

**ASSESSING PHYSICO-CHEMICAL
CHARACTERISTICS IN RELATION TO WATER
QUALITY AND TROPHIC STATUS INDICES IN
PUAH RESERVOIR, TERENGGANU**

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QUALITY AND TROPHIC STATUS INDICES IN
PUAH RESERVOIR, TERENGGANU**

by

ALYAA FILZA BINTI EFFENDI

**Thesis submitted in fulfilment of the requirements
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LIST OF SYMBOLS

DO	Dissolved Oxygen
COD	Chemical Oxygen Demand
BOD ₅	Biological Oxygen Demand
AN	Ammoniacal Nitrogen
NO ₃ ⁻	Nitrate
NO ₂ ⁻	Nitrite
TSS	Total Suspended Solids
TP	Total Phosphorus
TN	Total Nitrogen
mg/L	Miligrams per Liter
ktoe	Kilo-tonne oil equivalent

LIST OF ABBREVIATIONS

USM	Universiti Sains Malaysia
DEIA	Detailed Environmental Impact Assessment
NWQS	National Water Quality Standard
TNB	Tenaga Nasional Berhad
TNBR	TNB Research Sdn Bhd
ESG	Environmental, Social, and Governance goals
WQI	water quality index
TSI	Carlson's Trophic State Index
PERHILITAN	Department of Wildlife and National Parks Peninsular Malaysia
KETENGAH	Central Terengganu Development Authority
DOE	Department of Environment
NAHRIM	National Hydraulic Research Institute of Malaysia
HTHS	Hulu Terengganu Hydropower Station
SPSS	Statistical Package for the Social Sciences
ANOVA	analysis of variance

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PENILAIAN CIRI FIZIKOKIMIA BERKAITAN INDEKS KUALITI AIR DAN STATUS TROFIK DI EMPANGAN PUAH, TERENGGANU

ABSTRAK

Kajian ini menilai ciri limnologi dan kualiti air di Empangan Puah di Stesen Hidroelektrik Hulu Terengganu dari Februari 2018 hingga Februari 2020. Objektif kajian ini adalah untuk mengkaji variasi bermusim dan ruang dalam parameter kualiti air, profil oksigen terlarut (DO), dan status trofik bagi menyokong operasi hidroelektrik yang mampan dan kesihatan ekosistem akuatik. Pengambilan sampel dilakukan di tujuh tapak dalam tiga zon longitud; zon sungai, zon peralihan, dan zon tasik, dengan memberi tumpuan kepada empat belas parameter utama, termasuk oksigen terlarut (DO), suhu, pH, kekonduksian, kedalaman Secchi, pepejal terampai jumlah (TSS), permintaan oksigen kimia (COD), permintaan oksigen biologi (BOD), nitrogen ammoniak (AN), nitrat (NO_3^-), nitrit (NO_2^-), fosforus jumlah (TP), nitrogen jumlah (TN), dan klorofil-a. Penilaian ruang menunjukkan variasi yang ketara di antara zon-zon empangan. Zon tasik menunjukkan ketelusan air yang lebih baik (kedalaman Secchi 2.5 m) dan kepekatan klorofil-a yang lebih tinggi ($4.2 \mu\text{g/L}$) berbanding zon sungai, yang menunjukkan keadaan lebih eutrofik yang menggalakkan produktiviti primer. Sebaliknya, zon sungai mencatatkan ketelusan yang lebih rendah dan pepejal terampai yang lebih tinggi (purata TSS 20 mg/L) akibat peningkatan sedimen. Variasi temporal menonjolkan perubahan bermusim, terutamanya antara musim basah dan kering. Semasa musim kering, tahap DO menurun (minima 5.2 mg/L pada kedalaman) berbanding dengan nilai yang lebih tinggi semasa musim basah (sehingga 7.5 mg/L di permukaan). Profil menegak menunjukkan stratifikasi termal yang stabil, dengan termoklin yang jelas antara 3-9 meter, menyebabkan keadaan hipoksik pada kedalaman melebihi 10 meter di beberapa lokasi, terutamanya

hipolimnion. pH berada dalam julat sedikit berasid hingga neutral (6.5-7.2) di seluruh kedalaman, dengan sedikit fluktuasi bermusim. Indeks Kualiti Air (WQI) mengategorikan Empangan Puah sebagai Kelas II, sesuai untuk spesies akuatik sensitif, walaupun penurunan sedikit diperhatikan semasa tempoh kering. Indeks Status Trofik Carlson (TSI) menunjukkan status mesotrofik hingga eutrofik sederhana, dengan nilai antara 50 hingga 60, mencerminkan produktiviti sederhana dan potensi pertumbuhan alga secara berkala. Penemuan ini menekankan keperluan pemantauan berterusan untuk menguruskan kualiti air, terutamanya semasa musim kering, bagi mengurangkan potensi eutrofikasi dan mengekalkan fungsi hidroelektrik dan ekologi di empangan.

**ASSESSING PHYSICO-CHEMICAL CHARACTERISTICS IN RELATION
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ABSTRACT

This study assesses the limnological and water quality characteristics of the Puah Reservoir at Hulu Terengganu Hydropower Station from February 2018 to February 2020. The study aimed to examine seasonal and spatial variations in water quality parameters, dissolved oxygen (DO) profiles, and trophic status to support sustainable hydropower operation and aquatic ecosystem health. Sampling across seven sites within three longitudinal zones; riverine, transitional, and lacustrine, focused on fourteen key parameters, including dissolved oxygen (DO), temperature, pH, conductivity, Secchi depth, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), ammoniacal nitrogen (AN), nitrate (NO_3^-), nitrite (NO_2^-), total phosphorus (TP), total nitrogen (TN), and chlorophyll-a. Spatial assessments showed considerable variation across the reservoir's zones. The lacustrine zone exhibited greater water clarity (Secchi depth of 2.5 m) and higher chlorophyll-a concentrations ($4.2 \mu\text{g/L}$) than the riverine zone, indicating a more eutrophic condition favorable to primary productivity. Conversely, the riverine zone recorded lower clarity and higher suspended solids (average TSS of 20 mg/L) due to increased sedimentation. Temporal variations highlighted seasonal shifts, particularly between the wet and dry seasons. During the dry season, DO levels decreased (minimum of 5.2 mg/L at depth) in contrast to higher values during the wet season (up to 7.5 mg/L at the surface). Vertical profiling revealed stable thermal stratification, with a defined thermocline between 3-9 meters, leading to hypoxic conditions at depths beyond 10 meters in some locations, particularly the hypolimnion. The pH

