MITIGATION AND MANAGEMENT STRATEGIES FOR REDUCING EUTROPHICATION IN TROPICAL HUMID REGIONS

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Extensive growth of algal blooms as a consequence of eutrophication may bring serious health effects to humans including fatalities. Several attempts in reducing the eutrophication or algal blooms in waterbodies have been implemented in past few decades. However, most of the control methods were focused on temperate systems rather than tropical systems. Therefore, this study was aimed to develop a mitigation framework for reducing eutrophication and algal blooms in tropical regions. This work focusses more on humid tropic systems because there is a lack of research resources in this region. The study involved four main work packages: (a) systematic review study to track the available eutrophication control techniques; (b) development of eutrophication framework; (c) assessment of seasonal water quality in Durian Tunggal Reservoir (DT) and Jus Reservoir (Jus); and (d) evaluation of eutrophication management framework using DT and Jus reservoir as case study.

The study starts with systematic review study to track the available eutrophication control techniques. Findings from the systematic review were used to develop the eutrophication framework by providing the established method that can be used to mitigate the eutrophication problem. The framework consists of two stages; a pre-selection stage and a selection stage. The pre-selection stage requires the decision maker to evaluate the condition of the waterbody. Meanwhile, the selection stage is where suitable control techniques are suggested based on Multiple Criteria Analysis (MCA). The performance of the framework was demonstrated by using a case study of two reservoirs in Malaysia. The results presented in this thesis show that the framework that is proposed using MCA as a decision support tool allows for the selection of robust investments in eutrophication and algal bloom management. The integration of scenario analysis can provide complementary insights into sustainability and cost efficiency for eutrophication management and policy for developing countries by giving the best available techniques according to the selected criteria.

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List of abbreviation

2-4D	2,4-Dichlorophenoxyacetic acid
AL	Algicides
AWT	Advanced wastewater treatment
AWWA	American World Water Association
BM	Biomanipulation
C	Carbon
CBA	Cost Benefit Analysis
Chl-a	Chlorophyll-a
CW	Constructed wetland
DF	Dilution and flushing
DO	Dissolved Oxygen
DN	Doing nothing
DR	Dredging
DS	Destratification
DT	Durian Tunggal Reservoir
EPA	Environmental Protection Agency
ERM	Ecoremediation
EU	European Union
HA	Harvesting
HW	Hypolimnetic withdrawal
IIASA	International Institute for Applied System Analysis
Jus	Jus reservoir
LR	Law and regulation
MCA	Multiple Criteria Analysis
N	Nitrogen
NAHRIM	National Hydraulics Research Institute of Malaysia
NE	Northeast
NH_3-N	Ammonium nitrogen
NI	Nutrient inactivation
NO_3	Nitrate

OECD	Organisation for Economic Cooperation and Development
P	Phosphorus
PO_4^{3-}	Phosphate
PEG	Plankton Ecology Group
SC	Sediment cover
SD	Secchi depth
SE	Southeast
TN	Total nitrogen
TP	Total phosphorus
TSI	Trophic State Index
UNEP	United Nations Environment Programme
UNESCO	United Nation Education, Scientific and Cultural Organisation
USA	United States of America
USEPA	United States Environmental Protection Agency
WFD	Water Framework Directive
WHO	World Health Organisation

CHAPTER 1

Introduction

Chapter 1 : Introduction

This chapter gives a brief introduction to the ideas and background knowledge that has prompted the undertaking of this research. The issues that have led to this point will be introduced, followed by the research objectives.

1.1 Research motivation

The world population has increased significantly in the last five decades from 3 billion in 1960 to 7.3 billion in 2014 where 82 percent of the populations comes from developing countries (UN Department Economics and Social Affairs, 2015). Based on the current population growth rate, the world's population is projected to increase to 8 billion by 2025 (UN Department Economics and Social Affairs, 2015). The increasing world population will cause agricultural and non-agricultural water usage to grow rapidly (Rosegrant, Ringler and Zhu, 2009). By 2025, total global water withdrawal for agricultural and non-agricultural usage is projected to increase by 4772 cubic kilometres (km^3) from 3906 km^3 in 1995 (Rosegrant et al., 2002). Projected withdrawals in developing countries are expected to grow by 27 percent and in developed countries the growth is more moderate, at 11 percent (Rosegrant et al., 2002). The term of water withdrawal here refers to water that is removed from a source which may be returned to the original source with changes in quality and quantity (Jain and Singh, 2003; Norwine, Giardino and Krishnamurthy, 2005; Zander et al., 2008). Besides that, the total global water consumption also will increase by 71 percent of which more than 90 percent will be in developing countries which will have the highest per capita water consumption percentage (Rosegrant et al., 2002). Water consumption is water withdrawn from a source that is unavailable to be reused because of losses to evaporation or human consumption (Jain and Singh, 2003; Norwine, Giardino and Krishnamurthy, 2005; Zander et al., 2008). Demand for water will continue to increase as a result of growing population and economic growth especially in developing countries where water is no longer abundant because the greater number of people in the countries has led to greater household water use per capita. This later will create a water crisis when all the sectors compete for clean water supplies, but at the same time the water availability and quality is degraded due to the increased effects from anthropogenic disturbance and climate change (Rosegrant, Ringler and Zhu, 2009).

Rising global temperature (Feuchtmayr et al., 2009; Paerl and Huisman, 2009; Paerl and Paul, 2012) along with an increase in human activities (Smith, Tilman and Nekola, 1999; Dokulil, Chen and Cai, 2000) has increased nutrient loading into water bodies, thus stimulating further eutrophication and leading to deterioration in the quality of available water resources (Ryding, Rast and Unesco, 1989; Ansari et al., 2011a). It also has reached dangerous levels in many developing regions especially Brazil, China and South East Asia which are in tropical and subtropical climate (Jørgensen and Williams, 2001). A possible explanation is that algal blooms occur throughout the year in tropical climate regions because they receive constant solar input, higher temperatures and high rain intensities which favor algal bloom growth conditions (Oliver and Ganf, 2000; Singh et al., 2013). However, the eutrophication management research in developing countries (where most of the countries are tropical countries) is still limited (Thornton, 1987b; Rast and Thornton, 1996; Havens et al., 1996) whereas more extensive attempts in managing the eutrophication and algal bloom problems can be observed in developed countries (Harper, 1992; Sutcliffe and Jones, 1992). Previous attempts at applying temperate zone control measures for eutrophication in inter-tropical regions was shown to be largely unsuccessful (Rast and Thornton, 1996). Against this background, it is important to protect available water resources from the increasing harm of eutrophication and algal bloom. It is also important to increase the number of studies focused on the tropics. Therefore, this research aims to increase the level of water quality in tropical regions by developing a mitigation framework to help improve the decision making processes which control the proliferation of eutrophication and algal bloom.

1.2 Tropical lakes

Lakes can be classify by the frequency of complete mixing (Lewis Jr, 2000). Tropical lakes can usually be characterised as warm monomictic, oligomictic or warm polymictic. Warm monomictic is a condition where the lakes never been covered by ice, mixing once per year and the temperature never falls below 4^{o}C. Most of deep tropical lakes falls into this category (Chapman and World Health Organization, 1996; Osborne, 2012). Meanwhile, oligomictic is a condition that characterised by rare or irregular mixing with water temperatures well above 4 °C. This types of lakes normally too deep and probably not mixed completely each year because the wind strength may be insufficient to move the entire water mass (Lewis Jr, 2000; Osborne, 2012). Warm polymictic is a condition where lakes have frequent periods of circulation and mixing. This condition usually happen to shallow lakes where the depth is between 5m to 10m (Lewis Jr, 2000). Figure 1-1 shows the latitudinal distribution of lakes based on the mixing.

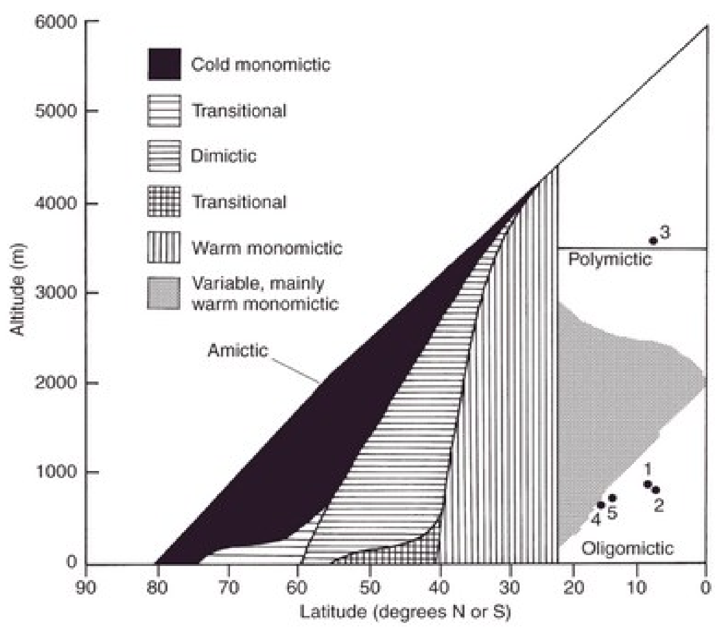

Figure 1-1: Latitudinal distribution of lakes based on mixing (Osborne, 2012)

Tropical lakes normally encounter threats arising from within the water catchment as well as in-lakes problems. For example, in Malaysia, changes in land use were widespread where part of the watershed consisted of secondary and primary forests were converted to agriculture areas specially the oil palm plantation (Sharip and Zakaria, 2007). Nutrient runoff from fertilizer, various types of pesticides (herbicides, insecticides and rodenticides) and palm oil mills effluent (POME) are all the potential factors that may affect water quality as a result from oil palm cultivation (Comte et al., 2012). Meanwhile, forest land is not the major nutrient contributors but the intensive forest practices such as clear cutting and scarification increase the exposure of soil, thereby resulting in the increased nutrient runoff to a waterbody (Ryding, Rast and Unesco, 1989). The increase of nutrient that goes into the waterbody will contribute to eutrophication problems.

1.3 Eutrophication

Eutrophication refers to the enrichment of nutrients in receiving waters which promote the excessive growth of various types of phytoplankton including blue-green algae where phosphorus (P) and nitrogen (N) are the two major elements controlling algal growth in surface waters (Reynolds, 1992; Straskraba and Tundisi, 1999; Schindler, 2012). Under natural conditions most of the lakes were initially were oligotrophic but through time, often thousands of years, they changed to a eutrophic state. The term eutrophication was introduced to describe this slow process of change (Bachmann, 1980; Thornton et al., 2013). The process of nutrient enrichment in water bodies can be classified by trophic states; oligotrophic (low nutrients content), mesotrophic (intermediate nutrients content) and eutrophic (high nutrients content) (Henderson-Sellers and Markland, 1987). Figure 1-2 represents the eutrophication process and defines the terminology of the trophic state of the water body. However, the discharge of excessive amounts of nutrients in the form of sewage, detergents, and fertilizers to the surface water accelerate the process of nutrient enrichment in lakes. This phenomenon is often referred to cultural eutrophication which indicates the causal relationship with human activities (Hasler, 1969; Bachmann, 1980).

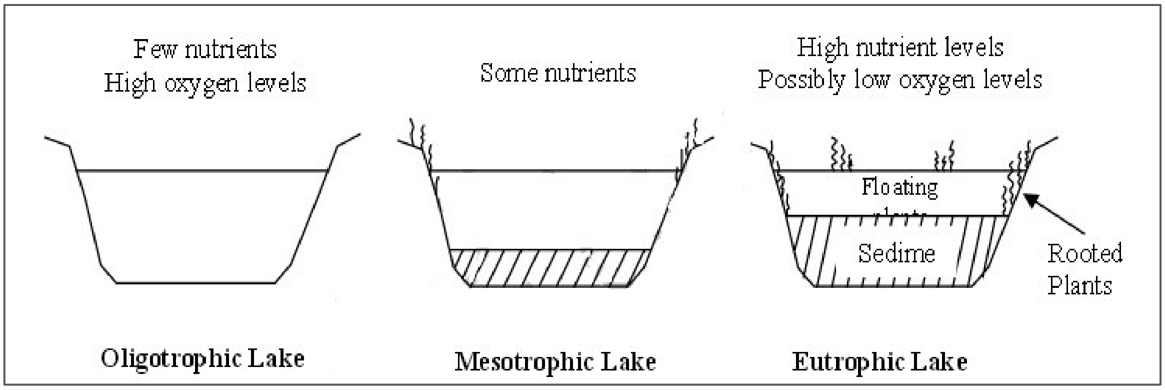

Figure 1-2: The eutrophication process. Adapted from (Henderson-Sellers and Markland, 1987)

The threat of eutrophication is reported for freshwater ecosystems and coastal and marine ecosystems (Smith, Tilman and Nekola, 1999; Smith, 2003; Smith, Joye and Howarth, 2006). The most harmful product of eutrophication is the growth of various types of microscopic plants including microalgae and cyanobacteria (i.e., green-blue algae) (Ansari et al., 2011a). Under favorable conditions, the rapid excessive growth and accumulation of microalgae is known as an algal bloom. Water containing algal bloom may have poor taste, odour, and colour, and some might have high concentrations of organic molecules that might form trihalomethanes and other by-products from raw drinking water disinfection with chlorine (Oliver and Shindler, 1980; Tsuji et al., 1997; Cooke and Kennedy, 2001). The toxic substances may pose serious health effects to living creatures, including humans that may even cause fatalities (Hitzfeld, Höger and Dietrich, 2000; Svrcek and Smith, 2004).

1.3.1 Harmful algal blooms (HABs)

The most harmful algae species are the blue-green algae or cyanobacteria. It is the ancient organism that was found to occur approximately 3.5 billion years ago (Schopf, 2000). At the present time, it has 150 genera and around 2000 species with at least 40 species able to produce toxic substances

(Carmichael, 2001). These organisms, with the combination of bacteria and algae characteristics, can be found in various habitats including extreme climates from Antarctic lakes to hot desserts (Whitton, 2000). Cyanobacteria are often considered to be distributed worldwide. However, some of the species are more prominent in tropical and sub-tropical such as Cylindrospermopsis raciborskii and Aphanizomenon ovalisporum (Chorus and Bartram, 1999; Granéli and Turner, 2006; Hudnell, 2008). Cylindrospermopsis raciborskii was widely found in Brazil (De Souza, Carvalho and Truzzi, 1998; Bouvy et al., 2000) and Australia (McGregor and Fabbro, 2000; Hawkins et al., 1997) freshwater, meanwhile, Aphanizomenon ovalisporum was found in Israel freshwater (Banker et al., 1997). Both species known to produce cylindrospermopsin which can give hepatotoxic effects that can cause death by liver poisoning (Chorus and Bartram, 1999). They are similar to bacteria which are microscopically small, unicellular or filamentous but unlike other bacteria, they have wall structure, pigments and the ability to perform photosynthesis and possess chlorophyll-a as their main photo pigment (Carmichael, 2001; AWWA, 2010).

Interaction with environmental factors such as light intensity, temperature, carbon dioxide, nutrient availability including trace elements such as iron, water flow rate and stability and also zooplankton grazing contribute to the expansion of the blooms (Chorus and Bartram, 1999b; Svrcek and Smith, 2004). Blue-green algae also have several ecological advantages compared to other aquatic organisms because they can survive in a variety of habitats. Most of the species possess gas vacuoles that allowed them to regulate cell density and move up and down in waterbody (Reynolds, Oliver and Walsby, 1987). The small size of algae also makes it lighter than water and helps them to float to the surface but this tendency normally interrupted by turbulence and diffusion current within the waterbody (Whitton, 2000). However, they have the ability to regulate their buoyancy depending on the environmental condition by modifying either the density of carbohydrate component or protein component that accumulates in the cell (Granéli and Turner, 2006). The advantages of buoyancy regulation include reduces sedimentation losses (Reynolds, Oliver and Walsby, 1987), improves light supply as buoyancy bring cells near to well-illuminated water layers, increase photosynthesis by allowing colonies to float into more favourable light climates and ability to overcome the vertical separation by migrating to optimal zones for nutrient and light captured (Oliver, 1994; Whitton, 2000). Besides that, they can also fix N when other sources of N are depleted from the water. This is because they do not only rely on soluble N but can use atmospheric N as their nutrient source (Whitton, 2000; Huisman and Hulot, 2005).

Moreover, blue-green algae can also reduce surface water quality by producing toxic substances. The toxins can be classified by their mode of action such as liver damage (hepatotoxins) , nerve system damage (neurotoxins), skin irritation (dermatoxins), cell damage (cytotoxins) and irritation of any exposed tissues(endotoxins) (Codd, Morrison and Metcalf, 2005; Mehra, Dubey and Bhownik, 2009). Among them, microcystins under the hepatotoxins group are the most frequently occurring in freshwater. More than 80 types of microcystins are currently identified but microcystin-LR is the most common. Most algal poisoning cases are associated with microcystin-LR. Therefore the World Health Organization (WHO) has produced guidelines values for microcystin-LR which should be less than 1μg/L in drinking water (WHO, 1998).

1.3.2 History of cyanobacteria poisoning

Reported cases of algal poisoning come from various parts of the world. The effects of exposure to algal toxins vary from skin irritation, digestion problems to liver damage. The earliest cases involving algal poisoning may have been about 1000 years ago from the Han dynasty in China where they lost their military troops after the soldiers drank green water from a river (Chorus and Bartram, 1999b). The first incidence that was properly reported in a scientific paper was in 1978 by Francis. In this paper, Francis reported the cause of death of livestock, which was related to algal bloom poisoning when he observed the excessive quantities of greenish algae on the surface of stagnant water. Human exposure to algal toxins may occur through ingestion of drinking water or other sources of water. There are a number of studies carried out a few years back claiming that conventional water treatment was insufficient in removing algal toxins from drinking water (Gassner and Fey, 2008; Hitzfeld, Höger and Dietrich, 2000). It was recorded that the earliest reported case of algal toxin poisoning in humans was in 1931 in Charleston, West Virginia, USA, when people who lived along the Elk River experienced gastroenteritis. This happened when a great drought occurred over a four-month period causing the expansion of algal blooms in a tributary river, the Kanawha river, which received high organic loading from a local solid waste incinerator and sewers. When a heavy rainfall event occurred, algal biomass was flushed into Elk River, which was the drinking water source for the people of West Virginia. It was estimated that nearly 10,000 people were affected, who showed symptoms of poisoning by vomiting followed by diarrhoea. That event was mostly restricted to people over 10 years of age (Tisdale, 1931). Another case in Zimbabwe, Africa was from 1960 to 1965 when seasonal gastroenteritis occurred among children. Investigations showed that only the children who were using a particular water supply became ill (Falconer, 2005). More severe cases of algal toxin poisoning happened in Palm Island, Australia when 140 children and 10 adults received hospital treatment after showing symptoms of poisoning such as vomiting, painful liver enlargement, constipation followed by bloody diarrhoea and kidney damage shown by urine testing where the symptoms were electrolyte loss together with glucose, ketones and blood in urine (Chorus and Bartram, 1999b).

In some developing countries, it is difficult to have access to treated water and the drinking water is normally drawn from natural sources such as ponds, wells, lakes and rivers. The consequence is that the population may ingest waters from eutrophic surface waters that may contain algal blooms. Cases were recorded in a survey in Central China when a researcher found a direct relationship of primary liver cancer among the villagers and the drinking water source they used (Falconer, 2005). Besides that, algal toxins may pose human health threats through dialysis. This happened in 1996 in Brazil where 76 out of

131 dialysis patients died after their dialysis water was contaminated by algal blooms. The water was obtained from Tabocas Reservoir and supplied by a truck to the clinic since the clinic was not connected to the public water supply. During the week of poisoning, the water collected from the municipal treatment plant was not filtered or chlorinated. The maintenance worker also said that the microspore filter that was usually changed every three months had not been changed in the three months before the tragic event (Jochimsen et al., 1998).

Another pathway of exposure to the algal toxin is through recreational activity. The first reported cases of algal toxin poisoning through recreation were in the United Kingdom where 10 out of 18 military personnel doing canoe exercises in the Rudyard reservoirs with algal blooms of M. aeruginosa suffered abdominal pain, vomiting followed by diarrhoea, sore throat, blistering mouth, dry cough and headache. Two were hospitalized and developed typical pneumonia symptoms and were believed to have swallowed some of the water while swimming (Turner et al., 1990). A case was also recorded in Winconsin, USA where a 17 year old teenager died two days after expose to algal blooms while splashing and diving in a golf course pond to cool down after soccer training. The coroner concluded that the teenager had ingested some anatoxin-a after Anabaena flos-aquae were found in his blood and stool sample (Campbell and Sargent, 2004). In short, algal toxins may come into contact with and cause serious health threats to living organisms including humans. The routes of exposure are through ingestion of the water, dialysis treatment and recreational activities while the effect varies from acute to chronic.

1.4 Aim and objectives

The primary aim of this study is to develop a framework that can be used in supporting decision making in tropical countries in order to solve the eutrophication and algal bloom problems. Two reservoirs in Malaysia were used as case studies to achieve the objectives of the study. The objectives of the study are:

1. To update to the latest eutrophication and algal bloom control techniques that are scientifically established;
2. To evaluate and compare possible mitigation measures from temperate systems that can be applied to tropical water bodies;
3. To develop a mitigation management framework to support decision making in controlling the eutrophication and algal bloom problem in tropical developing countries;
4. To explore the problems of eutrophication and algal bloom in the Durian Tunggal reservoir (DT) and Jus reservoir (Jus) as drinking water supply sources; and
5. To validate the framework by using the DT and Jus reservoirs as a case study.

