 2016). Severe depletion of aquatic life and reduced river flow capacity are other notable impacts of sedimentation and erosion. Timber extraction, uncontrolled development of land due to urbanization, agriculture, and mining are the major cause of sediment loads into the freshwater ecosystems of Malaysia (Harun *et al*., 2020). Although much attention has been given to the problem of sedimentation and erosion in Malaysia (Kamarudin *et al*., 2017; Rendana *et al*., 2017; Bylak & Kukuła, 2022), however, more needs to be done in tracking historical erosional events to further understand the pattern and causes of erosion and sediment delivery into lakes in Malaysia.

2.2.5 Species introduction

Most freshwater environments are vulnerable to invasive species because of their relatively high level of remoteness (David *et al*., 2017). Hence, the introduction of biological non-native species into freshwater ecosystems can cause important changes to their structure and functioning (Gurevitch & Padilla, 2004; Kamenova *et al*., 2017). Early impacts of biological invasion on freshwater habitats were recorded in the Americas (Lavery *et al*., 2014; DeWeese *et al*., 2021), Oceanic islands (van Leeuwen *et al*., 2005) and Australia (Dick *et al*., 2011), and most invasive species in paleolimnology records are from known biological taxonomical preserved forms, such as Cladocerans (Hairston *et al*., 1999; Eggermont & Martens, 2011) and diatoms (Stoermer *et al*., 1996; Reavie *et al*., 1998). Invasion by taxonomic groups that are less well-preserved can be inferred by tracking patterns of change in other taxa (Costa *et al*., 2021), for example, the presence of fish in a formerly fishless aquatic ecosystem can be tracked based on morphology, abundance, and size of invertebrate prey *Bosmina* and its predator *Chaoborus* (Labaj *et al*., 2017), and the extent to which non-invasive species drive ecosystem change, depending on the response to change driven by other factors such as eutrophication and catchment disturbance (Burge *et al*., 2014; Kamenova *et al*., 2017).

One of the key limitations of using paleolimnology to track biological invasion is the taxonomical challenge of identifying biological groups at the species level from preserved remains (Costa *et al*., 2021). However, recent developments in using a prehistoric record of DNA stored in lake sediments (Epp *et al*., 2015; Domaizon *et al*., 2017), have now made it possible to track the timing and degree of invasive species introduced to the freshwater environment (Preston *et al*., 2012; Stager *et al*., 2015). Therefore, this new tool can play a significant role in paleolimnology studies in helping to track a range of invasive species introductions and linking them to past and early human presence.

2.2.6 Pollution

Paleolimnological evidence for pollution on pre-industrial to millennial time scales is widespread (Catalan *et al.*, 2013). Available records of human pressure from contaminants indicated direct inputs at sites (Hillman *et al*., 2017), while inputs from remote regions, such as mountain regions or Artic come from atmospheric deposition (MacDonald *et al*., 2016).

Lakes sinks for pollutants and provide evidence of different metals and organic pollutants that have been in use for millennia around the world (Bragée *et al*., 2013). Elevated levels of lead (Pb), copper (Cu), or mercury (Hg) resulting from smelting have been detected in freshwater sediment over the last 3000 to 4000 years ago across Europe, Peru, and China (Cooke *et al.*, 2009; Wolfe *et al.*, 2013; Dubois *et al*., 2018). For pollutants that have both industrial and natural sources, such as polycyclic aromatic compounds and metals, paleolimnology often offers the only available means to ascertain whether elevated pollutants load in freshwater are due to naturally occurring or industrial activities (Korosi *et al*., 2015; Thienpont *et al*., 2017).

Studies on the environmental impact of pollution on freshwater have addressed the challenge of lake acidification in the 19th and 20th centuries (Monteith *et al*., 2005; Ginn *et al*., 2007), the problem of eutrophication from agricultural fertilizers and detergents during the 20th century (Jenny *et al*., 2016), and issues from atmospheric deposition of reactive nitrogen since the start of the 20th century (Spaulding *et al*., 2015). Consequently, in Southeast Asia (SEA), atmospheric pollution in Japan, China, the Philippines, and Malaysia, has been identified as a major inter-regional problem during the 20th century (Engels *et al*., 2018; Chen *et al*., 2020; Fong *et al*., 2020). As such, more palaeoecological investigations on the impacts of pollution on ecosystems need to be conducted in SEA, especially in Malaysia.