ranged from slightly acidic to neutral (6.5-7.2) across depths, with little seasonal fluctuation. The Water Quality Index (WQI) categorized the Puah Reservoir as Class II, suitable for sensitive aquatic species, although slight declines were observed during drier periods. Carlson's Trophic State Index (TSI) indicated a mesotrophic to moderately eutrophic status, with values ranging from 50 to 60, reflecting moderate productivity and occasional algal growth potential. These findings underscore the need for continuous monitoring to manage water quality, particularly during dry seasons, to mitigate potential eutrophication and sustain hydropower and ecological functions in the reservoir.

CHAPTER 1

INTRODUCTION

1.1 Study Background

Water is an essential resource for life. It helps in nourishing ecosystems and supports social and economic development. These resources play an important role in providing clean water, supporting agriculture, generating electricity, and supporting ecosystems. An example is the Puah Reservoir in Terengganu, Malaysia. It is one of the regional water sources. However, these water bodies are highly disturbed by human activities, such as land modification, agricultural irrigation and urbanization, affecting water and air quality (Dumitran *et al.*, 2020).

Understanding the physico-chemical properties of a water body is important. It is used to assess water quality and determine its trophic status. Parameters such as temperature, pH, dissolved oxygen and nutrients are important indicators of water quality as it affects the quality of organisms, which play an important role in assessing the health of the source environment (Li *et al.*, 2020). Environmental conditions that indicate the productivity of the water body from oligotrophic (low productivity) to eutrophic (high productivity) are assessed using parameters such as the Carlson Trophic State Index (TSI) (Li *et al.*, 2020). Examining these features provides information on the current condition of the tree and helps identify potential environmental issues.

1.2 Importance of Assessing Water Quality and Trophic Status

Water quality assessment is important for the sustainable management of freshwater resources. Poor water quality can lead to environmental and health problems such as algal blooms, hypoxia and water-borne diseases, in which give significant economic and social consequences to fishing, tourism and the availability of drinking water (Rivera *et al.*, 2022). Assessment of trophic state is also important because it provides a comprehensive measure of the nutrient and productivity of the water body. The trophic state of spring can influence its suitability for various uses, including recreation, fishing, and drinking water supply (Sharip *et al.*, 2014).

Recent findings have indicated that water quality and trophic state may be changing due to increasing human pressures. These changes require in-depth research to provide current data and facilitate effective management strategies (Dumitran *et al.*, 2020). By evaluating the physicochemical properties and assessing the trophic state of the spring, this study aims to provide an understanding of its ecological health and guide future conservation efforts.

1.3 Hulu Terengganu Hydropower Station (HTHS)

As Malaysia's largest energy company, Tenaga Nasional Berhad (TNB) has completed the development of a new hydroelectric station to meet the growing demand for electricity in the region. This hydroelectric station has been operating since 2016. It is also an important part of Malaysia's strategy to strengthen its renewable energy capacity and secure the electricity supply. This project demonstrates TNB's commitment to sustainable energy generation and its commitment to environmental regulations.

In addition, the development of Hulu Terengganu Hydropower Station (HTHS) must comply with the Environmental Quality Act 1974. The Act requires a detail environmental impact assessment (DEIA) so that the project does not cause negative effects on the environment. As a result, the DEIA study for the HTHS was comprehensive and addressed environmental impacts in various aspects of the project. In addition, the Environmental Impact Assessment (EIA) Agreement for the HTHS project is an Environmental Monitoring Plan (EMP). The EMP describes the procedures for monitoring and managing environmental impacts throughout the life cycle of the hydroelectric station. Monitoring is carried out on the EMP to ensure compliance with environmental standards and to minimize adverse effects on the local ecosystem.

HTHS is strategically located upstream of the Sultan Mahmud Kenyir Hydroelectric Station, within the Tembat and Petuang Forest Reserves in the Hulu Terengganu district based on its suitability for hydroelectric generation and its potential to contribute significantly to the region's renewable energy output. HTHS development encompasses two major hydropower dams: i) Puah Dam and ii) Tembat Dam. These dams play an essential function in the hydroelectric scheme, offering the vital water storage and flow regulation to generate strength efficiently. TNB Research (TNBR) has performed a complete environmental study encompassing all levels of the HTHS development: pre-construction, construction, impoundment, and operational levels. This holistic strategy ensures that environmental concerns are incorporated into each degree of the development, from preliminary making plans to complete operation. Hence, this thesis focuses on the operational phase of the Puah Reservoir via monitoring the physico-chemical characteristic of the reservoir.

1.4 Research Problem and Objectives

The impoundment of a hydroelectric station leads to various significant changes in the physical, chemical, and biological aspects of a river ecosystem transitioning from a lotic to a lentic environment. This alteration affects water flow, sediment deposition, and temperature stratification, subsequently impacting the chemical and biological characteristics of the reservoir (Woldemichael *et al.*, 2012). The impoundment indirectly influences local or regional hydrometeorology, precipitation and land use or land cover, thereby affecting the surrounding landscape and hydrologic processes (Woldemichael *et al.*, 2012). In particular, reservoirs can trigger earthquakes, as in cases such as the 2008 Wenchuan earthquake caused by the Zipingpu reservoir (Ge *et al.*, 2009; Gahalaut & Gahalaut, 2010).

In addition, the impoundment of reservoir causes a change in the composition and abundance of phytoplankton, thus affecting the balance of the ecosystem (Rodrigues *et al.*, 2009; Souza *et al.*, 2016). The variability of the sediment, which is observed in reservoir such as Tehri in the Garhwal Himalayas, is caused by seasonal loading, leading to measurable subsidence in the reservoir's vicinity (Yadav *et al.*, 2017). Reservoir impoundment can impact rainfall erosivity, riverbed adjustments, and sea level rise, thereby influencing the hydrological cycle and sediment transport (Ding *et al.*, 2022).