1.5 Structure of the Thesis

This thesis consists of seven chapters (refer Figure 1-3). Each chapter is independently referenced to acknowledge the contributions of related studies. The first two chapters described their respective theories and concepts. The following four chapters described different research approaches as well as the results and conclusions derived from the study. Each chapter is a stand-alone manuscript which includes introduction, methodology, results, discussion and conclusion. Last but not least, the last chapter summarised the research achievement, contribution and several recommendation for future study. A summary of each chapter is presented as below:

- **Chapter One** highlights the main aims and objectives of the study. It provides the background information and a brief description of the eutrophication and algal bloom problem which led to the undertaking of the research;

- **Chapter Two** is the literature review part which describes the background theory behind the process of eutrophication and algal bloom including the difference between eutrophication and algal bloom in temperate and tropical systems. Besides that, previous work on eutrophication management frameworks and the research gap are also discussed in detail;

- **Chapter Three** summarizes the systematic review carried out to synthesize the available technique to control eutrophication and algal bloom problems. Besides that, the systematic review was also used to track the history of application of the techniques in order to quantify the quality of each technique. This chapter was able to help in the development of the eutrophication and algal bloom management framework that is further developed in the next chapter;

- **Chapter Four** describes the framework that is developed as an aid to decision making in eutrophication and algal bloom management in tropical, low-income countries. The framework consists of two stages; a pre-selection stage and a selection stage. The pre-selection stage requires the decision maker to evaluate the condition of the waterbody. Meanwhile, the selection stage is where suitable control techniques are suggested based on Multiple Criteria Analysis (MCA). The performance of the framework will be demonstrated by using a case study of two reservoirs in Malaysia in the following chapter;

- **Chapter Five** discusses the results from the fieldwork conducted in the Durian Tunggal reservoir (DT) and Jus reservoir (Jus) in Malaysia. The results collected will be able to give a clear picture about the current status of eutrophication in the DT and Jus reservoirs;

- **Chapter Six** evaluates the framework that has been developed in Chapter 4 by using DT and Jus reservoir data as an example. In this chapter, seven scenarios from the three most important drivers which are population, economic and land use are built in order to support the MCA process. These scenarios provide the weight for the MCA criteria helping to select the best control techniques in managing the eutrophication problems; and

- **Chapter Seven** presents the overall conclusions of the study and the achieved objectives. Furthermore, the study's limitations and contributions are discussed briefly and suggestions for further research within the same scope of study are also presented.

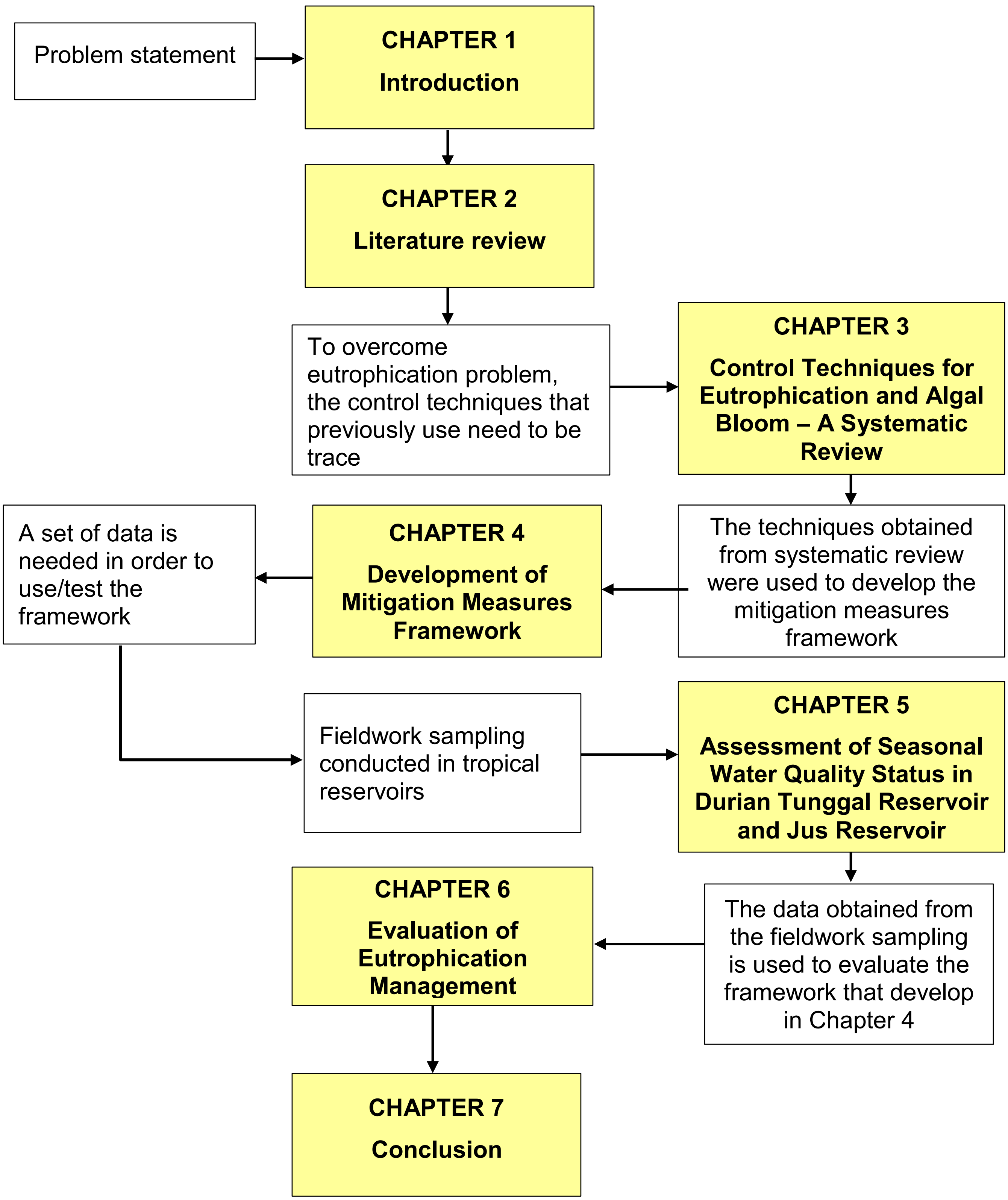

Figure 1-3: General view of research framework

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CHAPTER 2

Literature Review

Chapter 2 : Literature review

Research into eutrophication has a long history. The earliest work was done by Weber in 1907 and Naumann in 1919 (as cited in Hutchinson (1973)) who were the first to develop the term ‘eutrophic’ for nutrient rich and ‘oligotrophic’ for nutrient poor soil and aquatic system. Another early notable work in eutrophication research according to Hutchinson (1973) is by Thienemann who studied thermal stratification in 1917. In his study, he divided the thermal stratification layer into three regions; 1) upper region otherwise known as epilimnion which supports a crop of algae; 2) intermediate region otherwise known as metalimnion which is the region with maximum rate of change of temperature; and 3) lower region otherwise known as hypolimnion which is usually too dark to support algal growth. He also came to the conclusion that deeper lakes usually support an oligotrophic state and the shallower one an eutrophic state. More attention has been given to eutrophication in recent years because it has been found to leads to algal bloom formation and to create serious adverse effects (Rast, Holland and Ryding, 1989).

As noted by Thornton (1987b), not all the symptoms of eutrophication that normally observed in temperate regions necessarily occur in tropical or sub-tropical regions. He also mentioned that in 1981, the United Nations Education, Scientific and Cultural Organization (UNESCO) in association with the International Institute for Applied Systems Analysis (IIASA) and the Organization for Economic Cooperation and Development (OECD) acknowledged that tropical or sub-tropical water bodies may respond differently to eutrophication management techniques used for temperate water bodies. This was supported by a more recent study by Rast and Thornton (1996) which noted that the initial attempts at applying eutrophication control measures used in temperate regions to tropical regions had been largely unsuccessful. Therefore, this chapter aims to present essential information regarding eutrophication and algal bloom problems before developing a management framework for mitigating them in tropical regions in following chapters. The discussions will include the basic factors involved in eutrophication processes, the difference between temperate and tropical aquatic systems, previous work by other researchers and the identified research gaps.

2.1 Factor affecting the degree of eutrophication and algal bloom

To further explore eutrophication and algal bloom problems, it is essential to understand the factors that accelerate the degree of eutrophication and algal bloom in different systems.

2.1.1 Nutrients

The supply of nutrients is one of the most important factors which will determine the quantity and species of plant in lakes (Harper, 1992). According to Liebig's law of the minimum, P and N are the two principle nutrients that control the development of plant biomass in terrestrial ecosystems as well as in aquatic ecosystems (Smith, Tilman and Nekola, 1999; Krenkel, 2012; Ahearn, Pace and Groffman, 2013).

A source of nutrients to river, lakes and oceans can be divided into two categories: point sources which directly discharged nutrient to the catchment including industrial and domestic effluent, and non-point sources which are from diffuse sources and are transported to the catchment including urban runoff, runoff from agriculture and runoff from pasture land (Ryding, Rast and Unesco, 1989). Studies done by Carpenter et al. (1998b) discussed that the non-point source inputs were difficult to measure and control compared to the point source inputs because the sources came from a scattered area while the point source inputs are from a single area and this has become the major source of water pollution in the United States. This issue is of concern because eutrophication may lead to various adverse effects in aquatic ecosystems, drinking water problems; reduction of food production and loss of recreational amenity (Carpenter et al., 1998b; Smith and Schindler, 2009). Algae require P and N to support the growth because P is needed for DNA, RNA, and energy transfer, while N is needed for protein synthesis (Conley et al., 2009). Both nutrients are often related to the growth limiting nutrient. Hence, any increase in P and N loading will also rapidly increase the expansion of algal blooms in the water catchment.

2.1.2 Climate

Extreme wet and dry climate is one of the factors that drive the expansion of eutrophication and algal bloom. Periods of heavy precipitation can re-suspend bottom sediments, increase turbidity and bring more silt and pollution from the landscape to waterbodies. However, frequent rainfall events will also disrupt the algal blooms temporarily because it will create flushing to the downstream water and prevent bloom formation. For long periods after the rainfall, the water will become more stagnant and the contact time of the nutrients with the waterbodies will increase, boosting the potential for algal blooms. During turbulent mixing, the buoyancy function does not help the algal blooms to move towards the surface because they will be distributed throughout the water column by vertical mixing (Paerl and Huisman, 2008; Paerl and Paul, 2012; Reichwaldt and Ghadouani, 2012).

Dry climates or drought periods can results in; stagnation in lakes, creating longer water retention times due to the reduction in water renewal and increasing the water temperature which therefore contributes to algae growth and expansion (Bouvy et al., 2000). This view is also supported by (Paerl and Huisman, 2008; Environmental Protection Agency, 2013) who concluded that warmer temperatures increase a lake's thermal stratification and provide optimum conditions for harmful algal growth. At elevated temperatures certain harmful algae grow faster than other non-harmful algae. This was tested by a laboratory experiment by Butterwick, Heaney and Talling (2004) that shows at 35^{o}C, only Aphanizomenon flos-aquae (algal blooms species) survived. In a more recent study, Kosten et al. (2012) surveyed 143 shallow lakes from Sub-artic Europe to Southern America and found that algal bloom communities increase in proportion to temperature. They also observed that warmer climates may decrease the nutrient concentration but the algal bloom communities do not decline compared to colder temperatures in which algal blooms tend to disappear altogether. It shows that algal blooms can survive better with lower nutrient loading compared to cooler temperatures.

2.1.3 Water body morphometry

Lakes and reservoirs are two different types of waterbody. Lakes usually defines as natural waterbody, while reservoirs normally defines as man-made waterbody that for flood control, hydropower generation and water supply (Ryding, Rast and Unesco, 1989; Cooke et al., 2005). In contrast to lakes that naturally formed, reservoirs usually formed by constructing a dam across a river or stream, resulting in the impoundment of the water behind the dam structure (Jorgensen and Vollenweider, 1988; Ryding, Rast and Unesco, 1989). Few studies on the difference of lakes and reservoirs has been summarized by previous researcher has been compiled in a table by Cooke et al. (2005) as shown in Table 2-1. As can be seen in Table 2-1, reservoirs generally have larger drainage basins, surface areas and drainage basin to surface area than do natural lakes. The larger drainage basin to surface area ratio, the greater the water load is. This means that reservoirs typically received larger inputs of water as well as pollutant than lakes. However, because of the shorter hydraulic residence times and greater mean depths, reservoirs may therefore trap less nutrients than those in lakes (Ryding, Rast and Unesco, 1989; Cooke et al., 2005).

Table 2-1: Comparison of geometric means value between lakes and reservoris (Cooke et al., 2005)

Variable	Natural Lakes (N = 309)	Reservoirs (N = 107)
Drainage area (km^2)	222.00	3228.00
Surface area (km^2)	5.60	34.50
Maximum depth (m)	10.70	19.80
Mean depth (m)	4.50	6.90
Hydraulic residence time (yr)	0.74	0.37
Areal water load (m/yr)	6.50	19.00
Drainage/surface area	33.00	93.00
P loading ($gm/m^2/yr$)	0.87	1.70
N loading ($gm/m^2/yr$)	18.00	28.00

Natural lakes in Malaysia are few and most of them are partly swamp wetlands. Up to 2008, there are approximately 73 man-made lakes in Malaysia that have been built for the purpose of water supply, irrigation, hydropower generation, flood mitigation and others. They also become popular tourisms and recreational sites which expanding the water needs and exposing them to the water problems (Sharip and Zakaria, 2007). The Desk Study on the Eutrophication Lakes of Malaysia by National Hydraulics Research Institute of Malaysia found that more than 60% of the 90 lakes that involves in the study is experiencing eutrophication (NAHRIM, 2005). This later study done by Zati 2014 which involved 15 major lakes and reservoirs in Malaysia also found out the all 15 lakes and reservoirs were eutrophic. Different lakes show different symptom of eutrophication and macrophytes blooms are the most common symptom in lakes and reservoirs in Malaysia. Most of the source of pollutants was comes from the lakes drainage basins including from sewage effluent, surface runoff from the agricultural land and other non-point sources inputs associated to rapid development and land use changes. Besides that, the threat that comes from the in-lakes usually reported from weed infestation and nutrient from fish cages (Sharip and Zakaria, 2007).

2.1.4 Stratification

Most lakes with over 10 meters of depth are potentially easy to stratify. This is because water will continuously decrease in density per degree temperature increase above $3.98^{o}C$ (Dodds, 2002b). Light also led to stratification of lakes as this ultimately heats the water. This means that when a series of calm, warm days occur, the lake stratifies (Dodds, 2002b). The upper layer is called epilimnion, where most of the primary production happens. Dead organisms and faeces sink into the lower layer called the hypolimnion, where they will be decomposed by bacteria both in the water column and the sediment. The decomposition process of organic material including algae will increase biological oxygen demand (BOD). Besides that, the oxidation of ammonia in the water will also require dissolved oxygen. A higher BOD indicates a lower level of dissolved oxygen (Rahimi et al., 2011). Oxygen will be depleted in this layer as a result of respiration and the absence of any replenishment from the surface. This may occur on a daily basis, as in many tropical lakes or on a seasonal basis in the summer months of temperate regions. In most lakes the stratification is destroyed by night time (tropical) or autumn (temperate) winds which overturn and mix the lake (Harper, 1992). In shallow lakes, the wind generally prevents thermal stratification, and dissolved oxygen is not a problem. However, in this type of impoundment, the nutrients released from decaying plant material during the decomposition process can be recirculated quickly for reuse and further plant production within the same growing season (Fruh, 1967).

2.2 Difference between temperate and tropical lake systems

A survey on literature dealing with eutrophication research by Thornton (1987b) found that the symptoms of eutrophication observed in temperate systems do not necessarily occur in tropical systems. For example, compared to the temperature of temperate lakes that changes with the seasonal period such as ice cover, autumn and spring mixing, tropical lakes are characterized by highly seasonal rainfall and a mean annual temperature that is higher than temperate lakes (25^{o}C versus 10-15^{o}C). With constant temperature and annual solar input, the growing season generally extends throughout the year which makes productivity in tropical lakes higher than temperate lakes (Thornton, 1987b).

2.2.1 Irradiance and water temperature

A more comprehensive study that distinguishes the difference between tropical systems and temperate systems was done by (Lewis Jr, 1996). According to Lewis, the primary difference between tropical and temperate lakes is determined by the latitude which relates to solar irradiance. Solar irradiance is important to limnology because it is needed for photosynthesis and it also induces the stratification of lakes (Monteith, 1972). Generally, the mean annual solar irradiance received by tropical regions exceeds the amount received by temperate regions because in tropical latitude, the solar irradiance is more uniform across the year. Therefore, the higher irradiance in the tropics is responsible for higher water temperature in the water column and the stratification. Even though there is difference in the amount of solar irradiance, the basis of the response of the phytoplankton to light is still similar in both tropical and temperate lakes (Lewis Jr, 1996).

2.2.2 Seasonality and water mixing

In temperate zones, changes in the seasonality also alter the water temperature which is associated with the mixing and layering of the lakes (Lewis Jr, 1996). Seasonality is virtually not present in the tropics but is not totally absent. For example, in temperate systems, there is a period of ice cover, spring and fall mixing, and a stable stratification season. This type of lake is generally referred to as dimictic according to Hutchinson-Loffler classification (Lewis Jr, 1983). However, for very shallow temperate lakes, it must be classified as cold polymictic as it may be insufficiently deep to stratify even though they have the characteristic ice cover (Lewis Jr, 1983). Unlike the temperate zone, tropical lakes and reservoirs are characterized by seasonal rainfall and a more limited annual temperature cycle of 10^{o}C or less. There is no annual freeze-thaw cycle, thus, the growing season generally extends throughout the year (Ryding, Rast and Unesco, 1989). In general, the lakes in tropical regions classify as warm monomictic which is described as never having been ice-covered, mixing once per year and stably stratified the rest of the year (Lewis Jr, 1983). However, it only applies to tropical deep lakes. For tropical shallow lakes, the classification is warm polymictic which should be expected to have several episodes of complete mixing per year (Lewis Jr, 1983).

2.2.3 Primary productivity

If the primary production in an aquatic system depends on solar irradiance, the productivity in temperate and tropical systems will definitely be different (Lewis Jr, 1974). Kalff (1986) compared the temporal pattern of phytoplankton biomass in temperate lakes with two Kenyan lakes; Lake Naivasha and Lake Oloidien, and concluded that the phytoplankton dynamics in tropical lakes are not different from those in temperate lakes of the same trophy state during summer. Figueredo and Giani (2001) and Lv et al. (2014) however, points out that there is significant difference in the primary production between tropical and temperate system because the seasonal shifts in phytoplankton composition were closely related to climate, nutrient status, and hydrology in this reservoir.

Study done by Plankton Ecology Group (PEG) members proposed a model consisting of 24 statements which describe the pattern of phytoplankton productivity from late winter, through spring, summer, and autumn to the next winter Sommer (1985). Based on the PEG model, it can be concluded that rapid algal growth starts when stratification begins in spring with algal populations are initially dominated by green algae but later shift to blue green algae during the stable summer. They also pointed out that growth of phytoplankton is influenced by temperature where there is more fluctuation of the population during summer time. This later agreed by Elliott (2010) who tested the hypothesis on the sensitivity of the phytoplankton on flushing rate and water temperature. In the study, he concluded that phytoplankton seems to dominate the temperate lakes in the summer/autumn season. This is because summer often tend to be warm, stable water columns and having low flushing rates which favour the occurrence of the blue green algae (Reynolds, 2006). It is also clearly shown that low flows and high temperatures favour the dominance and bloom formation of the cyanobacteria.

In contrast to the temperate system, the effect of the rainy season on annual runoff patterns is significant in tropical regions. Greater volumes of precipitation will transport larger amounts of nutrient on land and result in nutrient rich waterbodies. However, frequent rainfall events will also disrupt the algal blooms temporarily because it will create flushing to the downstream water and prevent bloom formation. Therefore, the period of maximum algal production in tropical or subtropical lakes and reservoirs often takes place one or two months after the rainy season (Ryding, Rast and Unesco, 1989). The season and duration of drought will also affect the dynamics of algal blooms. During a drought event, the temperature will increase and reduce the volume of the water column through evaporation and evapoconcentration. The effect of volume reduction in the waterbody often results in higher nutrient concentrations, high phytoplankton biomass and lower water transparency in shallow and deep lakes and reservoirs (Brasil et al., 2015). This also agreed by a study conducted in 39 reservoirs located in north-east Brazil have shown that the lack of water renewal linked to an El Nino event seem to be the major factors responsible for both eutrophic conditions and cyanobacteria blooms (Bouvy et al., 2000). Apart from that, drought also may increase the water residence time in the waterbody, and some studies have shown that longer water residence times during dry years increase cyanobacteria biomass and dominance (Elliott, 2010).

2.2.4 Limiting nutrient

In the majority of temperate lake studies, P was consistently demonstrated as the primary limiting nutrient and its availability controls the use of N and carbon from the atmosphere (Harper, 1992). For example, Thomas (1953) demonstrated that P was the major element controlling productivity and promoting the growth of algae in Central European Lakes as a result from his study of Swiss lakes and comparison with other studies. From the analysis that had been done, he concluded that if there is no P input to the water bodies, the growth of algae would stop as soon as the algae consumed the basic P content. This was later agreed by David Schindler which investigated the response of N, P and carbon (C) on eutrophication by conducting whole-lake experiments in the Canadian Experimental Lakes Area in 1974. In the study, two basins of Lake 226 were divided into two equal areas by using a plastic curtain. Both sides of the lake received N and C additions, but P was only added to one of the basin. As a result, the basin that was enriched with P rapidly became highly eutrophic, while the water in the basin receiving only N and C remained as clear as its initial condition before the nutrients were added (Schindler, 1974).

In other studies on temperate lakes, however, both P and N were shown to be a primary growth limiting nutrient. For instance, a review study done by Elser, Marzolf and Goldman (1990) in North America Lakes involving the survey of enrichment bioassays data and whole lake experimental data between 1968 and 1888 found that both P and N were potentially limiting to algal growth in the lakes. Stronger growth responses were observed when the lakes were enriched with the combination of P and N than when the lakes were enriched by P and N alone. This view is supported by Xu et al. (2010) who also found that the combined P and N additions to waterbodies led to the maximum growth of algal bloom. In their whole lake experiment in Lake Taihu, China, he observed that the lake shifted from P limitation during winter-spring to N limitation during summer-autumn months. On the other hand, N limitation appears to be very common in many tropical countries (Harper, 1992; Lewis Jr, 2002). The remarkable studies that point out N limitation in tropical lakes include, Lake George, Uganda (Viner, 1977), Lake Lanao, Phillipines (Lewis, 1978), Lake Titicaca (Vincent et al., 1984) and various lakes in Cental Amazonia Basin, Brazil (Trevisan and Forsberg, 2007). All the whole lake experiments and bioassay experiments provide similar results which shows permanent shortage of N.