2.2.7 Habitat modification

Habitat modification involves any human actions that directly change the physical flow of water into the aquatic ecosystem (Arya, 2021). This includes groundwater manipulation, river engineering, and the creation of new aquatic ecosystems through damming (Saulnier-Talbot & Lavoie, 2018). The anthropogenic modification of the aquatic ecosystem will lead to changes in their distribution, sizes, shapes, biodiversity, physicochemical parameters, and functions (Downing & Duarte, 2009; Downing, 2010). More so, with the ever-increasing capacity to reshape the global environment and impact biogeochemical cycles, human actions have been creating new continental aquatic environments since the mid-20th century (Wada *et al*., 2017; Słowiński *et al.*, 2022)

The dynamics of a freshwater ecosystem are reflected in its sediment record which is influenced by basin morphometry, vegetation, and the situation at the catchment (Saulnier-Talbot & Lavoie, 2018). The building of impoundment raises water levels and fast increases the disposal of deeper, pelagic habitats, which may lead to increased pollution and sedimentation (Reeve *et al.*, 2016). Additionally, hydrological changes can impact flooding and the onset of stratification which may affect the freshwater nutrient budget (Tolotti *et al*., 2010) or intensify freshwater anoxia resulting in plant loss (Dick *et al*., 2011). The loss of plant habitat may lead to a reduction in the abundance and diversity of dependent invertebrates and vertebrate fauna (Fraser *et al.*, 2015; Kattel, 2019).

2.3 Aquatic ecosystem modified /created by humans to meet needs

2.3.1 Reservoirs and impoundments

For thousands of years now, humans have been constructing different types of reservoirs for water storage and other uses (Lehner *et al.*, 2011; Wohl *et al*., 2017). As the demand for water increases and is projected to rise significantly by 2050, farm ponds and large impoundments are also expected to increase by 1 to 2 % annually (Downing & Duarte, 2009). It has also been reported that 48% of the world's freshwater ecosystems are impacted by fragmentation and flow regulation; this figure is projected to rise to 93% by 2030 if all planned dams are constructed (Gill & Malamud, 2017). Not all reservoirs are human made, some are natural lakes where a dam is constructed to control the water level. (Bennion *et al.,* 2018). Man-made reservoirs are strips of land that are permanently flooded by an impoundment, forming a new lentic environment from what were originally terrestrial and lotic environments (Tranvik *et al.*, 2018). Therefore, transforming terrestrial environments into aquatic ones at a local to a regional level creates varying environmental conditions that can have significant impacts on biota composition (Rojas-Sandoval *et al.*, 2020). Also, river connectivity can be altered which might impact species dispersal (Havel *et al*., 2005).

Despite the gains that reservoirs provide, they can cause multiple and challenging ecological impacts; for example, the flow intermittent of some rivers in the USA was affected due to damming of the Colorado river (Flessa *et al*., 2013). Destruction of lands caused by the Three Gorges Dam, China (Huang *et al*., 2019), sediment and nutrient dispersal by Aswan High Dam, Egypt with impact on downstream productivity and seasonal inundating along the bank of River Nile (Nixon, 2003). Analysis of the sediment core from Futou Lake showed that the dams built in 1935 and the early 1970s stabilized the hydrological conditions of the Futou Lake and stalled the interaction with the Yangtze River, resulting in an increase in macrophyte-type related chironomids of *C. sylvestris*, *Paratanytarsus sp.*, *P.* penicillatus and decrease in elements (Al, Mg, Fe) transported into the lake (Zeng *et al*., 2018).

A study of algal pigment, chironomids, and diatoms in sediment cores from two similar prairie reservoirs showed that differences in hydrological regime and reservoir formation resulted in unique patterns of aquatic community change. Lake Diefenbaker, a reservoir established in 1968 by the impoundment of the South Saskatchewan River, experiences mean water level fluctuations of 6 m per year. In contrast, damming of Buffalo Pound Lake in 1952 inundated a natural lake, raise average water levels to -2.0 m, and reduced water level fluctuations from -3 to < 1 m yearly. A comparison of fossils showed that benthic algal and chironomid were rare, whereas planktonic taxa dominated the diatom community structure all the time in Lake Diefenbaker. In contrast, pigment analyses indicated a decline in the phytoplankton community after damming Buffalo Pound Lake, however, the macrophytes and chironomids population expanded (Hall, Leavitt, Dixit, *et al.*, 1999). Halac *et al.* (2020), revealed that fluvial influence, nutrient inputs, and hydrometeorological factors such as precipitation and change in water level influenced the phytoplankton community composition of San Roque reservoir Córdoba, Argentina.

In Malaysia, the creation of dams has resulted in the regulation of river flow by causing shifts in natural patterns, disrupting seasonal flooding and the flushing of river systems (Tang, 2019; Chong *et al*., 2021). This alteration affects nutrient cycling, sediment transport, and the overall well-being of downstream ecosystems (Sim *et al*., 2016). Additionally, fluctuating water levels behind dams can influence the habitats of aquatic species, especially those reliant on specific water levels for breeding, nesting, or feeding (Faizal *et al*., 2017). Furthermore, the damming of rivers in Malaysia may cause shifts in water quality, with increased sedimentation and the accumulation of nutrients. (Chong *et al*. 2021). These sediments can contain pollutants, heavy metals, and nutrients from upstream sources, impacting the health of aquatic environments (Faizal *et al*., 2017).

Therefore, more investigations are needed to address the impacts of impoundments on the hydrological condition and biota composition of freshwater ecosystems in Malaysia.