Additionally, the transition from a lotic to lentic environment can negatively affect the reproductive parameters of migratory fish, impacting their population maintenance in dammed rivers (Souza *et al.*, 2021). Reservoir impoundment can also alter soil properties, carbon distribution, and physico-chemical characteristics in the buffer zones of newly formed reservoirs (Yan *et al.*, 2022). Furthermore, the vertical thermal

structure of reservoirs during impoundment phase. As a result, this will affect water temperature and ecological conditions both within the reservoir and downstream (Dai *et al.*, 2019). Prediction by DEIA also on the chemical changes which involving the variations in water quality parameters such as nutrient concentrations, pH levels, and dissolved oxygen (DO). Stagnant condition occur when there is decreasing in water movement. Then, this will cause the accumulation of nutrients such as nitrogen and phosphorus and indirectly increase the risk of eutrophication. This then can lead to algal blooms and reduced oxygen availability. Such changes can have significant consequences for aquatic food web and water quality.

The impoundment of the hydroelectric station and the subsequent transition of a river ecosystem to a lentic environment are expected to lead to changes in species composition and abundance. This transition favours species adapted to still water conditions while disadvantaging those adapted to flowing water environments, potentially leading to a reduction in biodiversity. Moreover, the introduction of invasive species due to these changes can further disrupt the ecosystem balance (Ehrenfeld, 2010). The absence of current operational phase data for Puah Reservoir presents significant challenges in accurately understanding and addressing the expected environmental scenarios outlined in the Detailed Environmental Impact Assessment (DEIA). This data gap impedes the verification of DEIA predictions, monitoring of changes, and implementation of necessary management strategies (Agostinho *et al.*, 2008).

Research indicates that the formation of reservoirs initially boosts fish species richness due to the inclusion of surrounding habitats, but richness tends to decline as reservoirs age (Agostinho *et al.*, 2008). Reservoir construction can also result in the taxonomic homogenization of fish communities compared to river ecosystems, impacting both native and invasive species (Clavero & Hermoso, 2010). Additionally, the replacement of endemic riverine species by cosmopolitan lentic species in reservoirs can influence overall biodiversity and ecological balance (Ricciardi & MacIsaac, 2010). Without a comprehensive operational data, the actual impacts on water quality, nutrient dynamics, and ecological health cannot be assess such as the extent of nutrient accumulation and the risk of eutrophication cannot be effectively evaluated. Similarly, changes in species composition and biodiversity remain uncertain without continuous monitoring.

The primary aim of this thesis is to address this gap by conducting a thorough assessment of the physico-chemical characteristics of Puah Reservoir and evaluating its trophic status using established indices. The specific objectives of the study are to:

1. To determine the physico-chemical parameters of Puah Reservoir based on spatial and temporal variation.
2. To determine the vertical water profile of Puah Reservoir.
3. To determine the water quality index (WQI) and Carlson's Trophic State Index (TSI) of Puah Reservoir

1.5 Study Impacts

By assessing the physicochemical properties and evaluating the trophic conditions of Puah Reservoir, this study aims to contribute to the understanding of ecological health and introduce sustainable management practices. The findings will provide valuable information to policymakers, environmentalists and researchers and help determine the sustainability management of this water resource. With a detailed and systematic approach, this thesis aims to address existing knowledge gaps and provide practical solutions to the problems faced by the Puah Reservoir during operational phase.

CHAPTER 2

LITERATURE REVIEW

2.1 Dams and Hydroelectric Power in Malaysia

The demand for energy has been steadily rising due to factors such as population growth, industrialization, and urbanization in Malaysia. According to the Malaysia Energy Statistics Handbook 2020, the country's total final energy consumption in 2019 was 34,535 ktoe, 2.2% increase from the previous year. Tenaga Nasional Berhad (TNB) is Malaysia's largest electricity utility company, and it has been actively pursuing renewable energy development as part of its commitment to sustainable and responsible business practices. The construction of hydroelectric dams creates a new lentic ecosystem, transforming terrestrial land into an aquatic habitat and changing lotic habitats to lentic ones as a result of significant hydrological changes in water flow, volume, and depth. Deep man-made lakes especially created for hydropower generation are experiencing stratification problem (Sharip & Zakaria, 2008).

The construction and operation of over 1 million dams globally (Lehner *et al.*, 2011) has provided a variety of services important to a growing human population. Mohd Hazri (2019) reported that there is a total of 103 reservoirs in Malaysia that serve multiple purposes. Reservoirs are used for a range of purposes such as irrigation, water supply, hydropower generation, flood control, navigation, and water supply (Bonnet *et al.*, 2015). Occasionally, there are also reservoirs been open for recreational activities such as fishing, swimming, and boating. Most of these reservoirs located in the states of Sarawak, Pahang, Perak, Selangor, and Johor. While some of these reservoirs are small and used for specific purposes, others are large-scale projects that have a significant impact on the environment and surrounding communities. The development

of these reservoirs has helped to meet the increasing demand for water and energy in Malaysia, but it also poses significant challenges in terms of environmental management and sustainability. According to a preliminary desktop study on the current state of eutrophication in lakes across Malaysia, it was found that over 60% of the 90 lakes and reservoirs that were reviewed in the country are currently experiencing eutrophication (NAHRIM 2005, Zati & Zulkifli 2007).

2.2 Limnological Implications of Hydroelectric Projects

Hydroelectric projects reservoirs have significant limnological implications that can greatly impact aquatic ecosystems and biodiversity. The construction of dams in cascade schemes, can lead to substantial alterations in fish fauna, habitat, and species richness. These shall result in the decline of fisheries due to habitat loss and hydrological changes (Agostinho *et al.*, 2008). These changes disrupt the natural flow of rivers, affecting fish migration patterns and breeding grounds, leading to reduced fish populations and biodiversity (Agostinho *et al.*, 2008).