There seems to be general agreement that N limitation is more important at tropical lakes than it is in temperate lakes (Lewis Jr, 1996). Studies done at Lake Lanao, Philippines (Lewis Jr, 1974) and Lake George, Uganda (Viner, 1977) had concluded that N was limiting in tropical lakes. Lewis demonstrated that there was severe N depletion in Lake Lanao while Viner showed a permanent shortage of N and P in Lake George Uganda, with N supply being more critical. In his own review on tropical lakes, Lewis Jr (1996) listed three factors that might explain the N limitation in tropical lakes. These are: 1) P weathering from parent material is more efficient at elevated temperature, 2) evapo-concentration of P will be more pronounced at low latitudes, and 3) N losses from tropical environments are almost certainly higher than at temperate latitudes because of the high water temperatures of tropical lakes. However, not all the studies conducted in the tropical lakes agree with Lewis and Viner. For instance, Melack, Kilham and Fisher (1982) used experimental fertilization of natural algal populations taken from an equatorial African soda lake and showed P limitation of phytoplankton biomass. They concluded that phytoplankton in some tropical lakes can be controlled by the P limitation as seen in temperate lakes.

Land use and catchment characteristics may also differ between temperate and tropical zones. Intensive rainfall in seasonal patterns shown in tropical zones means that soil erosion is more significant, which could result in greater export of P bound to soil colloids. Thus, different land use and land cover will contribute to different problems. Cited by Harper (1992), studies done by Malthus and Mitchell (1988) show that agricultural practice in New Zealand differs from many other countries in the world due to the application of phosphate fertilizer which is very high while there is minimal N application, the latter nutrient coming from fixation by clover seeded into pastures. Besides that, patterns of fertilizer use are also different in many tropical countries, where some of the developing countries cannot afford the chemical fertilizer thus choosing human waste and manure as the alternative fertilizer (Rosemarin, Bruijne and Caldwell, 2009). An experimental study of algal growth on organic compounds such as urea, nitrate (NO_3^-) and ammonium (NH_4^+) found that the cyanobacteria Aphanizomenon ovalisporum, Microcystis and Synechococcus grew well on urea compared to NO_3^- or NH_4^+ (Berman and Chava, 1999). This also agree by later study that found cyanobacteria growth was faster with urea compared to other N sources (Donald et al., 2011).

In a nutshell, there is more difference rather than similarity between the temperate and tropical zones. Hence, those responsible for managing eutrophication and algal blooms should be more careful in selecting control strategies due to this fact.

2.3 Research gap

2.3.1 Previous work on eutrophication and algal bloom mitigation management

Mitigation of eutrophication and algal blooms in inland water is very important for the rest of the world to avoid shortages of drinking and domestic water (Cooke et al., 2005; Wang and Wang, 2009; Conley et al., 2009) and to protect environmental water quality as well as biodiversity (Hautier, Niklaus and Hector, 2009; Ansari et al., 2011b). The control measures to achieve desirable water quality can be expensive depending on the eutrophication level (Rast and Thornton, 1996). For example, taste and odour problems may occur in drinking water taken from a eutrophic reservoir even though it has been treated. Consequently, water treatment itself can be more expensive to remove all the impurities. Eutrophication and algal bloom formation in the water column can be avoided by measuring their growth requirement such as plant nutrients (Chorus and Bartram, 1999a). Thus, a growing body of literature has suggested this method of eutrophication control (Refer Oglesby and Edmondson (1966); Thornton (1987b); (1988); Carpenter et al. (1998b); Mainstone, Dils and Withers (2008); Conley et al. (2009). However, most of the control methods were focused on temperate systems rather than tropical systems.

As previously mentioned, there is a slight difference between temperate and tropics system in terms of factors that initiate eutrophication. Lewis Jr (2000) had suggested that the management approach to mitigate eutrophication must be different between tropic and temperate climates since the response towards eutrophication in the tropics is more sensitive to an increasing nutrient supply. Thus, one cannot simply apply existing technologies developed for temperate climate countries to the tropics. Moreover, economic differences also need to be considered because most developing countries are in tropical and subtropical regions. For instance, Lake Dianchi and Lake Taihu in China continue to suffer from extreme eutrophication where vast areas are covered by algal blooms because they cannot afford the pollution abatement management programme (Jorgensen, 2001). In his review, Thornton (1987b) identifies three gaps faced by tropical countries in managing eutrophication: 1) lack of funding; 2) insufficient technical and scientific staff; and 3) reduced concern for the management of water quality. This view is supported by Bonell, Hufschmidt and Gladwell (2005), who writes that for the countries which have become independent in the last few decades, there is a lack in long-term hydrological data. This problem has influence on governments in deciding suitable water management for specific problems. Besides that, lack of budgetary provision is the main issue for managing the tropical systems as most are located in a developing country. This is because the local government views managing water problems are not their prime task as there are more urgent needs to be tackled. Hence, the appropriate technologies that suit a developing countries' budget, environmental and management situation need to be identified.

According to Rast and Thornton (1996), in developed countries, the control measures focus more on the reduction of P loading to the water bodies by removing phosphate from wastewaters at the municipal wastewater treatment plants and restricting the quantity of phosphates contained in detergents. This is found to be the most effective and long-term measure for controlling eutrophication. There are also in-lake control methods which involve the addition of chemicals such as copper sulphate directly to the water body, biomanipulation and flushing. However, these methods are costly and produce side effects, and thus have only been applied when the reduction of phosphate to the drainage basin has failed. In contrast with developing countries where most of the nutrient inputs are primarily from non-point sources, the more effective control measure may be on reducing non-point source nutrient load compared to the point source load (Ryding, Rast and Unesco, 1989). The eutrophication problem in developing counties also usually occurs in areas with high population density and a growing economy (Thornton, 1987b).

Rast and Holland (1988) have provided general guidelines for making eutrophication management decisions. However, the focus of the guidelines is more toward the decision maker (policy maker). It should be noted that not all countries have legislation or guidelines to manage inland waters. For instance, in Malaysia, the inland water is owned by various agencies and individuals. There is also separation of powers in terms of management of lakes based on different usage (Sharip, 2008). This is the biggest challenge in securing surface waters. Hence, the framework for eutrophication management should be revised. An even greater source of concern is that the framework for eutrophication management should be validated and updated to the latest technology and new source of pollution.

2.3.2 Limitation existing approach

The research to date has not been able to provide a guideline for tropical countries especially for developing countries which have a budget constraint and lack of expertise. In conclusion, the limitations of the existing approaches to eutrophication management are as listed below:

1. A few management tools to support decision making were developed by the researchers and organizations in question, generally aimed at reducing eutrophication and algal bloom problems tailored to temperate systems;
2. Environmentally and economically, there are not suitable for tropical systems;
3. The tools are not easy to understand by management that has a lack in relevant technical expertise.

On the whole, there are some differences in the degree of the factors controlling eutrophication in temperate and tropical zones. Several control strategies have been demonstrated in literature to solve eutrophication problems but they are still scarce. Therefore, development of sound eutrophication management strategy is essential for tropical and developing countries. Hence, it is believed that this study will go beyond previous works or attempts in these broad parameters;

1. This study will explore the availability of methods treating eutrophication in literature;
2. This study will develop a framework on selecting the suitable method to mitigate eutrophication for tropical humid aquatic systems using multiple criteria analysis (MCA);
3. This study will use a case study from a water catchment in a tropical zone, i.e. Malaysia. A better understanding of the environmental factors contributing to eutrophication and algal blooms in tropical systems will be gained.

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CHAPTER 3

Control techniques for eutrophication and algal bloom – a systematic review

Chapter 3 : Control techniques for eutrophication and algal bloom – a systematic review

3.1 Introduction

Freshwater lakes and reservoirs water quality are degraded at ever increasing rates as a result of eutrophication. The most severe effects are when algal blooms appear which make the freshwater become unsafe for human consumption. During the last several decades, a number of attempts in managing the adverse effects of eutrophication and algal blooms have been implemented by developed countries. For instance, in developed countries, the control measures focus on the reduction of P loading to the water bodies by removing phosphate from wastewaters at the municipal wastewater treatment plant and restrict the quantity of phosphates contained in detergents (Rast and Thornton, 1996). This is found to be the most effective and long-term measure for controlling eutrophication. Thus, in European countries such as Sweden and Switzerland have legislated to restrict both detergent P content and effluent P concentration; similar legislation also exists in America (Harper, 1992).

In contrast in developing countries, there is often no formal legislation or action to control nutrients going into water bodies. Most of the world's developing countries are located in tropical climates and the studies conducted about eutrophication and algal blooms are limited. There are some differences between algal blooms occurring in temperate lakes and tropical lakes. For instance, algal blooms favour higher temperatures thus in temperate climates, blooms usually occur during summer (Paerl and Paul, 2012). In contrast with tropical climates, algal blooms may occur throughout the year because they receive a constant annual solar input and higher temperatures (Chorus and Bartram, 1999b; Jeppesen et al., 2005). However, according to Rast and Thornton (1996), control measures typically used in temperate zones should also work in the tropical regions, although with some difference in efficiencies.

Because eutrophication will continue to be a problem in many tropical countries, there is an urgent need to make practical use of such studies, to enable both accurate assessment and the effective long-term control of lake and reservoir eutrophication. In order to address these concerns, an approach to literature review known as the systematic review has been developed. Systematic review is a technique commonly used to identify and summarize all the available evidence in order to answer specific research question (Garg, Hackam and Tonelli, 2008). The evidence is collected from published and unpublished sources, screened for quality and synthesized into an overall summary of research in the field. The rationale for such reviews is well established. It has been used extensively by medical researchers and policy makers as it provides data for rational decision making. This technique is reliable as it can gather up to date evidence and is less costly than embarking on a new study (Mulrow, 1994). Thus, by performing a systematic review, it is expected that all experiences and studies reported by government organizations and academics is collected, characterized and analysed to provide an overview of control technologies existing nowadays, including the challenges, the importance of practices, and the reasons behind the mitigation strategies.

The aims of the systematic review are:

1. To synthesize the available techniques to control eutrophication and algal bloom problems in tropical reservoirs;
2. To track the history of application of the techniques in order to quantify the quality of the techniques; and
3. To examine the efficiency, advantages and disadvantages of each method in the systematic review

The systematic review study seeks to answer the following research questions:

1. What problems can be solved by the techniques? (i.e: nutrient reduction, algae removal)
2. Where can the techniques be applied?

3. How effective are the techniques?
4. How long does the effect of the techniques last?
5. Do the techniques have any undesired side effects on the environment?

3.2 Methodology

The systematic review is still new in the environmental management area. Because of that reason, a guideline to conducting systematic review by Pullin and Stewart (2006a) has been customized to achieve the objectives of the study. They propose four steps to conducting systematic review; (a) searching for data, (b) selection of relevant data, (c) assessing quality of data, and (d) data extraction and synthesis.

3.2.1 Searching for data

The search for relevant literature was conducted on 2nd April 2014 through five main online bibliographic databases which are;

1. Web of Science (http://wok.mimas.ac.uk/)
2. Science direct (http://www.sciencedirect.com/)
3. Springer link (http://link.springer.com/)
4. Taylor and Francis Online (http://www.tandfonline.com/)
5. Google scholar (http://scholar.google.co.uk/)

A search string to create a repeatable search was constructed to find the studies across a broad spectrum considering all available results, including from temperate systems. The important keywords were selected and combined, including their synonyms and related words. Different search criteria were applied for each database, due to the lack of standardization between the electronic databases. The keywords were as presented in Table 3-1.

Table 3-1: Search string use in database

No	Search string	Databases
1	**Topic search**: Eutrophication AND algal bloom* control OR management	**ISI Web of Science**
2	**TITLE-ABSTR-KEY**: Eutrophication AND algal bloom* control OR management	**ScienceDirect**
3	Eutrophication AND algal bloom* control OR management **Refined by:** Environmental science Pollution and remediation Environmental management	**Springerlink**
4	**Search everything**: Eutrophication and algal blooms management control	**Taylor and Francis online**
5	**Full-text:** Eutrophication AND algal bloom* control OR management	**Google Scholar**

The terms within each of the categories were combined using the Boolean Operator; ‘OR’ and ‘AND’. An asterisk (*) is a wildcard character that represents any group of characters including no character were also included. In terms of language, the search was restricted to papers published in English and in terms of publication date, papers published from the year 1984 to 2014 were selected. The journal papers were sorted by relevance. Once searching is completed, the first 100 hits (sorted by relevance) were saved and examined for appropriate data.

3.2.2 Selection of relevant data

Once the potential literature sources had been obtained from the search process, each study was filtered to quantify the quality of the studies. First, studies were considered for selection based on information provided in the title. The studies that include marine water as title were immediately removed. Duplicates articles were also excluded. Next, the abstract of the studies which include marine water, written in other than English and unrelated to the control of eutrophication and algal blooms were eliminated. The remaining articles were read further to find whether they matched the inclusion and exclusion criteria. All the steps were summarized as in Figure 3-1. The criteria used to filter the studies were based on the inclusion and exclusion criteria which are described as follows:

Inclusion criteria

1. Peer-reviewed papers that discussed about mitigation measures or prevention measures of eutrophication or algal blooms in freshwater (i.e; lakes, rivers and reservoirs) in any water systems (temperate or tropical);
2. Written in English and have full text; and
3. Describe the treatment methods in detail (i.e; effectiveness, advantages and disadvantages).

Exclusion criteria

1. Studies that do not relate to eutrophication or algal bloom management;
2. Studies that discuss estuarine, marine or coastal eutrophication or algal bloom management;
3. Studies written in languages other than English;
4. Studies that only discuss the basic concept of eutrophication or algal bloom;
5. Studies that discuss the general eutrophication or algal bloom problem or history but do not explain about the detail of how to manage the problem;
6. Studies that discuss eutrophication or algal blooms management in contexts other than water resources, for example, blue green algae in food industries; and
7. Modelling only studies.

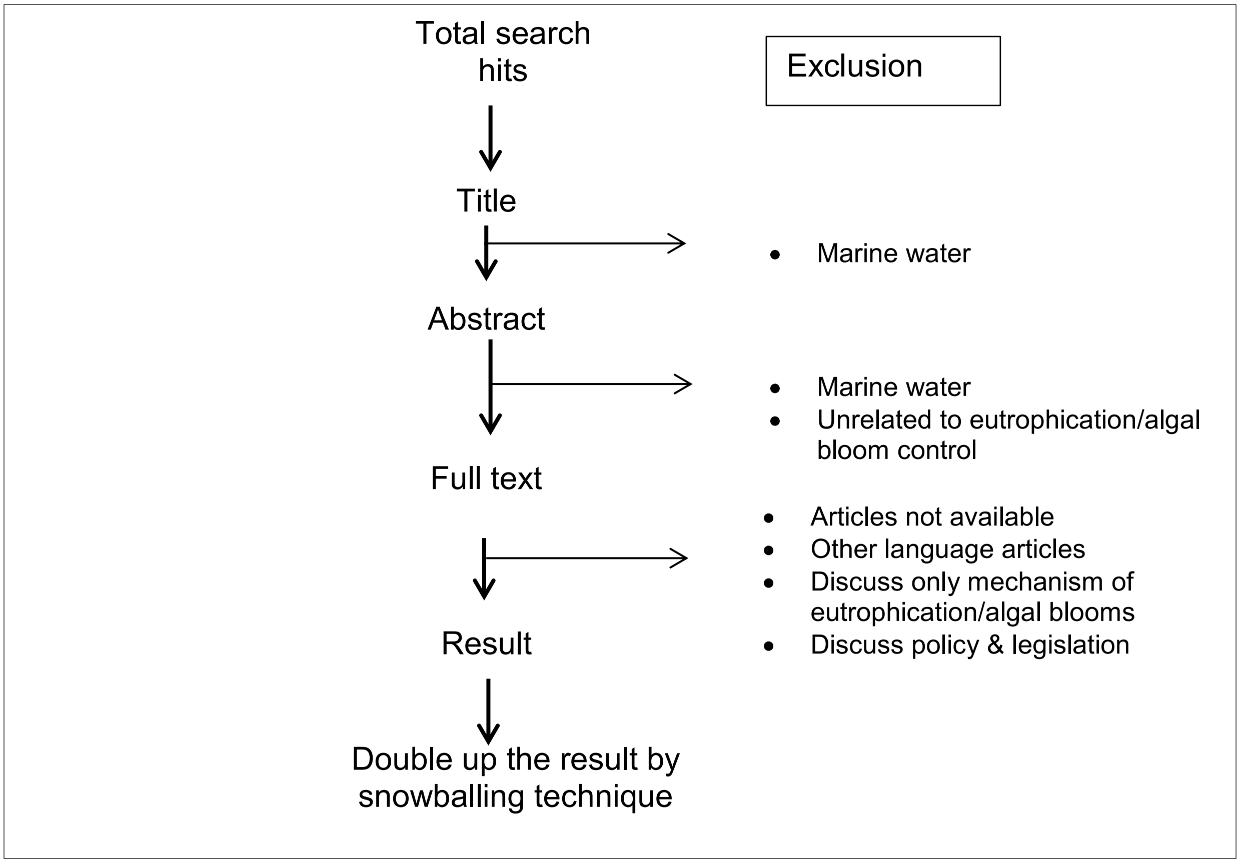

Figure 3-1: Flowchart of study selection

In order to improve the search results a snowballing method was used. Snowballing is the technique where locating, tracking and chasing down references in the bibliographies of articles is used to extent the number of available sources (Jalali and Wohlin, 2012). From the remaining potential articles, the full text was carefully examined. The relevant citations from the articles were then collected.

3.2.3 Assessing of quality of data

The studies were ranked according to the quality criteria met after the full text had been examined. Good studies were ones that were able to answer the following questions:

1. Has the treatment/control methods been discussed in detail?
2. How effective were the measures?

3. What were the advantages and disadvantages of the methods?
4. If the study was an experimental study, what was the efficiency of the treatment/control method?
5. If the study was a review study, does it explain the treatment method in detail?

Next, the outcomes and findings from the remaining studies were extracted and summarized in an effort to achieve systematic review objectives.

3.2.4 Data extraction

Data extracted from the remaining articles was systematically recorded in spreadsheets. In this review, the data extracted was divided into two spreadsheets: (1) measures included or discussed in the articles, regions or countries covered, and (2) results from the snowballing exercise recorded according to the techniques, year, effectiveness and duration of the effect.

3.3 Results

The search strings generated thousands of articles as summarised in Table 3-2. However, only the first 100 hits of articles from each database (Web of Science, Science Direct, Taylor and Francis Online Library, Springer Link and Google Scholar) were selected and examined according to the selection criteria.

Table 3-2: Searching results

No	Database	No of Hits	Date
1	ISI Web of Science	337	02-04-2014
2	Science Direct	133	02-04-2014
3	Springer Link	288	03-04-2014
4	Taylor and Francis Online	708	03-04-2014
5	Google Scholar	17600	04-04-2014

The specificity of this search was low, with many references identified multiple times. From 500 articles, the irrelevant studies either from the titles were excluded. Most of the articles which were excluded during the selection process were excluded because they were unable to fulfil the inclusion and exclusion criteria. For examples they could be measures for coastal water or merely discuss eutrophication and algal blooms in general terms. The selection steps of peer reviewed papers are presented in Table 3-3.

Table 3-3: Peer-reviewed literature selection stages

Stage	Description	Articles
1	Total number of detected papers after exclusion based on title, keywords and abstract	51
2	Total number of the candidate papers (after reading the full text)	18
3	Total number of the candidate papers (after removing the duplicate studies)	9

Since the online bibliographic database search technique drew a poor yield, the snowballing method was employed. The snowballing started from 9 articles which considered as pilot articles that resulted from the keywords search. The snowballing yielded a total of 316 relevant articles of eutrophication and algal bloom control techniques. As can be seen in Figure 3.2, only 19.61% out of 306 articles (exclude doing nothing) are conducted in tropical climate. Constructed wetland (CW) and biomanipulation technique can be said to be the popular techniques to be applied in both region. Up to 50% of the articles were from the tropical climate. The popularity of these two methods might because of the techniques require low capital and operational cost besides provide high efficiency. On the other hand, no articles regards to advanced wastewater treatment (AWT) in tropical was found during the snowballing. It is presumed that this technique does not favour by tropical region because of the high capital and operation cost even though it does effective in reducing the nutrient content from the wastewater. 32 articles found for nutrient inactivation which shows that this technique is also one of the popular choices considered by the water manager to control eutrophication besides CW and biomanipulation. However, only 1 article is from tropical region. This is probably because the major nutrient source in tropical region from external loading (Rast and Thornton, 1996). Nutrient inactivation is not suitable for a lake with high external loading which makes this technique is not the best option to reduce eutrophication in tropical regions.

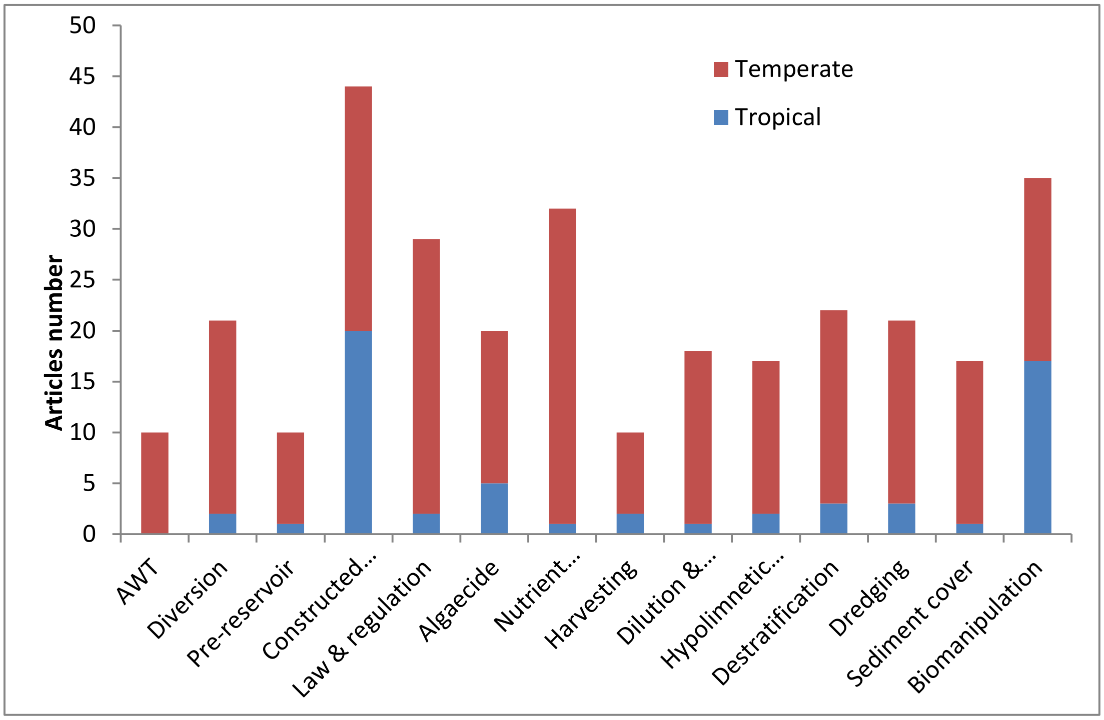

Figure 3-2: Articles yielded from snowballing technique based on types

3.4 Discussion

In this literature review, various measures used to combat eutrophication and algal blooms were identified. It was revealed that about half of the articles found had been published as long ago as the 1960s. After the year 2000, it was found that eutrophication and algal bloom abatement were more focused on marine waters than on freshwater. The trends in publishing the control measures based on the searching results in Table 3-3 were observed in two databases (Web of Science and Science Direct) since the other three databases (Springer link, Taylor and Francis Online and Google Scholar) were not sorted by year. As can be seen in Figure 3-3, published work increased from decade to decade. Moreover, most of the studies were conducted in the United States and Europe than in any other continent.