2.3.2 Stormwater ponds

Stormwater is the water that originates from precipitation events, such as rain, sleet, or snowmelt (Epele *et al*., 2018). It can accumulate on surfaces like roads, rooftops, and other impermeable areas and flow over land before eventually infiltrating into the ground or entering storm drains, rivers, and lakes (Messager *et al*., 2016). Stormwater pond creation has become important in urban development planning. For example, the SMART Tunnel (Stormwater Management and Road Tunnel) in Kuala Lumpur was designed to mitigate flash floods in the Kuala Lumpur city center and provide a traffic route (JPBD, 2017).

Such ponds play crucial roles in the management of runoff flows in areas with impenetrable surfaces (Williams *et al*., 2013). These tiny water bodies are exposed to significant environmental stressors as they carry pollutants such as hydrocarbon, salts, and metals to larger water bodies (Cereghino *et al*., 2010). Stormwater ponds and their linked wetlands in some instances can increase local biodiversity (Messager *et al*., 2016). Although studies have shown the potential of these structures to preserve biodiversity and other functions (Cereghino *et al*., 2010), information concerning their past water quality assessment may be lacking, which can be addressed through paleolimnology studies.

2.3.3 Rural ponds

Small rural ponds such as farm ponds, and dew ponds are linked with land reclaimed from rivers and other water bodies, but collectively, they may cover a large area (Epele *et al*., 2018). It has been estimated globally that a total of 77 000 km^2 area is covered by small agricultural ponds and is projected to increase by 60% annually due to pressure to provide food for the rising human population (Downing & Duarte, 2009). Rural ponds provide numerous ecosystem services, including water for livestock, flood protection, and irrigation. Additionally, these small aquatic ecosystems can affect biodiversity by providing a transient area for colonizing and migrating species (Erős *et al*., 2020).

2.3.4 Urban and rural wetlands

Wetlands are productive aquatic environments that play a vital role in maintaining biodiversity (Kennedy & Mayer, 2002). They are good natural filters for contaminants and nutrients and absorb the effects of floods, making them important ecosystem buffers between upland water sources and adjacent ecosystems (Xu *et al.*, 2022). They also tend to reduce temperature, thereby lowering heat-island effects (Calheiros *et al*., 2017).

Several wetlands globally are at risk of being wiped out due to increasing urban and agricultural developments (Zedler & Kercher, 2005). Still, new wetlands are being built to lessen the loss of this important type of ecosystem (Giosa *et al*., 2018).

2.3.5 Ditches

Ditches are distributed worldwide, mostly in wetlands and agricultural-rich regions, but also in urban and forest landscapes (Cital *et al.*, 2022). For example, the United Kingdom has an estimated 600 000km of intermittent and permanent ditches, which serves different purposes including as refugia for biodiversity (Biggs *et al*., 2017). Despite the low water quality in some environments, ditches have been discovered to support key biological diversity and provide good ecosystem services (Biggs *et al*., 2017; Grizzetti *et al*., 2019). Even with the significance of ditches in terms of the ecological benefit they provide, this man-made environment remains the least studied part of the freshwater ecosystem (Teurlincx *et al*., 2018; Merga & Van den Brink, 2021).

2.4 Limnological studies in Tropical Areas

Tropical freshwaters are highly diverse but can be largely categorized into lentic or lotic systems (Steffen *et al*., 2015). They are defined by fluctuations in water flow and/or water levels and are driven by a wide range of factors including landscape morphology, rainfall patterns, water quality, biotic interactions, hydrology, and connectivity (Carpenter *et al*., 2011; Saulnier-Talbot, 2016). Variations in these factors result in significantly different environments, including upland streams and rivers, large lakes, floodplain rivers, and wetlands (Rodell *et al*., 2018; Poikane *et al*., 2020).

In Africa, declines in water quantity are accompanied by deteriorations in water quality, making even available water unsuitable for use (Jones *et al*., 2014; Duker *et al*., 2020). These changes in water availability come about in response to natural and anthropogenic processes, including climate change and variability, domestic and industrial pollution, salinization, population growth, and competition for water (Harding 2015; Stager *et al*., 2020). All these are further complicated by inadequate and poor-quality water data and knowledge gaps (Sarmento, 2012; Harding, 2015).

Freshwater in India faces numerous challenges, including the lack of restoration efforts, rising water pollution, and ineffective wastewater management (Noriega *et al*., 2022). A large amount of domestic, industrial, and agricultural waste is being discharged into water bodies without proper treatment (Iglesias, 2020; Mishra, 2023). The challenges of the freshwater environment in Brazil are numerous and complex, with various factors contributing to the degradation and scarcity of water resources (Nobile *et al*., 2020). In Northeast Brazil, water stress is a significant issue due to the scarcity of groundwater resources, which are few, salty, and over-exploited (Torremorell *et al.*, 2021). The region relies heavily on water storage in reservoirs,