Limnological studies through analyzing spatial-temporal variations in limnological parameters, such as water quality and nutrient levels, shall provide insights into the ecological health of reservoirs (Couto & Olden, 2018). Monitoring water quality is essential to manage and mitigate the impacts of hydroelectric projects on aquatic ecosystems (Couto & Olden, 2018). The construction of hydroelectric dams can influence the zooplankton community structure by altering water flow and habitat, which consequently affects the composition and abundance of zooplankton communities (Santos *et al.*, 2020). These changes can have cascading effects on the food web and impacting the entire aquatic ecosystem (Santos *et al.*, 2020). Hydropower development is influenced by the need for sustainable practices and the impact of

climate change on hydroelectricity generation (Dahal *et. al*, 2024). Sustainable hydropower practices are crucial to minimize adverse environmental effects and ensure the long-term viability of hydroelectric projects (Dahal *et. al*, 2024). Small hydropower plants offer a sustainable alternative to large-scale dams, with fewer environmental impacts and significant benefits for local communities (Lange *et al.*, 2018). The physical and chemical characteristics of reservoirs, such as location, size, and material loading potential, play a significant role in the limnological development of lakes and reservoirs (Chomać-Pierzecka *et al.*, 2022). Operation decisions, like water release and level changes, have marked impacts on water column characteristics, influencing biotic communities (Chomać-Pierzecka *et al.*, 2022). Longitudinal gradients in physical, chemical, and biological characteristics are established due to interactions between river inflows, the reservoir basin, and water column characteristics (Nhiakao *et al.*, 2022). These gradients influence nutrient concentrations, algal production, and overall ecosystem dynamics within reservoirs (Nhiakao *et al.*, 2022). Water residence time is crucial in establishing gradients within reservoirs, with intermediate water residence times hypothesized to exhibit the greatest spatial heterogeneity (Hirsch *et al.*, 2016). Changes in water residence time can impact plankton populations, altering their distribution and abundance and affecting the overall productivity and ecological balance of the reservoir (Hirsch *et al.*, 2016).

2.3 Spatial and Temporal Variation in Reservoirs

Spatial and temporal variations in reservoirs play a crucial role in understanding the ecological dynamics and water quality within these artificial water bodies. These variations are influenced by several factors, such as reservoir morphology, hydrological inputs, climatic conditions, and operational practices. Research has demonstrated that

reservoirs vary significantly in terms of temporal and spatial variation in a range of limnological factors. Studies on phytoplankton in Brazilian reservoirs showed temporal and regional fluctuations in phytoplankton composition (Borges *et al.*, 2008). Furthermore, studies on cyanobacteria in China's Miyun Reservoir to uncover temporal and spatial variations in nutrients and phytoplankton communities to develop effective strategies for controlling their growth (Su *et al.*, 2014). According to Yang *et al.* (2013), studies conducted on methane emissions from the Three Gorges Reservoir in China have shown fluctuations in diffusive methane emissions in spatial and temporal. Similarly, studies conducted on Brazil's Dona Francisca reservoir revealed distinct spatial and temporal, highlighting the importance of considering of the fluctuations for effective reservoir management (Oliveira *et al.*, 2020).

2.3.1 Spatial Variation in Reservoirs

2.3.1(a) Reservoir Longitudinal Gradient

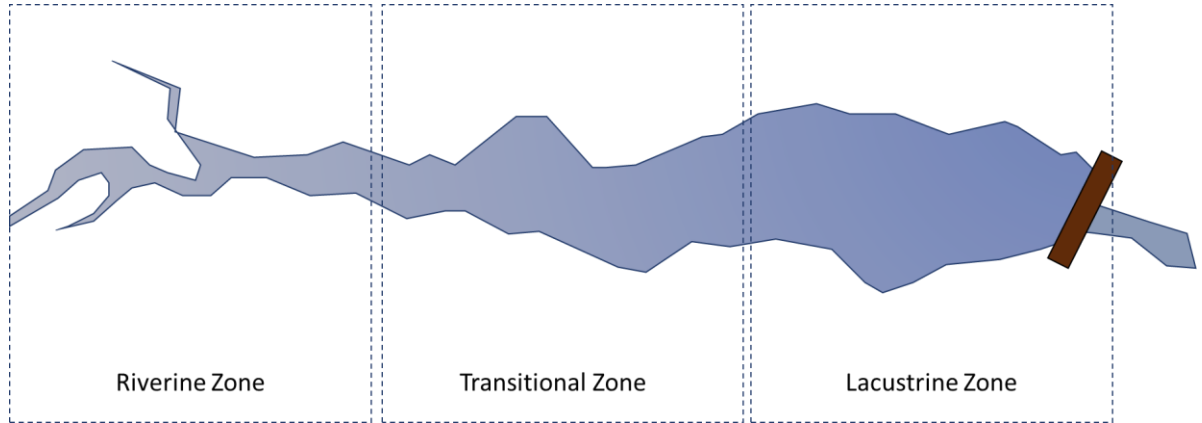
Longitudinal gradients in reservoirs are well-established phenomena that create distinct zones with varying physical, chemical, and biological characteristics. These zones are typically categorized as the riverine, transitional, and lacustrine zones (Figure 2.1) (Dai *et al.*, 2013). The riverine zone is characterized by a narrow and channelized basin with higher flow rates, while the transitional zone has a broader and deeper basin with reduced flow rates. The lacustrine zone, located immediately upstream of the dam, features a broader, deeper, and lake-like basin with lower flow rates (Dai *et al.*, 2013). These gradients are influenced by changes in basin geomorphology, hydrology, and physiochemical variables along the main reservoir axis (Dai *et al.*, 2013). Additionally, the inflow from the riverine zone into the reservoir plays a significant role in shaping the longitudinal patterns observed in the transitional-lacustrine zone (Ling *et al.*, 2019).

The structure of fish assemblages along longitudinal gradients is influenced by environmental factors such as habitat availability, discharge variations, and seasonal flow dynamics (Angulo-Valencia *et al.*, 2016). These gradients are attributed to variations in sediment and nutrient transport along the reservoir's longitudinal axis (Beghelli *et al.*, 2014). The longitudinal gradient also affects the distribution of macroinvertebrate communities, with spatial heterogeneity influencing benthic macroinvertebrates along transverse and longitudinal gradients.