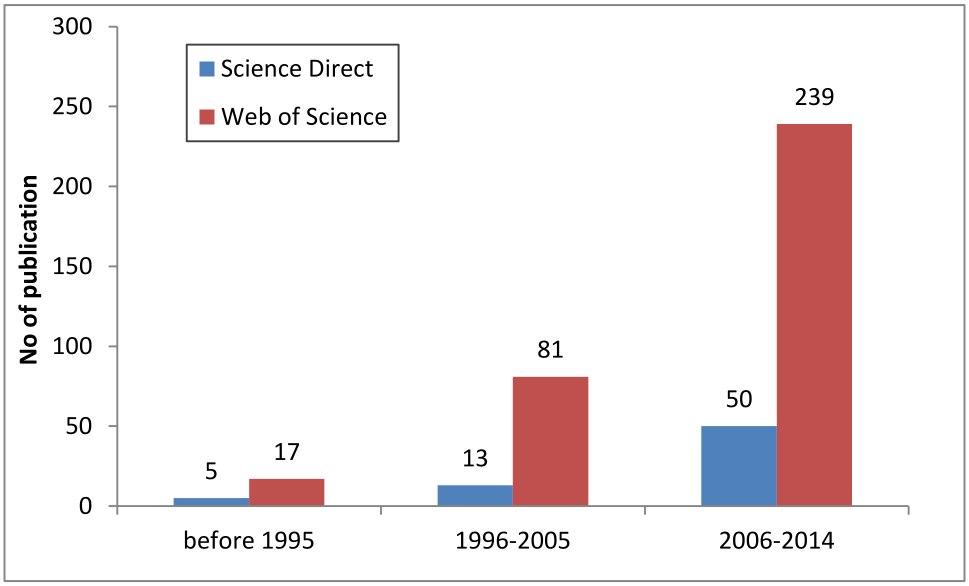

Figure 3-3: Searching result by year based on Science Direct (n=133) and Web of Science (n=337)

Eutrophication or algal bloom controls existed more than 100 years ago and highlighted the importance of abatement (Ryding, Rast and Unesco, 1989). It was recognized that control of external loads is the most effective and long-term measure in eutrophication and algal bloom control. In the articles reviewed, the measures were categorized into two categories; external control measures and in-lake measures. In some articles, external control measures was also referred to as treating of causes, and in-lake measures was referred to as treatment of symptoms. Meanwhile, some of measures also used different terms but served the same purposes. For instance, pre-reservoir also known as pre-dam or pre-impoundment and constructed wetland were also referred to as eco-remediation in different articles.

3.4.1 Discussion of articles

From the nine studies that have been analysed, two of them discuss eutrophication and algal bloom control in general without focusing on any region where the measures can be applied or have been applied. However the study done by Schindler (2006) which summarized recent scientific understanding in eutrophication and algal bloom management referred mostly to work coming from United States of America (USA). In these studies, Schindler discussed the development of knowledge in eutrophication management from the 1940s to 2000s, whereas the earlier eutrophication management had focused on reducing P load to the water body. A few control measures were implemented during the particular time such as changing laundry detergent formulation, removing P from human sewage, sewage diversion and changing agricultural practice. Next, a few attempts using liming, aeration, dredging, macrophytes harvesting and biomanipulation techniques were used to remove in-lake P and recover eutrophic water bodies after reducing the nutrient load. These did not end the eutrophication problem.

In contrast, work by Rast and Holland (1988) was found to be more general, making use of a model developed for temperate countries. They provided a framework towards eutrophication management, though it may not be up to date to the latest techniques or technologies. Three types of control were proposed which are reduction of nutrient input, in-lake control measures such as application of algaecides, nutrient inactivation and dredging, and the option of doing nothing. Nutrient input reduction was claimed to provide long term improvement of water quality. The techniques listed focused on point source and non-point source controls such as nutrient removal in wastewater effluent, diversion of wastewater effluent and agricultural management including management of livestock manure. Meanwhile, in-lake measures included aquatic plant harvesting, application of algicides, nutrient inactivation, dredging, sediment cover, flushing and biomanipulation. Doing nothing was also considered as an option in eutrophication management, which would ultimately be the most costly option over long term when the water quality degrades to the lowest quality and more expensive measures are needed later.

Two of the nine remaining articles, discuss specific control options in tropical and temperate regions. Thornton (1987b) discussed the management of eutrophication in tropical regions. In his work, he divided the control measures into two: treatment of causes and treatment of symptoms. Treatment of causes includes implementation of water pollution control legislation, diversion of sewage and P reduction in wastewater treatment. Meanwhile treatment of symptoms includes copper sulphate dosing, biomanipulation, aquatic plant harvesting, chemical control using 2,4-D which is a type of herbicide, and aeration.

In their discussion of the trends in eutrophication research and control, Rast and Thornton (1996) compare eutrophication control approaches in temperate and tropical regions. In temperate regions, the measures focused on the reduction of external P load to water bodies as it is more effective and provides a long term effect. The measures include advanced wastewater treatment by chemical precipitation or activated sludge treatment for point source, and containment systems for urban runoff and control of agricultural runoff for non-point source nutrient control. Meanwhile in-lake measures such as application of alum and sediment removal or dredging have only had been used when eutrophic lakes failed to respond to external nutrient load measures. In contrast in temperate regions, which primarily consist of developed countries that implement technology based control measures, tropical region countries tend to use less expensive techniques such as aquatic plant harvesting.

The remaining articles were found to focus on specific measures and techniques that have been implemented in different countries. For example, two articles discuss current eutrophication control strategies in China. Liu and Qiu (2007) reviewed the status of eutrophication of lakes in China and control strategies adopted to combat the problem. They point out that point source nutrient is the main source of eutrophication because until late 2005 only 382 out of 660 cities in China possessed wastewater treatment facilities. In order to overcome the problem, the government constructed more sewer collection systems and wastewater treatment plants for the treatment of municipal wastewater, and introduced controls which restricted industrial discharges. Moreover, from 1998 China started to prohibit the use of P based detergents in some static water areas. For in-lake measures, the techniques that are widely used in China are sediment removal or dredging, water flushing, aeration, aquatic or macrophyte planting and biomanipulation. Le et al. (2010) presented eutrophication control in China in a different way. They reported more on the principles of control rather than specific measures or techniques. The principles of control included pollutant load control by relocation of industrial parks, catchment management and human intervention, and ecological restoration through macrophyte plantation.

Another article was by Gulati and van Donk (2002) and reviewed various lake restoration techniques used in the Netherlands which most freshwater lakes is shallow (<2m). The efforts of lake restoration in the Netherlands started in the early 1980s which aimed at improving the water clarity of the lakes by controlling cyanobacterial blooms. The first control technique used was reduction of nutrient external load for Loosdrecht lakes that received untreated household waste and inlet of P rich (up to 3mg/L) from Vecht River. The restoration was started by replacing the Vecht River water by water from Amsterdam Rhine Canal which has been treated with ferric chloride to reduce its P concentration. The P dynamics in the lake and the sediments showed notable changes. However, no change was observed in the water clarity, phytoplankton and chlorophyll-a level. Other modelling study using the hydrological data from the lakes suggested three solution to improve the previous restoration result, 1) further reduction of external load is needed to gradually decrease the TP level in the lakes; 2) P removal by dredging and iron addition should be included; and 3) increased P retention in the sediment will improve the water quality.

Dilution and flushing also been used in the Netherland. Only few cases using the techniques have reported to be successful in improving the water quality. For instance, Lake Veluwe was flushed using poor polder water in winter 1978-1979. A reduction of TP was observed to drop 3-4 folds by the end of first winter and the Oscillatoria bloom virtually disappeared. In 1982 to 1983, the maximum internal P loading had decreased about 15% of what it had been 1979 and diatoms and green algae had become dominant. However, further recovery of the lake was disrupted by the wind, resuspension of detritus and inorganic matter from the bottom of the lake and the release of P from the sediment. This technique does not become the best technique in restoring the lake in Netherlands because the short supply in good quality of dilution water and the cost of transporting the water to lakes are not easy and cheap.

Other techniques that reported to be used in the Netherland is the combination of dredging and other measures which been used in Lake Geerplas that has been polluted by drainage from market gardens and nutrient-rich water inlet from a bird colony. As a result, chlorophyll concentration reduces by almost 50%. However, the cyanobacteria in phytoplankton and TP concentration did not decline. Besides that, the P release characteristic of the sediment exposed after dredging is the same as the sediments that had before dredging. Nutrient inactivation using ferric chloride ($FeCl_3$) also has been used to restore eutrophic lakes in the Netherland. For instance the application of $FeCl_3$ to the sediment in Lake Groot Vogelenzang using water jet has resulted in the reduction of TP concentration, chlorophyll-a concentration and suspended solids after three weeks application. However, TP concentration rose again after three months of application of $FeCl_3$ and P release from intact sediment cores had raised a year later. The failure of this technique was suspected caused either by high external loading or the loss of binding capacity of the $FeCl_3$ or both these causes. Meanwhile, artificial mixing is not popular in the Netherland because all the lakes are well mixed in shallow lakes. However, this technique has been applied to Lake Nieuwe Meer which suffered from *Microcystis* blooms during stratification in summer. This has resulted in the shift of *Microcystis* blooms to diatoms, green algae and flagellates. This technique gave instant results in reducing the algae blooms compared to the reduction of external nutrient loading but it does not reduce the nutrient concentrations.

Biomanipulation was implemented in Netherland after the failure in nutrient reduction measured. The article discussed biomanipulation techniques in detail with a few examples from case studies in Dutch lakes which showed that biomanipulation is widely used in the Netherlands compared to other measures. However, more failures than successes were recorded from the case studies and it was concluded that this related to insufficient decrease of in-lake nutrient loading and the increase of planktivorous fish. For instance, biomanipulation was applied from 1987 until 1999 in Lake Zwemlust which permanently occupied by *Microcystis aeruginosa* and the fish community was dominated mainly by bream species. However, no improvement in the condition of the lake and the water quality was observed during 12 years of biomanipulation application. Other examples biomanipulation is in Lake Wolderwijd, a shallow lake (1.5m) which suffered from *Oscillatoria agardhii*. The biomanipulation started on May 1991 where the lake stocked with 217 pike fingerling per hectare. Following to that, water clarity of the lake increased as a result of grazing by *Daphnia galeata*. However, the results only lasted for six weeks and Daphnia totally disappeared in June 1991 due to food limitation while most of young pike died.

Work done by Herath (1997) compared control measures used between Europe and Australia. Four options were discussed: physical measures, economic measures, regulatory approaches and biomanipulation. Artificial aeration, which is physical measure, has been applied to both regions, however, it was a failure in Australia when 70% of the reservoirs that adopted the technique shows no reduction in algal biomass. The economic measures approach such as water pricing and deregulation was adopted by both regions, this took the form of a tax on P (Europe only) and tradeable permits which are still under pilot in Australia. These were adopted to control P emissions into waterways. Other options to control nutrient loading were by using regulatory approaches. A reduction of detergent P was applied in Europe but not in Australia. This is because non-point sources from agriculture was the main concern of P loading in Australian freshwaters. Sewage treatment plants have been installed in both regions but the technology in Australia is not as advanced as that used in Europe. Last but not least, biomanipulation showed some success in Europe but not in Australia because the common native zooplanktons are not efficient grazers for the cyanobacteria.

Svircev et al. (2008) described the eutrophication and algal blooms status in Serbia alongside the methods for management of eutrophication in freshwater ecosystems in Vojvodina, Serbia. In their studies, they presented known reservoir sanitation methods which are mixing and oxygenation, methods of sediment treatment, biomanipulation, algicides and an ecoremediation (ERM) method. Attention focused on ERM since Serbia had not implemented this measure for eutrophication remediation, which here has been assumed that the other four methods discussed in the article have been implemented in Serbia. According to Svircev et al. (2008), ecoremediation works by utilizing natural processes to restore and protect water bodies, and one of the examples of ecoremediation is constructed wetlands. They listed twelve advantages of ERM such as efficiency in purification, cost, no mechanical or electrical equipment needed and others. The measure options extracted from the 9 pilot articles has been summarized in Table 3-4.

Table 3-4: Measures option extracted from 9 pilot articles

No	Measures discussed	Year	Region	Study (Reference)
1	Wetland P load reduction Sewage diversion Changes in agricultural practices Liming Aeration Dredging Macrophytes harvesting Biomanipulation	2006	General	Schindler (2006)
2	Nutrient reduction in wastewater effluent Waste water diversion Agricultural nonpoint source control Urban nonpoint source control Harvesting Nutrient inactivation Artificial oxygenation Dredging Sediment cover Water flushing	1988	General	Rast and Holland (1988)

	Biomanipulation			
3	Copper sulphate Biological control Mechanical harvesting Chemical control (2,4-D) Artificial aeration	1987	Tropical	Thornton (1987b)
4	Advanced wastewater treatment Detention, retention and infiltration techniques Containment Alum treatment Dredging Harvesting Waste water diversion	1996	Temperate and tropical	Rast and Thornton (1996)
5	Control of external nutrient loading Prohibition of phosphate detergent Sediment dredging Water flushing Aeration technology Planting of aquatic and/or submerged macrophytes Biomanipulation	2007	China	Liu and Qiu (2007)
6	Control of nutrients load Restructuring of industrial layout Wetland & Riparian zone Flushing Dredging Biomanipulation	2010	China	Le et al. (2010)
7	Nutrient control policy Control of external nutrient loading Biomanipulation Flushing Dredging P inactivation by ferric chloride Artificial mixing Liming	2002	Netherlands	Gulati and van Donk (2002)
8	Artificial aeration Mud deposits pumping Water pricing and deregulation Tax on P Tradable permits	1997	Europe and Australia	Herath (1997)

	Reducing detergent P Reduction of P in water treatment plant Biomanipulation			
9	Mixing and oxygenation Sediment treatment Biomaniulation Algicides Ecoremediation	2008	Serbia	Svircev et al. (2008)

3.4.2 Evaluation of measures

In this section, measures and options identified from the systematic review and snowballing exercise are discussed in detail. The measures are divided into two categories: (1) external measures and (2) in-lake measures. A random search using ‘eutrophication and algal bloom control using (measures)’ keywords was used in Science Direct to see the trends in publication for these measures in journal databases. As can be seen in Figure 3-4, sediment cover (1662 articles), constructed wetlands (1288 articles), algicides (1265 articles) and dilution and flushing (1207 articles) are the most published measures found in the database. Sediment cover and constructed wetland studies have increased decade to decade. Before 1995, sediment cover and constructed wetland studies were not as topical as other measures such as algicides, however this works increased during 1996 to 2005. Between 2006 and 2014, the number of studies of sediment cover and constructed wetland doubled over the 10 years before. Meanwhile, hypolimnetic withdrawal was the least prevalent studies found in the Science Direct database, and the published work was less than 100 articles for each measure.

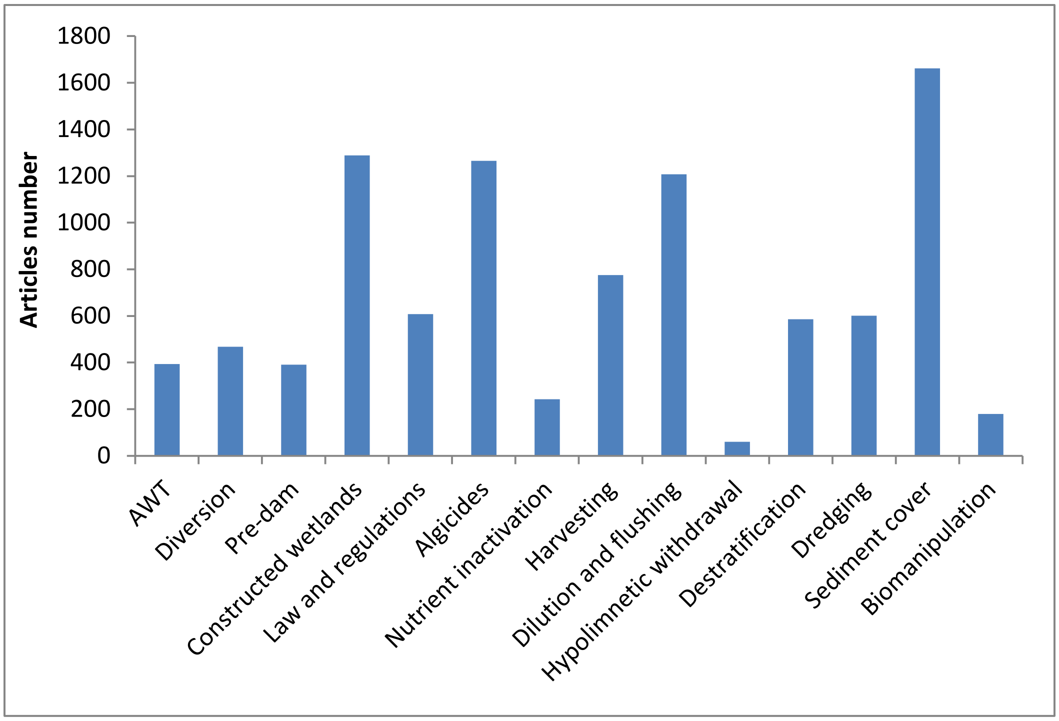

Figure 3-4: Result of random search of the measures option in Science Direct database until on 25th May 2014

3.4.2.1 External measures

3.4.2.1.1 Advanced waste water treatment (AWT)

Reductions in P and N at source can be achieved by the removal of associated nutrients in wastewater treatment plants. The technologies to remove nutrients can be retrofitted to existing sewage treatment processes at a later stage. It is usually referred to as tertiary treatment or advanced wastewater treatment. Nutrient removal can be achieved either through chemical treatment, advanced biological treatment or a combination both (Yeoman et al., 1988). For example, installation of AWT in a conventional wastewater treatment plant in Zurich was successful in removing almost 54 percent of the P load to Lake Zurich, and a decline in in-lake P over the last 13 years (Cooke et al., 2005). AWT also gave positive results to Shagawa Lake, Minnesota when it reduced P load to the lake by up to 70 percent at the beginning of operation. However, the lake remained eutrophic especially during July and August due to internal loading from an anoxic hypolimnion and P washout during summer storm events (Larsen et al., 1975). Because of the cost of installing and running treatment facilities, it has been disadvantageous to developing countries to apply such measures.

3.4.2.1.2 Waste water or runoff water diversion

Diversion of nutrient inputs is the second option if wastewater treatment fails to remove sufficient P and N. It works by re-routing the nutrient rich water from entering the lakes. Diversion is expected to have a similar result to nutrient removal through advanced wastewater treatment (Cooke et al., 2005). If the lakes are either P limited or N limited, diversion can also help to balance in-lake nutrient. For instance, for eutrophic lakes in which N is the limiting nutrient, P can be made to limit if the external P loading is sufficiently reduced. However, diversion only works for eutrophic lakes that have uncontrollable external nutrient loads from either point or non-point source pollution (Cooke et al., 2005). Lake Washington is perhaps the best known example of successful lake restoration using the diversion method. Water quality deteriorated after it received effluent from ten secondary treated domestic wastewater treatment works. The diversion started in 1963, and after 6 years phosphate in the lake decreased up to 28 percent while nitrate reduced less than 20 percent (Edmondson, 1970). The diversion continued after 1969 and phosphate has gradually declined especially in late 1990s due to lower flushing rates (Cooke et al., 2005). Another successful result of wastewater diversion was recorded in Lake Sammamish, Seattle. The diversion of effluent from sewage treatment and a dairy plant has decreased the mean annual concentration of P in the lake. During pre-diversion in 1964 to 1966, the average P concentration was 33 µg/L and it eventually decreased to 28 µg/L during post-diversion (1971-1975). The blue green algae component decreased by up to 50 percent. However, no visible reduction of phytoplankton and water transparency was observed (Welch et al., 1980). Besides these success stories, such measures may also have disadvantages where it they initiate poor water quality at downstream water bodies where the diverted water is returned.

3.4.2.1.3 Pre-reservoir

A reduction of nutrients in tributaries can also be achieved pre-reservoir. It works by retaining nutrient rich water for a short period of time prior to its entering the main body of the reservoir. The pre-reservoirs normally small in size and have a surface overflow plus a deep gate to allow water removal followed by sediment removal (Cooke et al., 2005). As been described by Pütz and Benndorf (1998), the reductions of nutrients in the reservoir happen as a result of a number of physicochemical and biochemical processes. The nutrient removal involves the biochemical conversion from the dissolved to the particulate form and the sedimentation of phytoplankton and other particulate matters within the pre-reservoir. The sedimentation process is enhanced by the presence of natural precipitants and flocculants. However, the effectiveness depends upon retention time and mean depth of the pre-reservoir. The optimum design of a pre-reservoir includes optimum retention time which allowed the particulate to settle down, mean depth should not exceed the depth of euphotic zone to prevent decreasing rate of internal P elimination and bottom sediment is to be removed in time intervals of 5 to 10 years.