These gradients align with the main reservoir axis due to changes in basin geomorphology and hydrology, leading to alterations in various variables (Oliveira *et al.*, 2004). Factors such as nutrient and organic matter loads in riverine inputs, reservoir morphology, and hydraulic retention time impact downstream plankton succession and biological processes (Šimek *et al.*, 2008). The distribution of fish species and their reproductive activities are affected by the longitudinal gradient in reservoirs, highlighting the ecological importance of these gradients (Gogola *et al.*, 2021). Longitudinal gradients are associated with geomorphological, biological, and chemical changes along the main channel of the former river, while transversal gradients occur in the reservoir arms due to changes in former tributary beds (Gogola *et al.*, 2021). Water-quality parameters exhibit longitudinal gradients along reservoirs, with distinct fish assemblage patterns observed as patchy overall biomass distributions (Perivolioti *et al.*, 2019).

Studies extensively analyze the physico-chemical characteristics of reservoirs along longitudinal gradients, focusing on parameters such as water temperature, transparency, alkalinity, chloride, sulphate, nitrate, phosphate, total dissolved solids (TDS), biological oxygen demand (BOD), dissolved oxygen (DO), chemical oxygen

demand (COD), and pH (Gokhale *et al.*, 2020). These investigations provide insights into the variations in water quality along the longitudinal axis of reservoirs and the factors influencing these variations.



Riverine Zone	Transitional Zone	Lacustrine Zone
Narrow, channelized basin	Broader, deeper basin	Broad, deep, lake-like basin
Relatively high flow rates	Reduced flow rates	Low flow rates
High suspended Solids - Low light availability at depth	Reduced suspended solids - Light availability at depth	Relatively clear - High light availability at depth
Nutrient supply advection - Relatively high nutrient levels	Advective nutrient supply reduced	Nutrient supply by internal recycling - Relatively low nutrient levels
Light-limited primary productivity	Primary productivity relatively high	Nutrient-limited primary productivity
Cell losses primarily by sedimentation	Cell losses by grazing and sedimentation	Cell losses primarily by grazing
Organic matter supply primarily allochthonous	Intermediate	Organic matter supply primarily autochthonous
More eutrophic	Intermediate	More oligotrophic

Figure 2.1: Longitudinal zonation of water quality and other variables in reservoirs (Source: Dai *et al.*, 2013)

2.3.1(b) Reservoir Zonation

Reservoirs can be ecologically categorized into distinct zones, including the littoral zone, limnetic zone, profundal zone, and benthic zone (Figure 2.2). The various zones in a reservoir, each play essential roles in the ecosystem dynamics and habitat preferences of different organisms (Bergkamp *et al.*, 2000).

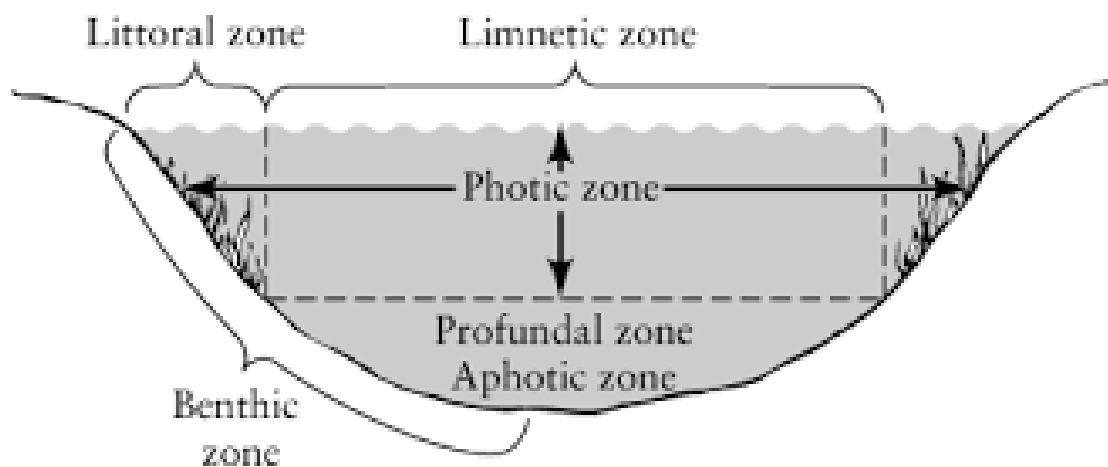


Figure 2.2: Lakes and reservoir are physical ecologically zonation diagram. (Source: Straškraba and Tundisi, 2004)

The division of reservoirs into distinct ecological zones, including the littoral, limnetic, benthic, and profundal zones, significantly influences their physico-chemical characteristics and water quality. Each zone plays a unique role in shaping the overall water quality parameters and ecosystem dynamics within reservoirs (Forbes *et al.*, 2010). The littoral zone, characterized by shallow waters near the shore, is crucial for many species, including planktonic microcrustaceans and invertebrates (Souza *et al.*, 2017). Factors such as nutrient inputs from terrestrial sources, vegetation cover, and sediment resuspension in the littoral zone affect nutrient concentrations, turbidity, and dissolved oxygen levels (Ibrahim *et al.*, 2020).

The limnetic zone, representing the open-water area away from the shore, is vital for primary production and shows variations in parameters like chlorophyll levels, pH, and temperature (Hulyal & Kaliwal, 2008). This zone often supports different species, such as phytoplankton and certain fish like sticklebacks (Jamal *et al.*, 2014). The benthic zone, which encompasses the reservoir bottom, plays a significant role in nutrient cycling and influences parameters such as sediment composition, organic matter content, and nutrient release rates (Willacker *et al.*, 2010). The profundal zone, being the deepest part of the reservoir, is characterized by low light levels and cold temperatures, impacting oxygen concentrations, nutrient availability, and organic carbon content (Ling *et al.*, 2017).

Research underscores the importance of understanding the spatial and temporal variations in physico-chemical parameters across these zones to effectively assess water quality in reservoirs (Sami *et al.*, 2022). Factors like nutrient loading, sedimentation rates, organic matter decomposition, and microbial activity can vary significantly among the different zones, leading to distinct water quality characteristics (Nadarajah *et al.*, 2019). Additionally, the zonation of reservoirs influences the trophic status, primary productivity, and nutrient dynamics within these aquatic systems, shaping the overall water quality (Zhang, 2024).