Work done by Pütz and Benndorf (1998) found that the efficiency of nutrient removal in 11 pre-reservoirs in Saxony, Germany is greatest during seasonally low flows but became limited during winter because of light intensity and temperature are low. Another successful example of P elimination is in Wahnbach reservoir, West Germany. A pre-reservoir was formed where the main inflow river, the Sieg, entered the reservoir and treated with 4–10 mg/L Ferric at pH 6.0–7.0. The pre-reservoir successfully removed up to 96% of the TP and 92% of the dissolved P (Cooke et al., 2005; O'Sullivan and Reynolds, 2008). This technique also had been successfully control the eutrophication in one of the reservoir in Luxembourg. In the study, the performance of two pre-reservoirs which were constructed at the same time as the main reservoir was evaluated. As results, the shallow Misère pre-reservoir retained approximately 60% of P while the deeper Bavigne pre-reservoir retained about 82% of P. The difference in the retention rate between both pre-reservoirs is probably due to their different flow regimes and morphology (Salvia-Castellvi et al., 2001).

3.4.2.1.4 Constructed wetlands

Constructed wetlands are treatment systems that use natural processes involving vegetation, soils, and their associated microbial to improve water quality. It works as a filter to trap nutrients by microorganism or plant uptake (United States Environmental Protection Agency, 2004). As was cited in Cooke et al. (2005), besides functions as P retention and storage, wetlands are also effective in NO_3 removal and the highest removal rates were in constructed wetlands dominated by cattails species that provided organic carbon for bacterial metabolisms and during periods of highest water temperature. One of the most successful usages of constructed wetlands was reported in Piracicaba, Brazil. The constructed wetland was first cultivated with rice (*Oriza sativa*) before being replaced with false flax (*Commelina beghalensis L.*) in order to control the pollution entering the Piracicaba river catchment which received effluent from the sugar cane industry. The efficiency of removal was up to 93% for P, 78% for nitrate, and 50% for ammonia (Farahbakhshazad, Morrison and Filho, 2000). A pilot scale of wetlands in Putrajaya, Malaysia was cultivated with Common Reed (*Phragmites karka*) and the Tube Sedge (*Lepironia articulate*) to treat surface runoff from development and agricultural activities, and also reported reductions of up to 82.11% TN, 70.73% nitrate–N and 84.32% phosphate (Sim et al., 2008a).

Nevertheless, effective wetland performance depends on effective maintenance. Maintenance that normally critical for constructed wetland are such as adjustment of water level and flow control, vegetation management, nuisance pest or insects control and odour control. Adjustment of water level and flow control is extremely important because changes in water level may also affect the hydraulic retention time, diffusion of atmospheric oxygen into the water apart from plant cover. Any changes in water level should be inspected as soon as possible as it may affect the wetland performance due to leaks in piping system, clogged low flow orifice, breached berms, storm water drainage or other causes (Crites, 1988; Hoyt and Brown, 2005). On the other hand, the purpose of vegetation management is to maintain desired plant communities and preventing the growth of unwanted species (Environmental Protection Agency, 1999). This is normally done by consistent pre-treatment, infrequent changes in the water level and harvesting the unwanted aquatic plants including by application of pesticides (Hoyt and Brown, 2005). In the case of deficient plant cover, management activities such as water level adjustment and replanting should be conducted (Environmental Protection Agency, 1999). Meanwhile, control of nuisance pest and insects are important to avoid hazard to the operator. In tropical regions, dangerous reptiles such as snakes and alligator may occur in the wetlands. Therefore, a walking trail, fencing and warning sign need to be provided to prevent unwanted accident. The present of mosquitoes borne-disease also critical issue in tropical wetland. Anti-mosquito fogging and erecting bat and bird houses option should be included in order to control the proliferation of mosquitoes. To control odours in the wetland, the organic and nutrient loading need to be reduced. This is because the odours normally generated from the excessive BOD and ammonia loading (Environmental Protection Agency, 1999).

3.4.2.1.5 Law and regulations

Nutrient export to water bodies can also be controlled by legislation and regulation. For example, it is possible to control or restrict the quantity of phosphates in detergents. Because of this, many developed countries such as Switzerland, Italy and Germany have introduced limits on P containing detergents (Herath, 1997). Only 23% by mass of P in detergent is permitted in Germany and 4% P by mass in detergent was allowed in Italy. The same goes for the USA and Canada where detergent is permitted to have up to 0.5% to 2.2% P which is equivalent to 2% to 9% of phosphate. Meanwhile, Switzerland has banned P use in detergents since 1986 (Zoller, 2004). No such regulation is found in developing countries. This may be because non-point sources such as urban runoff and agricultural runoff are the main concerns in developing countries. Besides for P detergent regulations, most developed countries also have wastewater effluent discharge guidelines. For example, in Europe, the EU Urban Wastewater Treatment Directive specifies a limit value of phosphate for effluent discharge in receiving waters by 2 mg/L for treatment capacity between 10 000 to 100 000 population, and 1 mg/L for treatment capacity more than 100 000 (Herath, 1997). More stringent limits for P effluent discharge are applied in the USA, where the U.S. Environmental Protection Agency (EPA) are requiring dischargers to reduce and achieve total P effluent concentrations as low as 0.009 to 0.05 mg/L (United States Environmental Protection Agency, 2007).

Besides that, best management practice (BMPs) in P management also can reduce the nutrient export to the waterbody. BMPs control P loss from agricultural land by erosion and runoff control and management of P. BMPs consist of wide range of measures from the complex action such as conservation tillage, cover crops and buffer strips to simple actions such as applying manure or fertilizer only after forecasted rainfall (Bundy et al., 2006). Conservation tillage practices can reduce runoff and erosion by maintaining at least 30% of the soil surface covered by residue after planting (Holdren, Jones and Taggart, 2001). The percentage of soil loss reduction is depending on the conservation tillage system. For instance, the use of three different types of tillage system in American Great Lakes Basin shows different results when no till system reduce up to 90% soil loss, disk plant system reduce between 70% to 90% soil loss and chisel plow reduce between 30% to 90% soil loss (Ryding, Rast and Unesco, 1989). Another popular practice is buffer strips or also known as vegetative buffer strips which are narrow strips of permanent vegetation that helps to reduce pollutant in surface runoff from agricultural land (Schmitt, Dosskey and Hoagland, 1999). A comparison study done by Borin et al. (2005) on the effectiveness of buffer strips in removing the pollutants in runoff shows that buffer strips may reduce total runoff up to 78% compared no buffer strips. The buffer strips also successful in reducing the total suspended solid (TSS) and trapped sediment-bound P components but not the soluble forms of nutrients. Others BMPs can be applied such as crop rotation where the soil erosion and nutrient applications can be reduce by alternating with nitrogen-fixing legumes such as tamarind and Inga tree; fertilizer management where nutrient loading can be reduce by controlling timing, amount, and type of fertilizer to crops; and manure management where the nutrient loading can be reduce by considering the size and design of manure storage facilities, controlling the frequency of manure spreading and the distance of spreading from waterbody (Ryding, Rast and Unesco, 1989; Holdren, Jones and Taggart, 2001; Bundy et al., 2006).

3.4.2.2 In-lake measures

3.4.2.2.1 Chemical control

Chemical control methods involve the application of specific chemicals to water bodies to kill or remove undesirable aquatic plants. One of the earliest methods used to combat algal bloom in lakes was by using copper sulphate. Copper sulphate is believed to have been used for more than 100 years (McKnight, Chisholm and Harleman, 1983; Hawkins and Griffiths, 1986). It has been widely used and the experience has been well documented in the literature. The primary advantage of this method is that it works rapidly. Based on a previous study by Gibson 1972 on two species of blue green algae (*A. flos-aquae* and *Scenedesmus quadricauda*) from Cefni reservoir, North Wales found that copper sulphate was able to kill both species of blue green alage within 12 days. Five shallow eutrophic lakes in Manitoba, Canada have also experienced the effectiveness of copper sulphate when total chlorophyll-a declines and A. flos-aquae disappeared after four days of treatment (Whitaker et al., 1978)

However, this type of treatment does not last long as has been the experience of Casitas reservoir, California in which algal regrowth occurred after 4 weeks of treatment (Cooke et al., 2005). Besides that, copper sulphate also has negative impacts on the wider aquatic environment. The accumulation of copper sulphate in bottom sediment may harm other aquatic life (Gibson, 1972; McKnight, Chisholm and Harleman, 1983). For example, fifty eight years of copper sulphate treatment in Fairmont lakes, Minnesota, found a unmber of negative impacts such as increased internal nutrient recycling, dissolved oxygen depletion, fish kill and increased tolerance to copper by some blue green algae species (Hanson and Stefan, 1984). In addition to the side effect of copper treatment, Kenefick et al. (1993) in their study, do not recommend copper sulphate be used in treating algal problems in drinking water sources because copper sulphate may release toxins contained in the algae species which can cause human illness. In the long run, this measure should only be used in extreme cases due to its negative impacts to the environment and potentially to human health.

In addition to copper sulphate, there are also other chemicals that have been used to control algal blooms, such as hydogen peroxide. Matthijs et al. (2012) tested the application of hydrogen peroxide in an enclosed lake and found it was successful in killing algal blooms without impacting on other aquatic life. They also suggest that this method is safer to use in drinking water resources since there is no side product left by hydrogen peroxide application as it degrades to water and oxygen. However, this method was not widely applied and it is only at the experimental stage.

3.4.2.2.2 Nutrient inactivation

Unlike chemical control which is used to kill and remove algal blooms, this method targets the nutrient supply that causes eutrophication or algal blooms. It provides long-term control of algal biomass by significantly reducing the supply of essential nutrient rather than killing the algae. The procedure consists of spreading certain chemicals such as lanthanum (Peterson et al., 1976; Reitzel et al., 2013a), zirconium (Kumar and Rai, 1978; Sanville et al., 1982), aluminium sulphate (alum) (Smeltzer, Kirn and Fiske, 1999; Rydin, Huser and Welch, 2000; Steinman and Ogdahl, 2008) and the latest Phoslock® which is lanthanum modified bentonite (Haghseresht, Wang and Do, 2009; van Oosterhout and Lürling, 2013; Reitzel et al., 2013b) in the water body to form flocculants that bind P and coagulate the algal cells, which then settle to the sediment floor preventing the P from diffusing back to the water column. From observation, most of the studies prefer to use alum to inactivate P in the water column. This may be because alum is relatively inexpensive compared to other salts (Jorgensen et al., 2005). For instance, the application of low dosage alum to one of eutrophic lake in New Zealand had shown no significant change in water clarity. However, the epilimnetic P concentrations has decreased from 40 mg/m^3 and TN:TP mass ratios increased from 7:1 to 37:1. This has resulted changes in the dominant phytoplankton species from *Anabaena spp*. to *Ceratium hirudinella* and *Staurastrum sp*. (Paul, Hamilton and Gibbs, 2008). Another successful story of alum application was recorded in Spring Lake, Michigan. The concentration of soluble reactive phosphorus (SRP) and TP were declined after the alum application even though there are no changes in the chlorophyll levels. P concentrations in water column also remain high due to high external loading which also resulted to high chlorophyll levels. Therefore, should be noted that this treatment is not suitable for lakes with high external loading (Steinman and Ogdahl, 2008).

Latest study has found that lanthanum modified bentonite or Phoslock®, as one of the effective adsorbent for P uptake. An investigation of the uptake of phosphate from synthetic and real wastewaters by Phoslock® in laboratory and field has found that P concentration decreased immediately after the application of Phoslock® in the laboratory test. Besides that, Phoslock® also successfully removed TP and FRP at 85% and 98% in the field test (Haghseresht, Wang and Do, 2009). A study that examine the effect of Phoslock® on the growth of phytoplankton such as green algae (*Scenedesmus obliquus*), cyanobacteria (*Microcystis aeruginosa* and *Anabaena sp*.) and rotifer (*Brachionus calyciflorus)* shows that the addition of Phoslock® caused a reduction in growth of all of the phytoplankton tested. It also been concluded that Phoslock® is suitable for field application. However, the effectiveness of the Phoslock® to adsorb P is depends on dose and reaction time where water mixing could promote the adsoption process (van Oosterhout and Lürling, 2013).

3.4.2.2.3 Plant harvesting

This method involves hand-pulling, cutting or mowing of nuisance growth of macrophytes and attached algae from the water body which are then collected mechanically and disposed of elsewhere. Various kinds of harvesting machinery have been developed to cut and remove the macrophytes. For instance one 2.5m cycle bar harvester has been used to remove macrophytes in Lake Sallie, Minnesota. The treatment provides immediate relief from nuisance macrophytes but it only removed 1.37% or TP input to the lake (Peterson, Smith and Malueg, 1974). Continuous harvest during the growing season was needed. In contrast, a similar study conducted in Chemung Lake, Canada, gave an efficiency of 92% of net annual P loading in the harvested lake. The efficiency of treatment was different between the lakes because Lake Sallie has a deeper body of water with 60 years history of nutrient enrichment by wastewater effluent (Wile, 1978). Meanwhile, Engel (1990) reported that the harvesting method removed up to 70% of the submerged macrophyte standing crop in Halverson Lake, Wisconsin, USA. However, it quickly regrew after a few weeks of harvest and becoming denser. Plant harvesting alone cannot counteract the high loading of nutrients as shown in Carpenter and Adams (1978) study in Lake Wingra, with only 37% of the P annual net loading. Harvesting in tropical is not clearly recorded. However one of the prominent work by Rodríguez-Gallego et al. (2004) shows that harvesting also successfully works in tropical lakes when macrophytes harvesting in Lake Rodó, Uruguay successfully decreased 58% to 88% of N load and 39% to 78% of P load in the water column. However, the harvests only manage to removes for only 1% to 2% of N and P sediments load. It is suggested that harvests will give optimum results if it carried out when the biomass level less than 1000 g DW m–2 and biweekly frequency of harvest will keep the biomass under control.

Besides that, this method has the drawback that it is usually energy and labour intensive. In some cases, the occurrence of littoral zone macrophytes growth can be so extensive and required more labour and equipment resulting in high operating cost. This treatment also must be applied repeatedly according to the growing season (Ryding, Rast and Unesco, 1989). Thus, it can be concluded that this treatment only provides immediate relief from conditions which impair the purpose of the water body. The efficiency may be increased if it is being used in conjunction with other in-lake control measures.

3.4.2.2.4 Dilution & flushing

Dilution works by adding nutrient poor water to the eutrophic water column. The poor nutrient water could be from the river (Welch and Patmont, 1990) or groundwater (Hosper and Meyer, 1986). As a result, the internal nutrient loads will be decreased. The lower the concentration of the dilution water will increase the effectiveness of the treatment. However, lakes with low initial flushing rates will not response to this treatment effectively instead increased the in-lake nutrient unless the dilution water is free from nutrients (Welch, 1981). Meanwhile, flushing can wash algae out of the lake faster than they can reproduce by adding large volumes of water. However this method might only be suitable for small lakes and reservoirs. Dilution and flushing have worked successfully in several lakes such as Green Lake, Moses Lake and Veluwe Lake. The long-term dilution of Green Lake in the Seattle using low nutrient water from Seattle domestic supply begins in 1962. Rapid improvement of Chl-a, TP and Secchi depth was observed during the first few years of dilution. Water clarity during summer increased nearly fourfold and Chl-a decreased more than 90%. The decreased in the blue-green algae fraction was also observed, particularly in the spring and early summer (Welch, 1981). The benefit of the dilution and flushing also been recorded in Moses Lake, Washington. The dilution water which is low in macronutrients was added to Moses Lake three times in 1977 and once during spring-summer period in 1978. The dilution water was comes from low-nutrient Columbia River that diverted through the lake. As a result of the dilution water application, Chl-a was reduced almost 80% and TP declined 50% to 60% after treatment (Welch and Patmont, 1990). Another successful case was recorded in Lake Veluwe, The Netherlands which suffered from Oscillatoria agardhii bloom. In this case, low

TP groundwater was pumped into the lake during winter to lower the internal P and reduce the algae bloom. This technique has resulted in the decreasing of chlorophyll-a and TP from 200–400 mg/L to 50–150 mg/L, and TP declined from 0.40-0.60 mg/L to 0.10-0.20 mg/L after treatment (Hosper and Meyer, 1986).

3.4.2.2.5 Hypolimnetic withdrawal

This method involves the withdrawal of nutrient rich water from the hypolimnion and reduces the anoxia condition. A study by Nurnberg (1987) provided a summary of hypolimnetic withdrawal procedures used in 17 eutrophic or hypertrophic lakes in the USA and Europe. The method has been used for 1 to 10 years on these lakes resulting in the immediate reduction of anoxia and TP concentration. A study in Lake Waramaug and Lake Wononscopomuc with anoxic release from the sediment shows only the smaller lake (Lake Wononscopomuc) successfully responded to hypolimnetic withdrawal treatment, and as a result epilimnetic and hypolimnetic P concentration, anoxia and internal loads were reduced. The reduction of anoxic period and P concentration was less pronounced in the larger lakes (Lake Waramaug)(Nurnberg, Hartley and Davis, 1987). While in Lake Varese, Italy, hypolimnetic withdrawal was coupled with oxygenation to enhance the efficiency of the eutrophication measures (Premazzi et al., 2005). Besides that, hypolimnetic withdrawal is also successful in eliminating cyanobacterial blooms from *Aphanizomenon sp.* by destabilized the water column and producing higher concentrations of nitrate (NO_3). However, this becomes favourable to *Microcystis sp* because it is positively correlated with NO_3. Thus to apply this method to a water body with an algal bloom problem, it is recommended to compliment it by other toxin management approaches. The effectiveness of this method can also present negative impacts on the downstream water. For instance, discharge from Lake Ballinger caused extensive periphyton growth and create an odour nuisance to users of an adjacent golf course(Cooke et al., 2005).

3.4.2.2.6 Hypolimnetic aeration / oxygenation

This method involves the introduction of oxygen to the hypolimnetic layer to prevent anoxia. Maintaining oxygenated conditions in the hypolimnion reduces the release of P from the sediment to the water column. Application of hypolimnetic aeration was recorded in a few studies. For example, application of hypolimnetic aeration in Black Lake, Canada improved water quality by increasing dissolved oxygen in the hypolimnion layer. P and ammoniacal nitrogen concentrations also declined after two weeks of treatment (Ashley, 1983). In Amisk Lake, Alberta, Canada, pure oxygen was injected to the hypolimnion layer of the lake and resulted in P and ammonium reductions. This method was also claimed to be cost effective since no power was required. However, the ability of this method to limit algal growth over a long period of time has not yet been demonstrated. The downside of this problem is the concern of supersaturation of N gas in the hypolimnion layer which has been experienced in Lake Waccabuc. The problem may cause gas bubble disease in fish (Cooke et al., 2005). However, this may only occurr in the deepest of treated lakes.

3.4.2.2.7 Dredging / sediment removal

Dredging or sediment removal works by removing the upper layers of the lake bottom sediments to reduce internal nutrient and algal production by preventing the release of P from the sediment. Peterson (1982) reviewed five studies using the dredging method and found that the most successful cases were in Lake Trummen. Using this method, P was reduced up to 90% and N was decreased by 80%. Blue-green algae were also drastically reduced and some species disappeared, notably *Oscillatoria agardhii*. The low nutrient and algae concentrations remained low for over 9 years (Jorgensen et al., 2005). On the other hand, a study by Van der Does et al. 1992 in Lake Geerplas, Netherlands, found that P concentration in the lake decreased and algal biomass was lowered during the first 4 years after dredging. After that, the P level and algal biomass increased and accumulation of organic matter continued. Successful result also been recorded in shallow tropical lakes in

India. Five years study on the effect of sediment dredging in three lakes in Udaipur, India found that N and P concentrations were decreased significantly in sediment and water column. As a result, the chlorophyll biomass and primary productivity also declined up to 41.4% and 32.2%. The reduction of the nutrient has also reversed the trophic status in the three lakes to oligotrophic condition (Pandey and Yaduvanshi, 2005).

However, not all dredging treatment cases have been successful. In Lake Herman, South Dakota, USA, orthophosphorous concentrations in the lake increased dramatically after the dredging process from 0.13 mg/L to 0.56 mg/L. Although the P increased, phytoplankton productivity remained the same because the lake was primarily N limited (Peterson, 1982). From the observation, dredging or sediment removal was used for various reasons such as to deepen the water body in order to improve fish production, to reduce macrophytes nuisance by providing limited light penetration to the sediment (shallow lakes) and to limit nutrient recycling (Cooke et al., 2005).

3.4.2.2.8 Sediment cover

The sediment cover method looks promising in reducing eutrophication or algal blooms compared to sediment removal methods. This method involves covering the lake bottom with plastic sheeting or particulate material to prevent nutrient recycling and reduce the macrophyte growth. A review of sediment covers to control macrophytes and nutrient release done by Cooke (1980) presented details about sediment cover using plastic sheeting, fly ash, sand and clay. In the review, he found that plastic sheeting was able to reduce macrophytes for approximately one year as was experienced in Marion Millpond and Lake Wisconsin. However disadvantages of this type of sediment cover have also been discussed. For instance, plastic sheeting by polyethylene was difficult to apply due to its buoyancy, thus it is easy to dislodge by wave action and it also degrades rapidly in sunlight. Unlike polyethylene cover, hypalon cover is heavier which prevents it from dislocating, it is inert to sunlight and does not rip. However it is almost five times the cost of polyethylene. Meanwhile, laboratory experiments showed that fly ash was effective in removal of up to 95% reactive P and prevented P release from the sediment. Despite the high efficiency, fly ash was found to create hazards in the water body. Application of fly ash resulted in high pH, dissolved oxygen depletion, heavy metals accumulation and toxicity to fish and other aquatic life. An alternative, safer and cheaper technique was to use clay or sand. However, not much information regarding the use of clay or sand in nutrient release prevention and macrophyte reduction can be found in published databases which raise doubt in the effectiveness of this method.