Studies have shown that habitat shifts occur among fish species in reservoirs, with movements between the littoral and limnetic zones based on factors like ontogeny and feeding preferences (Schluter, 1996). For example, *Galaxias gracilis* in Lake Kanono, New Zealand, exhibit ontogenetic shifts between the littoral and limnetic zones, moving to deeper waters during the day and returning to the littoral zone at night for feeding (Vamosi & Schluter, 2002). Similarly, three-spined stickleback show

adaptations along the benthic-limnetic axis, with benthic individuals found in the littoral zone associated with vegetation and limnetic individuals predominantly in the pelagic zone (Matsuzaki *et al.*, 2010). These habitat preferences and adaptations are crucial for the survival and ecological interactions of these species within the reservoir environment.

The distribution of phytoplankton and zooplankton also varies across the littoral and limnetic zones of reservoirs, with different densities and biodiversity observed in each zone (Bess, 2021). Phytoplankton density tends to be higher in the limnetic zone compared to the littoral zone, reflecting the availability of light and nutrients in different parts of the reservoir (Debastiani-Júnior *et al.*, 2016). Invertebrate zooplankton predators in tropical reservoirs show preferences for the littoral zone, which serves as a source of recruits to the limnetic zone, highlighting the interconnectedness of these habitats (Fernando *et al.*, 1990). Additionally, the presence of macrophytes in the littoral zone can influence the composition and dynamics of phytoplankton functional groups in tropical shallow reservoirs (James & Graynoth, 2002).

Moreover, the habitat structure and composition of the littoral zone impact the diversity and abundance of benthic fauna, with habitat heterogeneity playing a significant role in shaping the benthic community in reservoirs (Morse & Rowe, 1999). The presence of denitrifying bacteria in the limnetic zone of reservoirs like Lake Tota, Colombia, highlights the importance of microbial communities in nutrient cycling processes within different reservoir zones (Graynoth, 1999).

2.3.2 Temporal Variation in Reservoirs

2.3.2(a) Seasonal Changes

Seasonal changes, particularly between the dry and wet seasons in tropical regions, significantly influence the physico-chemical characteristics of water quality and the trophic status of aquatic ecosystems. Research has demonstrated that these seasonal variations affect various limnological parameters, leading to shifts in water quality and ecosystem dynamics (Guan *et al.*, 2015). In tropical forests, canopy photosynthesis can exhibit seasonal variability. Some regions experience a decline in photosynthetic activity during the dry season, while others maintain or even increase their photosynthetic rates compared to the wet season (Guan *et al.*, 2015). This variation in photosynthetic activity impacts nutrient cycling and primary productivity in tropical ecosystems, thereby influencing water quality and trophic interactions.

Changes in the length and intensity of dry seasons in tropical regions can exacerbate water deficits and affect ecosystem water demand, leading to shifts in hydrological patterns and water availability (Xu *et al.*, 2022). These alterations in the hydrological regime can influence nutrient transport, dissolved oxygen levels, and overall water quality in tropical aquatic systems. The regime shifts between wet and dry seasons in the tropics under global warming have implications for water availability and trophic interactions in aquatic environments (Guo *et al.*, 2022).

Understanding these shifts is crucial for assessing changes in water quality parameters and trophic status, especially in regions experiencing alterations in seasonal precipitation patterns. In tropical rivers, the wet-dry seasonal pattern of flow drives variations in river ecosystem structure and processes, affecting nutrient cycling, habitat availability, and species interactions (Warfe *et al.*, 2011). The distinct wet and dry

seasons in tropical regions contribute to the unique characteristics of river ecosystems and influence water quality parameters.

Seasonal variations have a significant impact on the limnological parameters and water quality of reservoirs. Changes in temperature, precipitation, and wind patterns lead to seasonal stratification and mixing events, affecting the physico-chemical characteristics of these aquatic systems (Figueiredo & Becker, 2018). Research has shown that reservoirs undergo substantial changes in limnological variables between the heavy rain season and severe drought periods, underscoring the impact of extreme hydrological events on water quality (Figueiredo & Becker, 2018). Limnological dynamics in semiarid reservoirs are notably influenced by seasonality and prevailing hydro-climatic conditions, highlighting the importance of understanding seasonal variations in water quality parameters (Coelho *et al.*, 2017).

Following river damming, the seasonal fluctuation in limnological variables may decrease, resulting in a more uniform environment with consistent pH, conductivity, and phosphorus levels throughout the year (Silva, 2023). The seasonal distribution of limnological variables in reservoirs is linked to factors such as advection flows from river inputs due to rainfall, horizontal flow from water outflow at different depths, and surface flows influenced by seasonal wind action (Chaves *et al.*, 2013). Seasonal changes in reservoirs can impact phytoplankton structure, nutrient availability, and hydrodynamic conditions. This underscoring the significance of understanding the influence of seasonality on limnological factors (Loaiza-Restano *et al.*, 2020).

Moreover, the thermal regime of reservoirs is influenced by seasonal variations in the net heat flux received by the surface layers, which dictate the seasonal cycle of stratification and mixing events (Yang *et al.*, 2020). Alterations in physical and environmental conditions during different seasons can lead to reservoir stratification, with cooler water layers at the bottom during summer months, highlighting the seasonal variability in water chemistry and stratification patterns (Toller *et al.*, 2020). Seasonal fluctuations in water level can affect the physico-chemical and biological characteristics of reservoirs, impacting water quality and trophic status (Rocha *et al.*, 2018).

2.3.2(b) Rainfall and Water Level

TNB stations play a crucial role in managing reservoirs for hydropower generation by collecting and analyzing essential data such as rainfall measurements and water levels. This data is vital for making informed decisions related to hydropower generation, water management, and flood control, ensuring the sustainable and efficient operation of the reservoirs. By closely monitoring rainfall and water level data, TNB can anticipate hydrological shifts and variations, enabling them to adjust operations accordingly (Kabo-bah *et al.*, 2016).