3.4.2.2.9 Biomanipulation

Biomanipulation is also known as biological control for lake restoration, and involves the use of specific organisms such as fish and zooplankton to control growth of algae, macrophytes or phytoplankton in the food web. According to Jorgensen et al. (2005), there are two types biomanipulation which are top down control and bottom up control. Top down control works by reducing the feeding pressure of fish on zooplankton and the remaining large zooplankton will keep phytoplankton levels down. Meanwhile, bottom up control work based on the idea that productivity of aquatic plant and zooplankton can be control by limiting the supply source such as light, nutrient and temperature such as shown in Figure 3-5.

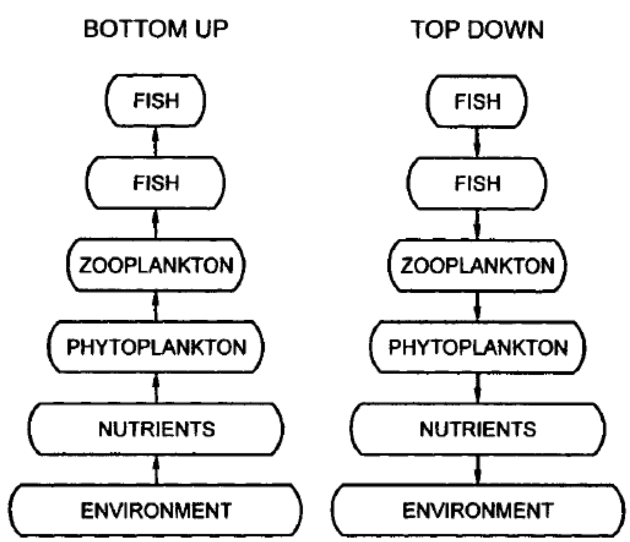

Figure 3-5: Types of biomanipulation (Jorgensen et al., 2005)

Applications of biomanipulation in tropical climate have successfully recorded. For instance, a mesocosm experiment to access the impact of silver carp on eutrophic Paranoa Reservoir, Brazil observed that silver carp have a potential to improved water quality in the reservoir. 41 g/m^3 of silver carp were put in four translucent fibre glass tanks that set in a shallow area of Paranoa reservoir has successfully reduced chl-a and net primary productivity which instantly improved the water quality (Starling, 1993). On the other hand, whole lake experiment in Lake Paranoa, Brazil which was experiencing cyanobacterial growth at the end of the dry season also gave successful result on the application of biomanipulation. The bloom resulted in high turbidity, nutrient and chlorophyll a which made the clarity of the lake less than 50 cm. Application of biomanipulation through addition of tilapia fish to the lake after nutrient reduction lowered chlorophyll-a concentration and enhanced water transparency (Jeppesen et al., 2007b). Another study which compare between silver carp, bighead and tilapia on *Microcystis* grazing in one of large man-made eutrophic lake in India found that silver carp is the most suitable species to reduce the *Microcystis* biomass in the lake. The sharp reductions between 60%-93% in Microcystis biomass were observed on the third day from all the species were introduced (Jana, 1998).

3.4.3 Limitations

Even though the literature search was systematic and transparent some limitations still exist. First and foremost, because of time constraints, the grey literature was excluded which may have resulted in bias. Next, the searching was limited by the chosen keywords. Poor combinations of key wording might have resulted in some studies remaining unidentified. However, the snowballing method proposed by Pullin and Stewart (2006b) was utilized to ensure that most of the relevant studies were included in the review. Some of full text content of the identified studies was not available online and these were ignored due to time constraints. Next, the study also looks only at in English language publications, and this might introduce bias. In addition, because the chosen topic is multidisciplinary in nature, spanning science and technology, water pollution and water resource management, relevant studies may have been overlooked through some poor indexing in electronic databases. Since this might be the first systematic review on eutrophication and algal bloom control, there are some flaws that can be improved by future research. Thus it is recommended for future research to include grey literature (e.g. institutional report, thesis and proceedings) and exploring wider databases. This might help to solve the poor representation of articles from tropical region.

3.5 Conclusion

Eutrophication of freshwater is one of the serious problems on a global scale because of its potential harmful impact to human and environment. It will continue to be a problem in many countries especially to the tropical regions because eutrophication may occur throughout the year. Therefore, there is an urgent need to find a solution in determining the best practice to mitigate this problem. In this study, a systematic review was used to summarise the available techniques that have been used in mitigating eutrophication problem. From the findings, it has been concluded that a systematic review is the best method to locate the scientific evidence of techniques used in eutrophication management. Fourteen techniques that include external measure and internal measure that normally used to mitigate eutrophication from 1960s to 2014 were found. The trends of the published studies revealed that after the year 2000, eutrophication management is more focused on marine waters than freshwater. Besides that, most of the studies were conducted in USA and Europe which makes most of the techniques are more suitable for temperate regions than tropical regions. However, according to Rast and Thornton (1996) even though most of the techniques typically used in the temperate regions, they should also work in tropical regions although there will be some differences in relation to their efficiencies. Therefore, the result from this study will be used to develop the eutrophication mitigation framework in the next chapter by providing the techniques that frequently used to manage the eutrophication problem.

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CHAPTER 4

Development of mitigation measures framework

Chapter 4 : Development of mitigation measures framework

4.1 Introduction

Extensive attempts in reducing the eutrophication or algal blooms in waterbodies have been implemented in developed countries for the past few decades (Harper, 1992). A few management frameworks for lakes and reservoirs were developed by the government, private agencies and corporations generally aiming to reduce the eutrophication and algal bloom problem for the temperate system. For an example, the Clean Lakes Program that was supported through United States Environmental Protection Agency (USEPA) to provide financial and technical assistance to states in restoring publicly-owned lakes (Lapensee, 2011). This program provides guidance for the citizen who would like to protect, restore and managing their lakes and reservoir. It consists of three phases which are; a) phase 1: diagnostic or feasibility study; b) phase 2: restoration or implementation project; and c) phase 3: post-restoration monitoring studies (United States Environmental Protection Agency, 2013). It also provides printed copy of general guidance on lake restoration and management techniques that have been tested on lakes throughout the United States and Europe in 1988 and 1990 (United States Environmental Protection Agency, 1990).

Other well-established framework is the European Union Water Framework Directive (EUWFD). It is a general framework which was built to cater to all types of water problems within the European region, including eutrophication and algal blooms. EUWFD works by providing the water treatment framework for the country, to develop a common basis for the protection and sustainable used of the water. The overall aim is to maintain and improved the aquatic environment through attention to quality issues (United Nation Environment Programme, 2004). Since the framework was designated to European countries, it might only suitably apply within the temperate region. More general framework for making eutrophication management decisions was developed by Rast and Holland (1988). However, the focus of the guidelines is more toward the decision maker or policy maker. It should be noted that not all countries have legislation or guidelines to manage inland fresh waterbodies. For instance, in Malaysia, the inland water is owned by various agencies and individuals, not the state. There is also a separation of powers in terms of management of lakes based on different usage (Sharip and Zakaria, 2007). This division or responsibility is the biggest challenge to secure surface waters in this area. Thus, the framework for eutrophication management should be revised in order to take these issues into account. A greater source of concern is that the framework for eutrophication management should be validated and updated to the latest technology and new source of pollution.

Hence this study was aimed to develop a mitigation framework for reducing eutrophication and algal blooms in tropical regions. This is not an attempt to derive new techniques to reduce eutrophication and algal bloom problems. Instead, it is an attempt to update and develop a framework that specializes in reducing, treating or preventing eutrophication or algae blooms. The non-technical approach also incorporated in this framework allows use by people with different skill levels and backgrounds in order to protect their local water supplies. This work focusses more on humid tropic systems because there is a lack of research resources in this region. This output can also be applied to other tropical systems as well who have the same terms of ownership and administrative as Malaysia.

4.2 Pre-selection

The mitigation management framework consists of two steps: pre-selection and selection. Pre-selection identifies the problems within the waterbodies, establish relevant management goals, and assess the source of pollution. There are four important steps involved in assessing the lake condition. These are;

1) determination of management goals;
2) determination of water quality criteria;
3) determination of limiting nutrient; and
4) determination of pollutant source

In pre-selection, the choice of restoration measures and management are dependent on the nature of the waterbody and is function. After this stage, one can decide either to treat, to reduce or to prevent the symptoms of eutrophication or algal blooms. Then, one can decide which level the treatment process should be by selecting from the selection step.

4.2.1 Step 1: Selection of goals

Different sectors of society such as domestic, agricultural and industrial, use water for different purposes. 70% of total fresh water use globally goes to agricultural industries, while industrial accounts for 20%, domestic 10%, figures subject to country and local environments. Developed countries use more fresh water for industry than developing countries, where agriculture dominates (UNESCO, 2014). Water quality requirements also vary depending on water usage. For instance, water quality of a lake used as a drinking-water supply should have high dissolved oxygen content with less productivity (oligotrophic) so it will only require a minimal amount of necessary pre-treatment. If the eutrophic water did not treat efficiently, the toxin contained in the algae may harm the human population as discussed by Codd et al. (1999). Besides that, eutrophic water also increases the cost of drinking water treatment because the filter unit needs frequent cleaning. The same water quality is also needed for livestock. Poor water quality may affect the livestock, which results in death, sickness or impaired growth, as experienced in few countries as a result of cyanotoxin (Codd, 2000). Some substance present in water used for the livestock also may cause poisoning which occasionally passed to other consumer including humans. Different water quality is needed for recreational purposes which are less stringent than water used for drinking. Recreational water quality criteria are established to protect human health from contamination by microorganisms which could cause skin related illness. Thus, a lake with heavy productivity (eutrophic) may seriously limit the usage of water for recreational use including swimming, fishing, boating and other water related activities. For water used for aquaculture, the water quality criteria may be more or less the same as water used for recreation purposes. Generally, fish productivity increased in eutrophic lakes, with some changes between fish population. However, as the eutrophic become severe (hypereutrophic), fish populations can collapse due to lack of oxygen in the water especially during night time (respiration) and an excess of toxic gases in the waterbodies. Some water uses does not need to have specific water quality such as water use for agriculture, transportation and fire-fighting purposes as it does not give direct or indirect contact to humans. Therefore, the uses of a water resource need to be determined before associated water quality criteria are assigned. The required and tolerable trophic status is as shown in Table 4-1.

Table 4-1: Intended lake and reservoir water uses related to trophic condition adapted from Rast and Holland (1988); Straskraba and Tundisi (1999)

Water purpose	**Trophic degree**	
	Required	**Tolerable**
Drinking water	Oligotrophic	Mesotrophic
Bathing	Mesotrophic	Slightly eutrophic
Water sports (excluding bathing)	Mesotrophic	Eutrophic
Landscaping in recreation area	-	Slightly eutrophic
Irrigation	-	Strongly eutrophic
Process water	Mesotrophic	Slightly eutrophic
Cooling water production	-	Eutrophic

4.2.2 Step 2: Determination of water quality and trophic status

Several indicators may be used to determine the severity of a lake's problem. It is important to evaluate water quality before suggesting the best remedial measures for the problem. Thus, before choosing any remedial measures, in-lake data such as P, N and chlorophyll-a (Chl-a) concentration are needed to describe the quality of the water. P and N are the essential nutrients necessary for the growth of plants in lakes, while, Chl-a is one of the major photosynthetic pigments in plants and algae. Thus, Chl-a is the parameter used as an estimator of algal biomass.

According to Chapman et al. (1996), Chl-a can give an approximate indication of the quantity of material suspended in the water column. For instance waterbodies with low levels of nutrients normally will have low levels of Chl-a where the concentration is less than 10 μg/L annually. In this condition, water resources for drinking water only need standard treatment which only involves conventional treatment unit before it reaches the end user (Table 4-2). Some exceptions of treatment unit will be involves in treating slightly eutrophic water as the extent of treatment depends on the source of raw water. This is because other treatment unit is incapable to remove the pathogen from the raw water except for disinfection unit. For waters with high nutrient contents which normally contain more than 60 μg/L of Chl-a annually, special treatment such as electrodialysis, ion-exchange or reverse osmosis might be needed before distribution to the consumer. Chl-a measurement is easy and inexpensive, hence it is often used to estimate the productivity of plants and algae in a waterbodies.

Table 4-2: Trophic class based on Chl-a for water drinking adapted from Straskraba and Tundisi (1999)

Chl-a (μg/L) Summer average	Chl-a (μg/L) Annual maximum	Trophic grade	Raw water	Treatment
0.3 - 5	< 10	Oligotrophic	Excellent	Standard
5 - 10	10 - 30	Mesotrophic	Suitable	Standard
10 - 25	30 - 60	Slightly eutrophic	Not very suitable	Exceptions
> 25	> 60	Highly eutrophic	Unsuitable	Special treatment

As cited by O'Sullivan and Reynolds (2008), the OECD report in 1982 advises managers to establish a water quality objective with the expected trophic response taking into consideration the intended use of the water and the natural trophic conditions of the area. Following this advice, it is important to measure the status of the waterbody in order to decide the water quality objectives. There are many ways to measure the status of the waterbody such as using Carlson's trophic state index (TSI) and EUWFD reference system. TSI was developed by Carlson (1977) on the belief that in many lakes, the degree of eutrophication is primarily related to increase nutrient concentrations which P, in particular. He derived the TSI by log (base 2) transformation of secchi disk transparency and concentration of phosphorus and Chl-a. Each 10 unit division of the index represents doubling in the algal biomass. Because concentration of algal biomass often corresponds with the transparency, a doubling of biomass concentration often corresponds to halving of SD. The range of index is from 0 to 100 (refer to Table 4-3) which give an advantage to the user as it easier to memorize the unit of 10 rather than the decimal fractions of the parameter values.

On the other hand, as illustrated in Figure 4-1, EUWFD reference system is much more complex as it used the combination of four different types of assessment which are;

1. Assessment of the status of biological quality elements such as fish, invertebrates, plants or algae;
2. Assessment of compliance with the standard of physico-chemical quality elements such as dissolved oxygen, phosphorus and ammonia;
3. Assessment of compliance with the standard of environmental quality standard for specific pollutant such as zinc, arsenic and cypermethrin;
4. Series of test to make sure that hydromorphology is largely undistributed

As a result, the ecological status will be assigned into 5 classifications which are high, good, moderate, poor and bad (Water Framework Directive, 2009). Therefore in this study, TSI was selected to be used to access the trophic status of the reservoir because it only requires minimum data which are secchi depth, TP and Chl-a compared to EUWFD reference system which requires more complex data. TSI also more economical and suitable to be used in tropical regions which are mostly consist of the developing countries that normally have limited budget.

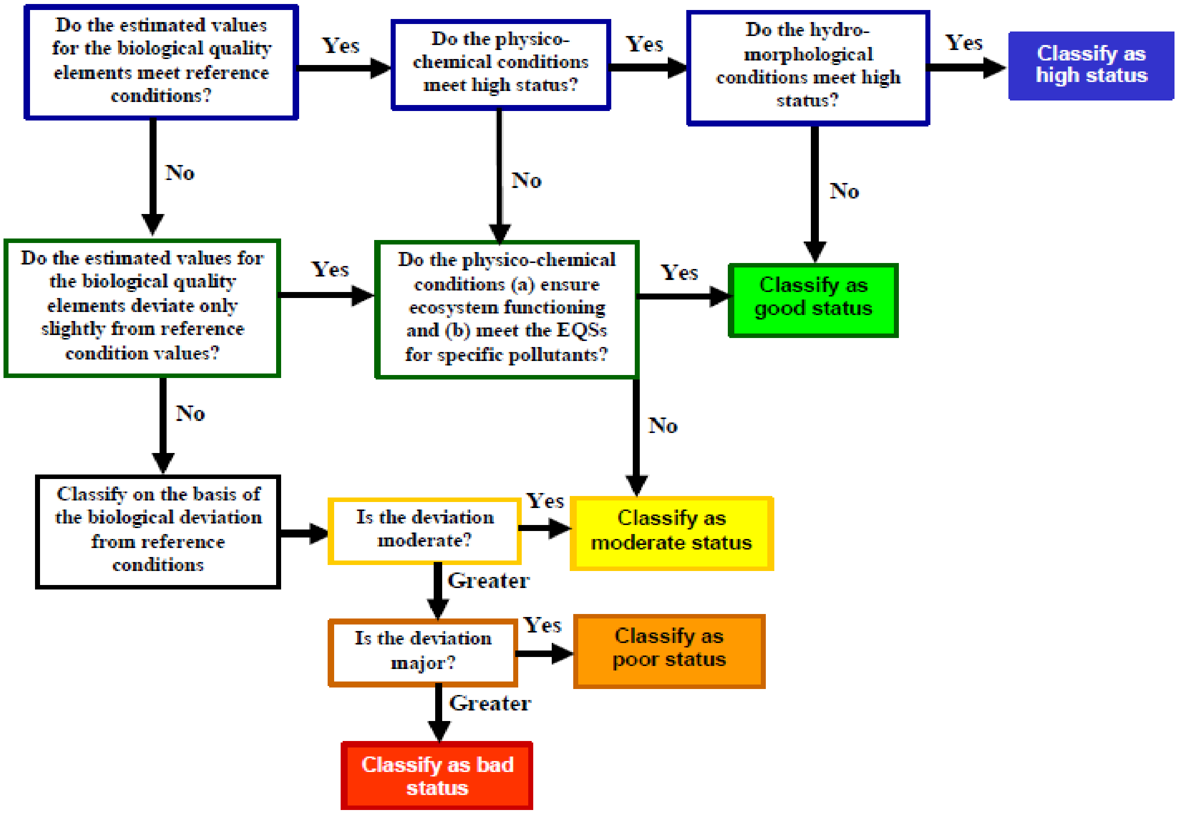

Figure 4-1: Decision tree on how classification of waterbody were determine based on biological, hydromorphological and pysico-chemical from Water Framework Directive (2005)

Using the TSI also give advantage for those who have limited access to the nutrient data because secchi depth can also be used to estimate the condition in the waterbodies as well as the P and Chl-a content. This is because the TSI can be used to predict values of one variable from measurements of another. Hence, by entering the secchi depth value in the equation 4-1 below, one will get the TSI values and referring to Table 4-3, P and Chl-a value can be estimated.

$$TSI = 60 - 14.4 \ln (SD) \quad (4\text{-}1)$$

$$TSI = 14.42 \ln TP \quad (4\text{-}2)$$

$$TSI = 9.81 \ln (Chl) + 30.6 \quad (4\text{-}3)$$

Where;

TSI = Trophic State Index
SD = Secchi depth, m
TP = Total Phosphorus, µg/L
Chl = Chlorophyll, µg/L

Table 4-3: Carlson's Trophic State Index (TSI) adapted from Carlson (1977)

TSI	Secchi depth (m)	Chl-a (µg/L)	Phosphorus (µg/L)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1183

Based on Carlson's study, an indicator has been developed by Heiskary and Walker (1988) which divided the waterbodies into 4 states which are oligotrophic, mesotrophic, eutrophic and hyper-eutrophic (Table 4-4). In the study, 10 µg/L of Chl-a is considered as eutrophic where algae might appear at this stage, while, the waterbodies are considered to be in the severe stage when Chl-a concentration is more than 20 µg/L. Even though the calculation of TSI SD, TP and Chl-a is correlated with each other, it do different in some cases. For instance, TSI values calculated for Chl-a may not be similar to simultaneous calculations of TSI from SD or TP measurements because the presence of suspended materials reduce light attenuation and therefore algal productivity. Active zooplankton grazing also may reduce the algae biomass

(United States Environmental Protection Agency, 1988). Furthermore, accuracy in Chl-a measurement cannot be predicted in turbid lakes because much of the phosphorus is probably bound in clay or other non-algal particles that make P unavailable for algal growth (Carlson, 1991). Therefore understanding the lakes situation is a must to avoid misinterpretation of using the indicator. Beside some small weakness, this indicator also has been used extensively in temperate as well as tropical climates such as used by Omar (2010), Sheela, Letha and Joseph (2011), Te and Gin (2011) and Oliveira et al. (2014) to predict the condition of the water bodies even though it was developed based on the condition of a temperate lake.

Table 4-4: Trophic State Index Classification adapted from Heiskary and Walker (1988)

TSI Value	**Secchi Disk (m)**	**Total Phosphorus (µg/L)**	**Chlorophyll (µg/L)**	**Classification**
< 40	0-4	0.75-12	0.04-2.6	Oligotrophy
40-50	4-2	12-24	2.6-6.4	Mesotrophy
50-60	2-1	24-48	6.4-20	Eutrophy
>60	< 1	> 48	< 20	Hypereutrophy

Based on 30 years' experience in phycology and limnology, Raschke (1993) observed that there is no problem or discoloration of the water when Chl-a concentration is less than 10 µg/L in temperate water. However, water could start to become discoloured and algal blooms start develops at a range of 10-15 µg/L. Algal blooms is the condition when there is rapid increased of the number of algae in the waterbody. Between 20-30 mg/L, water is deeply discoloured, the appearance of algae is more frequent and algal scums can occur especially during calm weather when bloom-forming species rise to the water surface. Beyond 30 mg/L of Chl-a, discolorations and algal blooms are more severe. Based on study data, expert opinion and literature, the guidelines in temperate water especially in Carolina, USA, were developed. Chl-a in the waterbodies used for drinking water purposes was limited to less than 15µg/L and for recreational water, it is recommended for the Chl-a to be less than 25µg/L to preserve the aesthetic of the waterbodies.

Because of the difference in temperature and solar exposure, it is expected that the Chl-a concentration in tropical system will be different to those within the temperate. However, there is no difference in terms of Chl-a criteria in both tropical and temperate areas. Based on a study cited in Walker (1985), a tropical lakes study based on water quality data collection, observation and interviews with the water manager and operator, found that algal scums were visible at 10 to 20 µg/L of Chl-a and become severe when the Chl-a concentrations more than 30 µg/L. The same situation also discussed by Hart and Allanson (1984) in their study in the southern hemisphere which includes South African and Australia data in their examples, Chl-a concentration more than 30 µg/L has created algal nuisances in the waterbodies. Study done by Nürnberg (2009), which review worldwide data and literature also agree that threshold for Chl-a concentration above 25 µg/L is the boundary for eutrophic and hypereutrophic state. In that case, it is acceptable to keep the Chl-a concentration in recreational water below 25 µg/L and 15 µg/L for drinking water in tropical systems, the same as would be applied in temperate zones. This is because the trophic boundary in temperate area is low compared to tropical (Table 4-5), and keeping the Chl-a concentration to the minimum is the best option in achieving the high quality of water.

Based on consideration from trophic status and experiences from the experts stated above, one should identify the optimal water quality that suitable for the water uses. Besides that, one also should consider that the increase in the world's population will increase the world's food demand which will increase the agriculture and aquaculture water use accordingly. The increase in the agricultural activities will induce similar increment trend of fertilizer and pesticides consumption to improve the crop production. Although, it do depend on the owner to set their own acceptable criteria, to keep the trophic state to the minimum is the best option to ensure that the water quality suitable and safe for any purposes.

Table 4-5: Trophic boundary in temperate and tropical as cited in Thornton (1987a)

Parameter	Upper limit mesotrophy in temperate	Upper limit mesotrophy in tropical
Mean primary productivity (gC m-2 d-1)	1.0	2-3
Chl-a (ug/L	10-15	10-15
TP (ug/L)	30	50-60
TN (mg/L)	0.5-1.0	0.2-1.0
Photosynthetic efficiency	<1%	2-3%
Nutrient limitation by	P	N
Dominant algal family	Bacillariophyceae	Cyanophyceae

4.2.3 Step 3: Determination of limiting nutrient

Besides the water quality, one should also know the limiting nutrient in their waterbodies. The limiting nutrient is responsible for controlling the growth rate of a plant, and the idea is to exhaust the nutrient before the plant blooms out of control. The most established limiting nutrient study is by Redfield (1958). In the study, he found that the average atomic ratio in the phytoplankton samples to be 106C to 16N to 1P. It also mentioned that carbon (C) only becomes an algal growth limiting nutrient when the water become saturated with both N and P. Therefore to determine the limiting nutrient between N and P, the reference value that widely use for N and P uptake by algae is 16N:1P (atomic ratio) or 7.2N:1P (mass ratio) (Ryding, Rast and Unesco, 1989). However, it is recommended to used the mass ratio as it much more easier to be used to calculate the limiting nutrient. To calculate the mass ratio, the N concentration in mg/L must be divided by P concentration in mg/L to correspond to the mass ratio of 7.2N:1P. As a results if the ratio of measured N:P greater than 7.2, P is the potential limiting nutrient and if it is less than 7.2, N will be the potential limiting nutrient.

In the majority of temperate lakes, P was found to be the primary limiting nutrient and its availability controls the use of N and C from the atmosphere, for use by the algae (Harper, 1992). Study done by Thomas (1953) on Central European Lakes shows that P was the major element controlling productivity and promoted the growth of algae in lakes. From the analysis results, he concluded that if there is no phosphate input to the waterbodies, the growth of algae would stop as soon as the algae consumed the basic phosphate content. He also noted that phosphate will decrease while NO_3 will increase with heavy rain. However, Morris and William M. Lewis (1988) have showed a contradictory finding from their experiment in Colorado mountain lakes. They reported that N has been found to be the limiting nutrient in 3 out of 8 mountain lakes, one was P limited and the other four were the combined nutrient limitation. A different situation happened in Lake Taihu, China where the lake shifted from P limitation during winter-spring to N limitation during summer-autumn months. The combination of P and N addition has encouraged the maximum growth of algal bloom in Lake Taihu (Paerl et al., 2011).

On the other hand, N has been found to be limiting in many tropical lakes for most of the year (William M. Lewis, 1996). Studies done at Lake Lanao, Philippines (Lewis, 1978) and Lake George, Uganda (Viner, 1974) have concluded that N was limiting in tropical lakes. Lewis demonstrated that there is severe N depletion in Lake Lanao while Viner showed permanent shortage of N and P in Lake George Uganda, with N supply being more critical. In his own review on tropical lakes, William M. Lewis (1996) listed three factors that might explain the N limitation in tropical lakes. These are:

1) P weathering from parent material is more efficient at elevated temperature;
2) Evapoconcentration of P will be more pronounced at low latitudes; and

3) N losses from tropical environments are almost certainly higher than at temperate latitudes because of the high water temperatures of tropical lakes.

For this reason, one cannot assume the condition of the waterbodies as some of temperate water bodies might have N limited and tropical lakes also might have P as the limiting nutrient. By knowing the limiting nutrient, it helps to identify which nutrient should be the main concern with suitable remedial measures in reducing the particular nutrient can be suggested.

4.2.4 Step 4: Determination of pollutant source

Besides the determination of limiting nutrient, the source of the nutrient should also be known. This is important because different sources need different abatement strategies. Nutrient inputs to waterbodies are often categorized as being either from point or non-point sources. Point sources are defined by EPA as pollutant loads that discharge at a specific location from pipes, outfalls, and conveyance channels from the two most common types of point sources which are domestic wastewater treatment plants (particularly those containing detergents) or industrial waste treatment facilities (United States Environmental Protection Agency, 2012). Pollutant that comes from this source is generally easier to monitor and control compared to non-point source because it can be controlled by applying some form of regulatory standard to the quality of the discharge effluent. There are three basic steps for estimating point source nutrient as cited by Ismail and Najib (2011) in equation 4-4;

1) Measuring water discharge, Q=AV (m^3/s)
2) Measuring nutrient concentration, (mg/L)
3) Calculating pollutant load (tons/day) ;

$$L = C \times Q \qquad (4\text{-}4)$$

Where;

C = concentration of pollutant (mg/L)
Q = water inlet discharge (m^3/s)

On the other hand, non-point sources or diffuse pollution are associated mainly with land drainage and surface runoff, which enters a waterbodies by dispersal and poorly defined ways. Atmospheric depositions which are chemicals and particulate matter are also classified as possible diffuse sources of pollution once they reach waterbodies. Runoff from agriculture activities and cities are the major P and N contributors around the world. Agricultural sources which are associated with runoff or leachate from agricultural lands are as a result from excess application of fertilizers, pesticides and animal manures. Meanwhile, diffuse pollution from urban areas comes from poor drainage and wash out from streets, roads or roofs (Hranova, 2006). Considering the different natures of this pollutant and how it can be generated, the nutrient that comes from this source is difficult to be evaluated and controlled. Non-point source nutrient loading can be estimated from consideration of export from soils, per capita discharge of sewage and runoff volume (equation 4-5) as derived by Patalas (1972);

$$L_n = E_s \times \frac{A_d}{A_o} + \frac{E_c C}{A_o} + 0.15 L_{nu} \times \frac{A_o(a)}{A_o} \qquad (4\text{-}5)$$

Where; E_s = nutrient export from soil in g total P/m^2 of land drainage. Year
A_d = Area of the land drainage in m^2
A_o = Area of lake in m^2
E_c = Per capita discharge of P reaching the lake in g total P/capita. Year
C = Basin population
L_{nu}= Total nutrient loading for upstream in g total P/ capita
$A_o(a)/A_o$ = ratio of the area of the next lake upstream to the area of the lake considered

From the information gathered, one can then have an option on whether to reduce the loading from point or non-point sources or to protect the lake from the increase of the nutrient loading. The pre-selection are then summarize in decision tree shown in Figure 4-2.

4.2.5 Flowchart

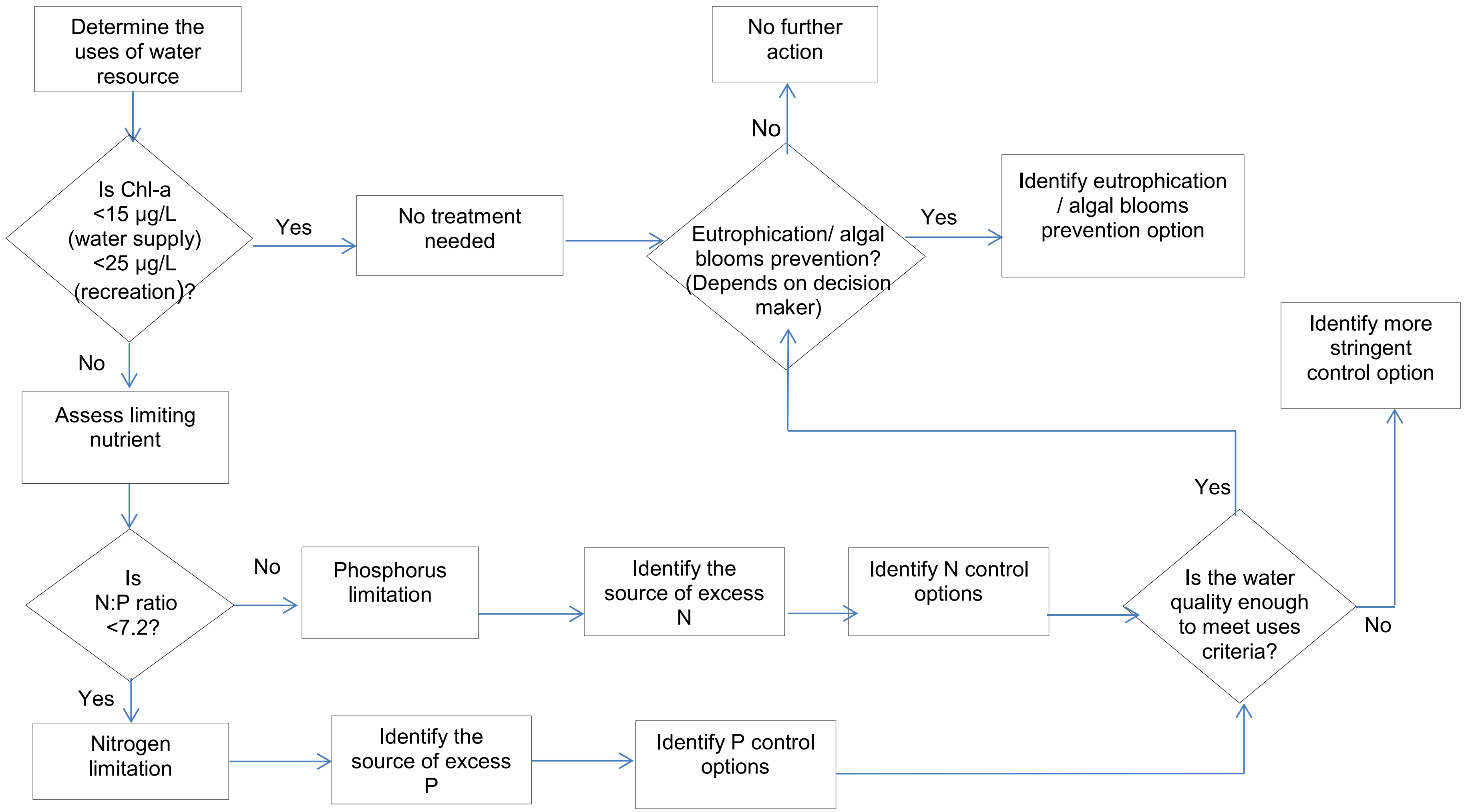

Figure 4-2: Pre-selection decision tree

4.3 Selection of measures techniques

The diagnosis in pre-selection is designed to determine the causes of lake problems and to evaluate the waterbody‘s current state or severity. This data and evaluations will be used to select the best measure option and the most cost-effective treatment available to achieve the desired lake quality based on the individual goals. Various measures in managing eutrophication and algal bloom options are available, which need to be further evaluated as to their performance in respect to the evaluation criteria that largely reflect the priorities of the study system. Table 4-6 shows suggested measures option based on the problems to be solved. However, a few criteria such as cost of each treatment, effectiveness and longevity need to be considered so that it can tackle the specific water problems and tailor individual or organization budget. Therefore, to help in selecting the best measures, multi-criteria analysis (MCA) was adopted to help organize the decision making process, determine the best alternatives for eutrophication and algal bloom management and to rank the alternatives based on the specific criteria.

Table 4-6: Measures suggested based on water problems

Problems	**Measure option**
High external nutrient load	• Advanced wastewater treatment (AWT) • Waste water diversion • Pre-reservoir • Constructed wetland • Law and regulation
Excess in internal nutrient	• Nutrient inactivation • Dredging • Sediment cover • Dilution and flushing • Aeration • Hypolimnetic withdrawal
Eutrophication	• Mechanical harvesting • Algicides • Biomanipulation

Algal bloom	• Algicides • Dilution and flushing • Biomanipulation • Hypolimnetic withdrawal

4.4 Decision matrix using simple additive weighting

Multi criteria assessment (MCA) refers to methods used to help decision making more explicit, rational and efficient by ranking the management alternatives based on evaluation criteria and weighted by the user (Mahmoud and Garcia, 2000). It has been widely used in tackling environmental problems such as in environmental impact assessment (Janssen, 2001), in selection of alternatives for remedial action for contaminated land (Linkov et al., 2005), selection of solid waste management system (Vego, Kučar-Dragičević and Koprivanac, 2008), selection of nitrate management in contaminated aquifer (Almasri and Kaluarachchi, 2005). The use of MCA for the measure selection has many advantages. First and foremost, it has the capacity to simplify complex situations, straightforward and easy to understand which make this method suitable to be used by all regardless of education or background. The choice of objectives and criteria that any decision maker may make are open to change if they felt inappropriate. Furthermore, the usage of score and weight is explicitly developed according to the established techniques. Finally, MCA provides important means of communication not only to the decision making body but also between the waterbody and wider community (Dodgson et al., 2009).

MCA was used instead of cost benefit analysis (CBA) because some of the criteria cannot easily condense into monetary value such as the confidence to apply the measure. If it were possible to create a monetary value to apply to criteria, the decision will become muddled in the middle, preventing a clear decision. Furthermore, these criteria may involve the change of ethical or moral principles, which may not have any economic or monetary value. There are six steps involved in developing the MCA in this study.

4.4.1 Step 1: Identify the alternatives or measure options

Eutrophication and algal bloom management techniques can be grouped several ways such as physical, chemical or biological treatment. However, in this study, the management is divided into two groups: external measure and in-lake measure. External measure or preventive measure works by reducing the excessive nutrient load that will stimulate the excessive growths of aquatic plants in the waterbody. This approach is the most effective techniques in reducing the pollutant load and it provide long-term improvement effect to the water quality. It is suitable to be used by the water body that received a high amount of external nutrient. Meanwhile, in-lake measure is concentrated on treating the cause of eutrophication and algal bloom problems. This approach, however, is usually not as effective over long-term water quality improvement and needs to be applied repeatedly to prolong the effectiveness. Nevertheless, the in-lake methods are effective for at least some period of time and may even be the most reasonable approach in situations where it is too costly or otherwise unfeasible to build municipal wastewater treatment plants such as in developing countries. It also offers supplementary control measures in cases where the primary control programme is in adequate to achieve the control goals. In this study, 15 measure options including external measures and in-lake measures were used in the MCA development. As can be seen in Table 4-7, A1 to A5 are external measures and A6 to A14 are in-lake measure option. A15 is the option of doing nothing which can be applied when the decision maker does not want to implement any measures to control the eutrophication and algal bloom problem.

Table 4-7: Alternatives for eutrophication and algal bloom management

Alternative	Measures	Alternative	Measures
A1	AWT	A9	Dilution and flushing
A2	Diversion	A10	Hypolimnetic withdrawal
A3	Pre-dam	A11	Destratification
A4	Constructed wetlands	A12	Dredging
A5	Law and regulations	A13	Sediment cover
A6	Algicides	A14	Biomanipulation
A7	Nutrient inactivation	A15	Doing nothing
A8	Harvesting		

4.4.2 Step 2: Define criteria

Five criteria are used in this study to evaluate the measures options; effectiveness (C1), longevity (C2), confidence (C3), impact (C4) and cost (C5). The criteria were evaluated based on the collected articles that obtained from the systematic review which been discussed in previous chapter. Constructed wetland (CW) in Appendix 1 will be used as an example to explain how the performance score from the criteria was derived.

Effectiveness

Effectiveness can be defined as a degree to which specific management practice meets stated objectives. For instance, CW would be considered effective when it meets the specified objectives such as treating the municipal or industrial waste water discharge or reducing P and N loading before entering the water column. If the objectives were partially met, the management practice can be considered as partially effective. For example, constructed wetland may reduce the P if it is coming from external sources. However, it might fail to reduce the P level currently available in the water column which results from the sediment released. Therefore, initial determinations of the measures option can be based on their features such as their mode of action and specific design. If the waterbodies only suffered from external nutrients sources, constructed wetland will be the effective measures as all the objectives will be met. In this study performance scores were divided by the percentage of effectiveness as reported in the literature. If most of the studies using CW reported that the technique successfully reduced more than 75% of P loading into the waterbody, the score for CW will be rated as excellent. Else, if most of the case studies reported that the efficiency of P removal is between 50% to less than 75%, CW will be rank as good. If most of the studies recorded the P removal efficiency using CW is less than 50% but not less than 25%, CW will be rated as fair. Last but not least, if most of the studies reported the efficiency of P removal using CW is less than 25%, CW will be rated as poor. For instance, in this study, 54.5% of the total articles obtained for CW reported that this technique was successfully removed more than 75% of P loading to the waterbody (refer Appendix 1); hence, the score for CW is rated as excellent.

Longevity

Longevity of each measure reflects the duration of effect for the measures option. The measures option can be categorized as short term if the duration of its effect is only effective for one year or less (Olem and Flocks, 1990). One of the examples of a short term measure is algicides. Algicides might be one of the most effective measures in controlling the algal bloom because it rapidly eliminates algae from water column and increase the water clarity immediately during the growing season. However, the duration of effect of algicides may only last for several weeks or for a single growing season. Therefore, to increase the effectiveness and duration of effect, reapplication of algicides might be needed for the lakes with high flushing rate. An example of long-term measure is effective for more than a year. The longevity of the measures however depends on the waterbody and environmental conditions and the measures mode of action or design. For instance, CW will provide long term effectiveness if the specific environment conditions such as type of pollutant loadings and suitable macrophytes were considered in the design. The regular maintenance will also prolong the effectiveness of the measures option. For longevity criteria, if most of the studies reported that CW treatment last more than 5 years, excellent rating will be given. If most of the studies reported that the longevity of CW is less than 5 years but more than 1 year, it will be rated as good. However, if most of the studies recorded that CW only last less than a year without re-application or replanted of the macrophytes, fair rating will be given. Longevity that less than a year with several re-application or replanted will be rated as poor. For instance, in this study, 38.6% of the total articles obtained for CW reported that this technique last between 1 to 5 years (refer Appendix 1); hence, the score for CW is rated as good.

Confidence

Confidence in this study refers to the number and quality of previous studies that supporting the effectiveness of eutrophication measures that work efficiently in tropical climates. The measures will be rated as excellent if there is a successfully documented result from tropical system. For example, constructed wetland has been reported to give high efficiency in reducing the pollutant loading to the waterbodies as reported in Brazil (Salati Jr, Salati and Salati, 1999; Farahbakhshazad, Morrison and Filho, 2000), Malaysia (Sim et al., 2008b) and India (Juwarkar et al., 1995b). Hence the confidence in application this technique to the tropical countries is excellent. Other techniques such as dredging, even though has been extensively studied and applied in the temperate, however, has not been extensively applied in tropical. Hence, dredging can be rated as fair where it has the potential to be successful if applied in the tropical system. For confidence criteria, the rank was developed as below:

i. Excellent – most of the case of the application in tropical was successful
ii. Good – successfully applied in tropical with few of failure
iii. Fair – successful recorded in temperate but might have potential to be applied in tropical
iv. Poor – not fully understood, poor record in both regions

Potential negative impact

In selecting the measures option, one should ensure that the measures option does not produce adverse effect to human health or ecological health. This is because, it will create other indirect cost such as addition of filtration unit in drinking water treatment plant (if the water used for drinking water supply) for removing the toxin from the water. For instance, control of algae blooms in potable water supply by using copper sulphate may initiate certain cyanobacteria species to release their toxins and the consumption of the untreated water will resulted in livestock and human illness and death as happen in Queensland, Australia (Bourke et al., 1983). On the other hand, some of the techniques have short term negative impacts that cannot be eliminated such as dredging that usually destroy the benthic community (Peterson, 1982). The summary of the potential impact of each technique is presented in Table 4-8. Therefore, for potential negative impact criteria, the measures are rank as below;

i. Excellent - no side effect to human health, living organism and the environment
ii. Good – shows minimal effect to the environment which can be controlled or avoided
iii. Fair – gives side effect to the aquatic life and environment
iv. Poor – gives side effect to human health, aquatic life and environment

Table 4-8: Potential negative effect from the treatment measure

No	Measures	Potential negative impact
1	AWT	Gives adverse effect to the environment if the sludge does not dispose in proper way
2	Diversion	Negative effect to the cumulative pond if not treated
3	Pre-dam	May develop eutrophication if the pre-reservoir does not operated proper way
4	Constructed wetland	Provide habitat for mosquitoes
5	Law and regulations	User conflicts

6	Algicides	Impact target and non-target plant species Initiate some cyanobacteria species to release their toxin Toxic poisoning to human and aquatic life (bioaccumulation in fish)
7	Nutrient inactivation	Toxicity through aluminium accumulation Reduce fish production Impact to benthic organism due to aluminium accumulation
8	Harvesting	Potential to spread plant species by fragmentation
9	Dilution and flushing	Possible washout fish and other aquatic life Reduce fish production Gives effect to downstream water
10	Hypolimnetic withdrawal	Impact biota with thermal sensitive species Impact to downstream water
11	Destratification	Potential to gas bubble disease in fish Potential enhance some species habitat
12	Dredging	Destroy benthic ecosystem Impacts biota in water column
13	Sediment cover	Impact to benthic organisms Potential of gas form under sheet (if polyethylene used)
14	Biomanipulation	Eliminated non-target aquatic species Migration of unintended species to water column
15	Doing nothing	Increased turbidity Absence of oxygen which may kill fish and release P from sediment Increase in-lake nutrient Produce toxic algal blooms (algae blooms produces many other negative effects such as algal poisoning that may kill domestic animals and effect human health, give bad taste and odour to water) Decrease fish production Restricted access to recreation activity (e.g: water sport, boating), swimming, fishing Create loss to water treatment plant due to pump or piping systems clogging

Cost

Cost is one of the key factors to consider when choosing the suitable option for eutrophication and algal bloom removal. The cost of eutrophication and algal bloom control vary extensively depending on type of restoration (material used, quantity of media or chemicals) and the size of the area. Three important costs included in the criteria for selection of the measures option are capital cost, operating cost and maintenance cost. Capital costs are one-time expenses used for the purchase of chemicals, equipment or construction of the specific treatment, while, operating cost and maintenance cost is repetitive costs which are needed in operating and maintaining the treatment. Operating cost is including contract labour or local labour cost, supplies such as material and chemical and power supply such as fuel and electricity for operating the equipment. For maintenance cost, the items that include in the maintenance works are such as breakdown maintenance (repairs when equipment fails and effect the production), corrective maintenance (repairs made to improve the working condition) and preventive maintenance (periodic maintenance to reduce the anticipated breakdown). All the measures required some capital cost and only differentiate by the degree of the cost. Because of the complexity in determining the cost for each control measure, this study has defined the cost using activity based cost (ABC) method. This method conclude that the more the activity, the more cost involved. For instance, the cost for AWT is considered as poor because it involved construction of the treatment facilities, purchased of equipment, installation of pump and piping, operation of the treatment unit (i.e., application of chemical or biological substances, power supply (electricity), maintenance (i.e., maintenance of dosing pump or backwash filter unit) and contract and local staff labour (refer Appendix 2). In contrast, the cost for harvesting is good as it only required the operating cost which include cost of lease boat and truck, cutting tools, and contract labour even though it is repetitive activities (the assumption is made based on hand pulling or cutting technique) (Holdren, Jones and Taggart, 2001). Therefore, the cost criteria are rank as below;

i. Excellent – low capital cost, low operation cost, low maintenance cost
ii. Good – fair capital cost, low operating cost, low maintenance cost
iii. Fair – fair capital cost, low operating cost, high maintenance cost
iv. Poor – high capital cost, high operating cost, high maintenance cost

4.4.3 Step 3: Obtain performance score for the decision matrix

Performance score is where measurements are made for each criterion. Using five previously established criteria, an estimated measurement were given to each measure option. The score given in this study is based on the result collected during systematic review. It is then rated by the keywords of “Excellent”, “Good”, “Fair” and “Poor” where the evaluation criteria is elaborate in Table 4.9.