The study conducted covers the transition from the wet season to the dry season, focusing on rainfall variations and water level patterns recorded in previous years (Kabo-bah *et al.*, 2016). This approach allows TNB to optimize water release strategies, especially during the dry season and monsoon transitions (Kabo-bah *et al.*, 2016). Understanding the impact of climate variability on hydropower generation is crucial for developing effective mitigation measures, as temperature and rainfall exhibit high spatial and temporal variability at different scales (Kabo-bah *et al.*, 2016).

Changes in rainfall and temperature significantly affect the potential for hydroelectric power by influencing water availability in reservoirs (Perdinan, 2023). Moreover, hydropower production is susceptible to challenges due to its reliance on water availability and rainfall variability (Perdinan, 2023). Monitoring water levels at TNB stations is essential for effective reservoir management, reservoir scheduling, flood control, and integrated water resource management (Xie & Zhu, 2022). Water level monitoring is crucial for ensuring the optimal performance of hydropower stations and preventing issues such as sediment accumulation, which can impact storage capacity and turbine efficiency (Wang *et al.*, 2018).

The acquisition of TNB's rainfall data at HTHS in 2018 and 2019, averaging approximately 282.31mm per year, is crucial for understanding the wet and dry seasons experienced in the region. The wet season, characterized by rainfall exceeding 150.0mm, typically occurs from October to January, while the dry season, with rainfall below 150.0mm, spans from February to September. This data is essential for TNB to make informed decisions regarding hydropower generation, water management, and flood control, ensuring the efficient and sustainable operation of the reservoirs based on historical rainfall patterns (Fan *et al.*, 2020). By close monitoring these rainfall variations and water levels, TNB can optimize water release strategies and adapt operations to seasonal changes, ultimately enhancing the performance and resilience of the hydropower systems.

Based on Figure 2.3, the highest rainfall amount was recorded in November 2019 (1,708.14 mm) while the lowest amount was recorded in January 2020 (94.63 mm). Puah Reservoir had experienced the lowest mean water level with the value of 288.63 m (November 2019) while the highest was recorded in January 2019 (292.44m).

According to the Malaysian Meteorological Department (MET Malaysia), the identification of the wet and dry seasons is based on the amount of rainfall recorded over a period. Therefore, Puah Reservoir experience wet season in month October to January and vice versa for dry season based on the standard.

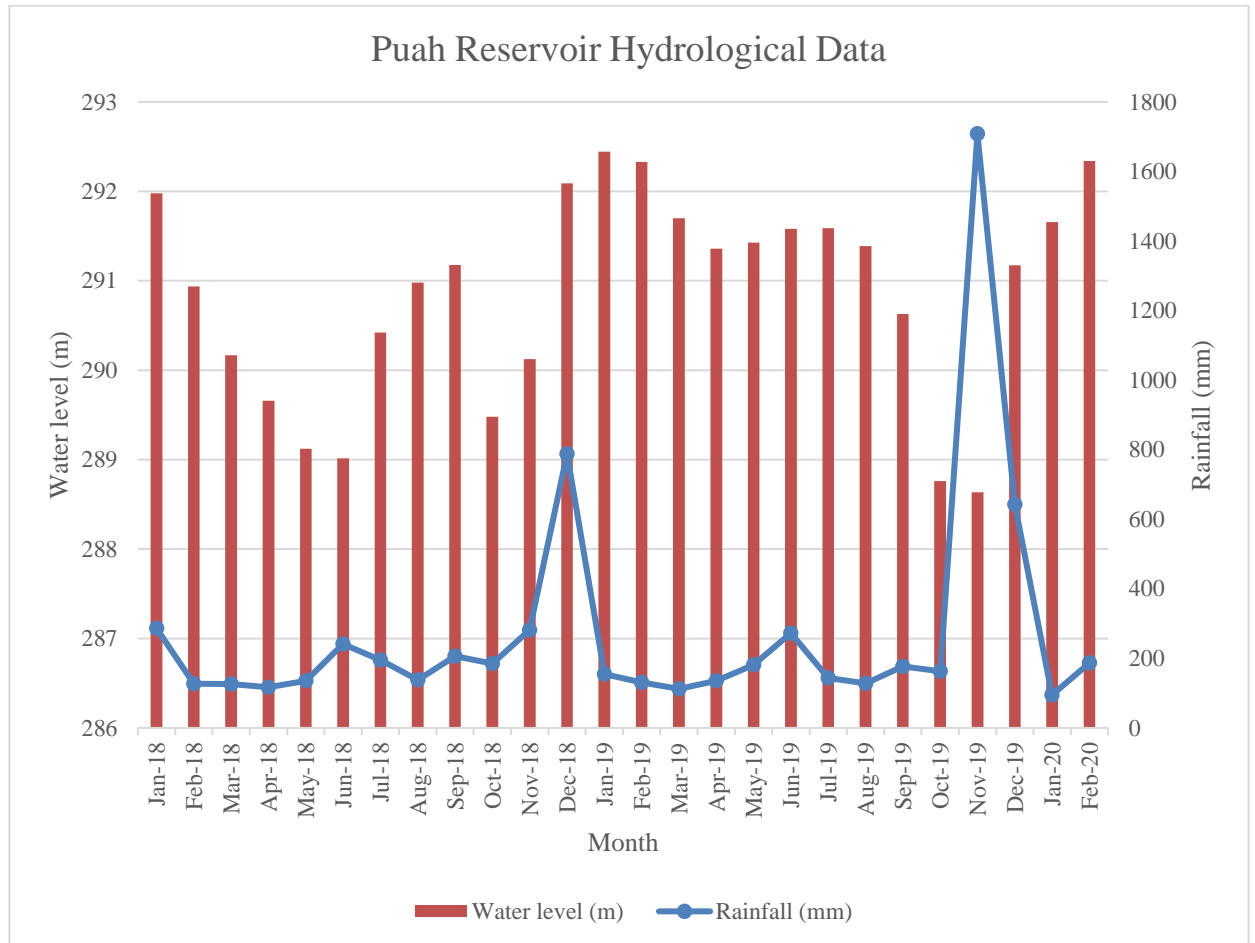


Figure 2.3: Graph of Puah Reservoir hydrological data illustrating for water level based on above sea level (asl) and rainfall from January 2018 – February 2020 (Source: Tenaga Nasional Berhad).

2.4 Profiling of Reservoir

2.4.1 Stratification

2.4.1(a) Thermal Stratification

The phenomenon of thermal stratification in lakes and reservoirs significantly influences the physical, chemical, and biological characteristics of aquatic ecosystems (Obrador *et al.*, 2014). Thermal stratification leads to the formation of distinct thermal layers namely, the epilimnion, metalimnion, and hypolimnion, which are crucial in shaping the structure and functioning of these ecosystems (Caissie, 2006). The thermocline layer, which separates the epilimnion from the hypolimnion, is essential for maintaining stratification and supporting distinct ecological zones within the water column (Leach *et al.*, 2017). Thermal stratification impacts the vertical distribution of microbial communities in reservoirs, influencing bacterial community structure and nutrient dynamics (Zheng *et al.*, 2014). Seasonal thermal stratification also affects the functional diversity and composition of microbial communities in drinking water reservoirs, reflecting the vertical stratification within the reservoir (Strock *et al.*, 2017). Mixing processes in reservoirs, influenced by factors such as wind events and outflow elevations, affect water temperature, dissolved oxygen levels, and nutrient distributions, thereby impacting overall water quality (Carr *et al.*, 2020). These processes lead to the formation of underflows during winter and near-surface flows during spring and summer, affecting the distribution of thermal layers within the water column (Mi *et al.*, 2018).

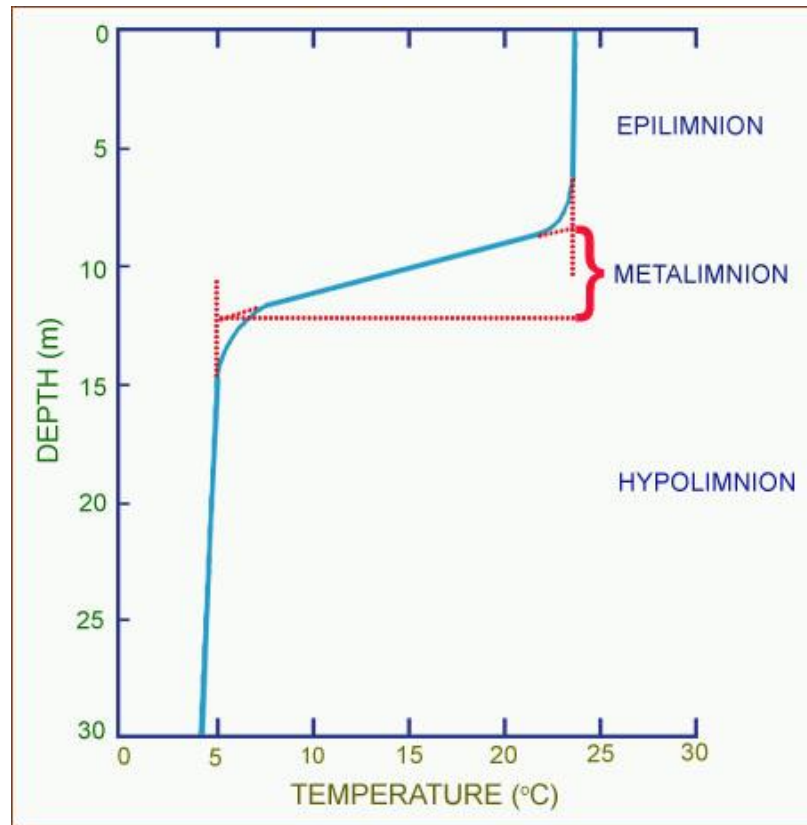


Figure 2.4 Typical temperature profile from a stratified reservoir in the temperate zone, showing the division of the water into three layers of different density (Source: Hassan *et al.*, 2014).

In aquatic ecosystems, the inflow of water plays a crucial role in influencing thermal stratification dynamics. For instance, in reservoirs, the introduction of cool inflowing water during late summer and fall can gradually erode thermal stratification by mixing anoxic waters with oxic waters (Baldwin *et al.*, 2022). This mixing process is essential for balancing oxygen levels and nutrient distribution within the water column, impacting the overall health of the aquatic habitat. Moreover, the temperature of inflowing water directly affects the formation of vertical temperature stratification in water bodies. In reservoirs like Xiluodu, the temperature of inflowing water controls the development of density currents, supporting vertical stratification by forming underflows in winter and near-surface flows in spring and summer (Long *et al.*, 2019). This demonstrates how the characteristics of inflowing water drive the establishment and maintenance of thermal stratification patterns in aquatic environments.

The impact of inflow velocity on thermal stratification is also notable. High inlet velocities can induce water turbulence and disturbances within water bodies, affecting thermal stratification dynamics (Kozłowska & Jadwiszczak, 2018). This highlights the importance of considering not only the temperature but also the flow characteristics of inflowing water in understanding and managing thermal stratification in aquatic systems.

Thermal and oxygen stratification shape the phylogenetic composition of microbial communities in reservoirs, highlighting the impact of vertical stratification on microbial diversity and community structure (Kędra & Wiejaczka, 2016). Furthermore, the distribution of zooplankton species is influenced by vertical stratification, with the vertical distribution of dominant species strongly related to phytoplankton distribution within the water column (Wilson *et al.*, 2020). The settling velocities of microplastic particles in stratified reservoirs are affected by thermal stratification, impacting particle distributions and residence times in different thermal layers (Stasio *et al.*, 2016). The research conducted by Yue *et al.* (2021) and Yang & Zhang (2015) highlights the significant impact of thermal stratification on bacterial communities and microbial diversity in water columns of reservoirs. Yue *et al.* (2021) showed that the emergence of thermal stratification influences the vertical distribution of bacterial communities, affecting bacterial community structure and nutrient dynamics. Yang & Zhang (2015) emphasized that seasonal thermal stratification significantly influences the functional diversity and composition of microbial communities in drinking water reservoirs, reflecting the vertical stratification within the reservoir.