Table 4-9: Rating definition for the measures criteria

Criteria	Excellent	Good	Fair	Poor
Effectiveness	The efficiency is more than 75%	The efficiency is more than 50%	The efficiency is more than 25%	The efficiency is less than 25%
Longevity	More than 5 years	Less than 5 year but more than 1 year	Less than 1 year without reapplication	Less than 1 year with few reapplication
Confidence	Most of the case of the application in tropical system was successful	Successfully applied in tropical with few of failure recorded	No record found in tropical system but successfully applied in temperate system	The treatment does not extensively study
Potential negative impact	No side effect	Minimal side effect which can be controlled or avoided	Impact the aquatic life and environment	Impact human health, aquatic life and environment
Cost	Low capital cost, low operation cost, low maintenance cost	Fair capital cost, low operating cost, low maintenance cost	Fair capital cost, low operating cost, high maintenance cost	High capital cost, high operating cost, high maintenance cost

The keywords are then expressed into fuzzy logic in this study as shown in Table 4-10. Because the criteria are always in different unit, transformation of the linguistic term to fuzzy logic was done to turn them onto commensurate scale so that it can be calculated later.

Table 4-10: Fuzzy number for score

Linguistic term	Linguistic value
Excellent	1
Good	0.75
Fair	0.5
Poor	0.25

Table 4-11: Performance score of criteria in unnormalized form

	C1	C2	C3	C4	C5
A1	1	1	1	1	0.25
A2	0.75	0.75	0.75	0.5	0.5
A3	0.75	1	0.75	0.75	0.5
A4	1	0.75	0.75	0.75	0.75
A5	1	1	1	1	1
A6	0.75	0.25	1	0.25	0.75
A7	1	0.75	0.75	0.5	0.75
A8	0.75	0.25	0.5	0.75	0.75
A9	0.5	0.5	0.5	0.5	0.5
A10	0.75	0.75	0.75	0.5	0.5
A11	0.5	0.5	0.5	0.25	0.5
A12	0.25	1	0.5	0.75	0.75
A13	0.75	0.75	0.75	0.5	0.75
A14	0.75	0.75	0.5	0.5	0.75
A15	0.25	0.25	0.25	0.25	0.25

The performance score for each measure was shown in Table 4-11. For option of doing nothing (C15), the cost (C5) is evaluated as poor (refer to Table 4-10) because according to Pretty et al. (2003), the damage cost caused by eutrophication USD 15 million per year which involved in drinking water treatment costs for nitrogen and algal toxin removal, economic losses from tourism industry and negatives effect to environment including effect on biota.

Normalization is necessary for if the performance score in unnormalized form because at the end of the process, the criteria will be summed up so the measurement has to be in the same scale. Normalization serves to transform given a criterion score into a series of normalized values between zero and one. To transform the score into normalization form, percentage of maximum method was chosen because it is the most common techniques used in normalization. The normalized value (V_i) can be calculated as equation 4-6 (Yilmaz and Harmancioglu, 2010). In this case, Table 4-11 is already been normalized form.

$$V_i = \frac{S_{ij}}{\max S_{ij}} \qquad (4\text{-}6)$$

Where;

S_i = performance score of the alternative for criteria j
max S_{ij} = maximum score of the alternative for criteria j

4.4.4 Step 4: Criteria weighing by decision maker

Weighting the criteria is very subjective as it will be evaluated by the decision maker. A weight is a measure of the relative importance of a criterion as judged by the decision maker, thus, all criteria is not going to be equally important. A decision maker may find one criterion more or less important than another. For instance, in developing countries, cost might be the priorities before considering the measures option since the economic condition in the developing countries is not as good as developed countries. In this study, linguistic variables consist of five linguistic terms for the importance of each criterion is expressed in fuzzy number. Weights are expressed by means of a linguistic variable whose values are “Very Unimportant”, “Unimportant”, “Fair”, “Important”, and “Very Important” are then converted to fuzzy number as shown in Table 4-12. The rating technique allows the decision maker to place each criterion on a scale by assigning a number to each criterion. For example, the decision maker might find that the effectiveness (C1) and the cost (C5) of the alternative are ‘very important’ compared to other criteria therefore assign the weighting for the criteria as 1. Meanwhile other criteria such that the decision maker does not found as important as effectiveness and cost might be assign as 'fair', 'unimportant' or 'very unimportant'. The weight of the criteria decided by the decision maker will give impact to the total performance score of the alternative. This is because the weighting criteria will be multiply by the performance score of each criterion (Table 4-13) in the decision matrix ranking which will be explain in the next section.

Table 4-12: Fuzzy number for criteria

Linguistic term	Fuzzy number
Very important	1
Important	0.8
Fair	0.6
Unimportant	0.4
Very unimportant	0.2

4.4.5 Step 5: Decision matrix ranking

Decision matrix is a standard feature of MCA which consist of measure option the row and criteria in the column. The weights, representing the relative importance of indicators are then multiplied by the normalized scores and summed up to determine the overall score of the measure options. The end result will be produces as shown in Table 4-14. The highest scoring option according to the ranking will be the best option. The evaluation matrix was calculated based on equation 4-7 which was derived from the general additive value function as used by Roy (1990) and Hobbs et al. (1992) as below;

$$A_i = \sum_{j=1}^{m} S_{ij} \left(W_j\right) \qquad (4\text{-}7)$$

Where;

A_i = measures alternative;
S_{ij} = performance score of the alternative for criteria j, i=A1, . . . , n; and
w_j = weighting factors for the criteria, j=1, . . . , n;

Table 4-13: Decision matrix ranking

Weight	**W_{j1}**	**W_{j2}**	. . .	**W_{jth}**	
	C1	**C2**	**. . .**	**C_j**	**Ranked**
A1	S_{11}	S_{12}	. . .	S_{1j}	$(S_{11}xW_{j1})+(S_{21}xW_{j2})+(S_{1j}xW_{jth})$
A2	S_{21}	S_{22}	. . .	. . .	. . .
. . .	. . .	. . .	. . .	. . .	. . .
A_i	S_{1i}	S_{2i}	. . .	S_{ij}	$(S_{1i}xW_{j1})+(S_{2i}xWj2)+(S_{ij}xW_{jth})$

4.5 Evaluation of selected measures

4.5.1 Monitoring

After executing the control measure, monitoring should immediately be implemented in order to define the status of the waterbody. The purpose of the monitoring is to help in identifying the changes in the lake as a result from the measure applied. If the waterbody does not show any improvement, the data gathered during monitoring can be used in order to diagnose the cause of the failure in measure. Thus, by maintaining the monitoring programme, such problems can be detected at early stages allowing preventive and more cost-effective measures to be implemented. Monitoring does involve some cost depending on the frequency of the sampling, the sampling parameter, the sampling station and the number of samples taken. However, the monitoring cost is the most cost-effective compared to other water management programme because from the monitoring, the cost of correction can be saved.

Table 4-14 shows the suggested frequency for water quality monitoring. The frequency should be increased when there are changes in seasonal event because the water quality usually changes after rainfall event due to pollutants being carried by surface runoff into the waterbody.

Table 4-14: Monitoring frequency modified from Jorgensen et al. (2005)

Water purpose	Sampling frequency
Drinking water	Daily to weekly
Bathing	Daily to weekly
Water sports (excluding bathing)	Daily to weekly
Landscaping in recreation area	Daily to weekly
Irrigation	Weekly to monthly
Process water	Weekly to monthly
Cooling water production	Weekly to monthly

4.5.2 Lake response

In some cases, the waterbodies seem to lack response to the implemented control measures, even though a thorough analysis was done before executing the water quality management program. There are several factor that can be examined such as those discussed by Jorgensen et al. (2005) to determine the reason of the control measure failure.

1. Assess the response time

A lake or reservoir will not necessarily respond immediately to the control measure especially when using the external nutrient reduction option. Unlike streams which respond quickly to external nutrient reduction (unless the sediments contaminated by the nutrients), lakes and reservoirs trap and recycle their nutrients. There is usually a lag period between the implementation of the control measure and the expected results. This is because the waterbody requires sufficient times to reach the new steady state condition after the alteration of the external or in-lake nutrient. The response time can be estimated using the residence time of the nutrient (τ_p) in equation 4-8 as reported by Rast and Lee (1978) because the concept is approximately same as the hydraulic residence time.

$$\tau_P = \frac{[P]_\lambda}{[P]_{in}} \qquad (4\text{-}8)$$

Where;

$[P]_\lambda$ = mean in-lake phosphorus concentration (m^3/L)
$[P]_{in}$= annual phosphorus input to waterbody ($m^3/L.yr$)

2. Reassess the nutrient loading

The inaccurate estimation of nutrient loading may also be one of the possible reasons for waterbodies failing to respond to the control measure. Direct measurement of the water discharge will always give the most accurate nutrient loading values for a give waterbody. If it is not possible to directly measure the loads, the estimation of nutrient load can be made using unit area loads for specific pollutants and types of land uses in a drainage basin as shown in equation 4-5. There is also a potential of the P in the sediment to diffuse back to the water column under anoxic condition, thus this must be considered when reassessing the nutrient loading.

3. Reassess the limiting nutrient

The nutrient limitation is also worth reassessment. This is because under certain condition, the nutrient limitation might change. For instance, the increased of atmospheric N deposition in lakes in Norway, Sweden and Colorado, United States, has shifted the nutrient limitation. As a result, the phytoplankton which favours those conditions might also be shifted. This is because under low N deposition, N will be the limiting nutrient and in high N deposition, P will be the limiting nutrient (Elser et al., 2009).

4. Reassess the sampling programme

The water quality may change over seasonal variation. Therefore, more frequent sampling during the periods of water quality changes should be executed. For instance, in tropical regions, the sampling should be executed biweekly from the start of the rainy season until three months after the season's end. For waterbodies which exhibit year to year fluctuation in hydrological conditions, Ryding, Rast and Unesco (1989) has suggested to cover at least three years of sampling period as the calculation based upon a single year is inadequate.

5. Consider the physical, chemical and biological factors

The shape or the features of the waterbody can significantly influence its response to the control measure. For example, it is generally difficult to determine the average of the water quality condition for the entire waterbody for those containing multiple sub-basins. Therefore for the water bodies that are of a longitudinal shape, it is critical to have several sampling point to characterize the average water quality (Ryding, Rast and Unesco, 1989). Besides that, the chemical reaction between the nutrient load and trophic reaction is also worth considering. For instance, in hard-water lakes, the biota is not as sensitive to the presence of toxic element as in the soft-water lakes. The selective feeding of fish on the invertebrates is also an important process which cannot be overlooked. This is because with the absence of fish, overgrazing by zooplankton can reduce phytoplankton concentrations to very low level even if the dissolved P concentration is extremely high.

After reassessment and considering all the possible factors that cause a failure in responding to the control measure and the waterbodies still does not achieved the desired result, more stringent control measures should be applied. Even though it does not produce the desired results, it also does not produce any negative side effects. Therefore, more time should be given to see the effect of the control measures as the response time is different between waterbodies. The framework can be summarized as in Figure 4-3.

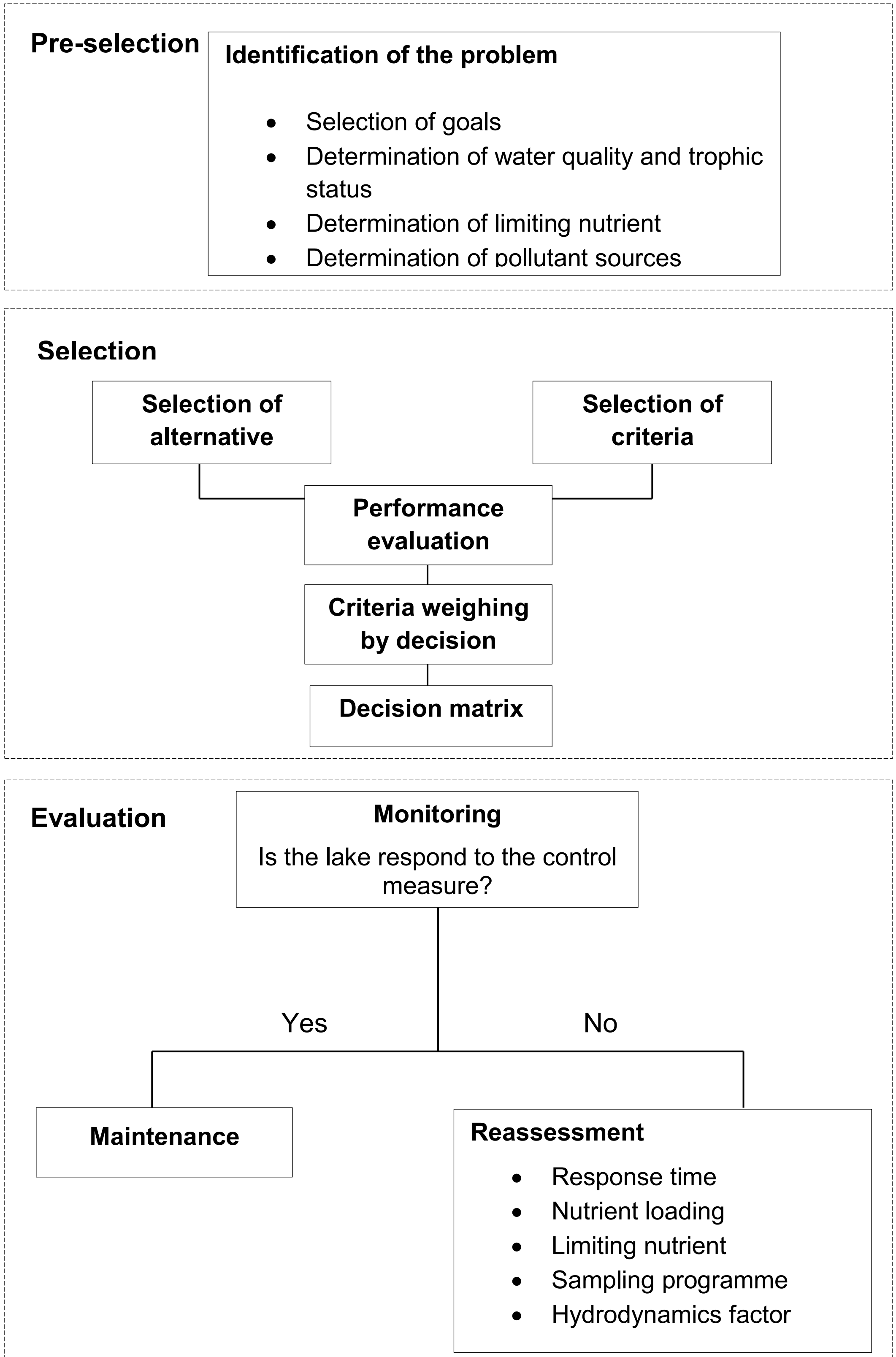

Figure 4-3: Eutrophication and algal blooms control framework

4.6 Conclusion

The framework been developed to provides the simplest and economical way in diagnosing and managing the eutrophication and algal bloom which can overcome the tropical budget constraints and the lacking in the technical expertise. Therefore pre-selection and selection stage as shown in Figure 4-3 have been derived to meet above objective. On the other hand, the evaluation stage is the normal procedure that been established in many studies for lake monitoring such as include in Ryding, Rast and Unesco (1989); Cooke et al., (2005); Jorgensen et al., (2005). In selection stage, MCA was used as a supporting tool in selecting the best options that will assist the organization or individual in selecting the suitable treatment based on their preferences. Compared to CBA which only focuses on the cost and benefit of each alternative, MCA provides the decision maker with more criteria which is worth considering. In tropical where cost is the most critical criteria, it is always desirable to have low cost treatment that can rapidly achieve the targeted results. However, the longevity of a control measure is more important as it can reduce other cost such as reapplication of the control measures when the previous measures only effectives in a short term. Therefore, if this framework was put in place, this framework can give benefits to everyone including small organization or even individual to protect their water bodies. To use the framework, the decision maker only needs to follow the process in pre-selection decision tree in Figure 4-2 and selection step using decision matrix in Appendix 3 which presented in Microsoft Excel. However, it should be noted that the water body usually does not respond instantaneously to the eutrophication control programme, especially those based on reducing the external nutrient input. This is because there is usually lag periods between the implementation of the control programme and the observable results in the water body.

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CHAPTER 5

Assessment of seasonal water quality status in Durian Tunggal reservoir and Jus reservoir

Chapter 5 : Assessment of seasonal water quality status in Durian Tunggal reservoir and Jus reservoir

5.1 Introduction

The relationship between chlorophyll-a (Chl-a) and water quality parameters in aquatic systems has been recognised as a valuable management tool (Huszar et al., 2006; Rocha et al., 2009). In particular, information about Chl-a and nutrient relationships has allowed water managers to predict and manage water quality problems such as eutrophication or algal bloom occurring in lakes. However, most of the studies on the relationship between nutrients and phytoplankton biomass in freshwater comes from temperate systems (Huszar et al., 2006). Differences in seasonality between temperate and tropical might give different result in nutrient-chlorophyll relationships. Study done by Oliveira et al. (2014b) compared the changes of water quality during dry and rainy season in tropical reservoir in Brazil. From the study he found that higher concentration of P and N were detected during the rainy season compared to dry season. This is because the land nutrient was transported to the waterbody by the rainfall runoff. On the other hand, Tundisi, Matsumura-Tundisi and Abe (2008) found that the concentration of TN and TP in Barra Bonita reservoir were higher in dry season compared to rainy season because precipitation dilute the current concentration of TP and TN hence decrease their concentration in the water

Besides that, morphology of the reservoirs also gives influence on the increased nutrient load to a lake or reservoir. For instance, deep lake with large surface area had a thicker epilimnion and a thinner hypolimnion than a lake with same mean depth but with small surface area. These two morphological balance each other because thicker epilimnion diluted recycled P while the thinner hypolimnion promoted more P recycling. On the other hand, the entire water column is included in epilimnion in shallow lake which the size of the surface area does not give any effect to P recycling (Genkai-Kato and Carpenter, 2005). The important of the morphology also emphasized in Vollenweider model when he demonstrated that few hydrological and morphological factors especially lake depth did influence the relationship between nutrient loading and in-lake concentration. He also noted that the lakes of different sizes are able to be compared if external nutrient inputs were expressed in loadings per unit area (O'Sullivan and Reynolds, 2008).

Thus, the primary objectives of this chapter were to assess the water quality in Durian Tunggal and Jus reservoir. This chapter also seeks to test the following hypotheses; 1) the degree of eutrophication increases during the Northeast Monsoon in Malaysia because it receives a higher intensity of rainfall that washes off nutrients into water bodies, 2) the morphology of the reservoir influences the increase or decrease of the trophic status, 3) human alteration and disturbance results in greater pollutant export to the water body, 4) N management may be more useful in the tropics because it is typically the limiting nutrient in tropical water bodies.

The purpose of the fieldwork sampling is to obtain information which is not provided by the Government Water Agency. This data will be used as a base line in order to achieve the research objectives. The environmental parameters that were collected are namely; water temperature, turbidity, pH, dissolved oxygen (DO), chlorophyll-a, phosphate (PO43-), total phosphorus (TP), ammonia nitrogen (NH3-N) and total nitrogen (TN). Water temperature was measured because the change of the water temperature will affects physical, chemical and biological processes in the waterbody. High temperatures of water will increased the rate of chemical reaction such as evaporation and volatilisation of substances from water and decrease the solubility of gases in water (Chapman and World Health Organization, 1996). Turbidity also been measured because it can vary seasonally according to biological activity in the waterbody and suspended particles resulted from surface run-off carrying soil particles (Chapman and World Health Organization, 1996). To determine the amount of nutrients and heavy metals that can be dissolved in water and be utilized by aquatic life, pH was measured (Michaud, 1991). Meanwhile, the determination of DO in the water is important as it can help to determine the level of pollution caused by oxygen demanding substances such as biodegradable organic matter and nutrients (Chapman and World Health Organization, 1996). Chlorophyll is the major photosynthetic pigment in plants, both algae and macrophytes. Therefore, by measuring Chl-a, the amount of algal biomass can be estimated (Michaud, 1991; United States Environmental Protection Agency, 2000). Furthermore, P and N were measures because it is essential nutrient for aquatic plant growth. TP and TN were measured because it contains all form of phosphorus and nitrogen including dissolved and particulate form. Meanwhile PO4 was measured because it is the common dissolved form of phosphorus that is immediately available for consumption by aquatic plants. Ammonia nitrogen was also been measured as it can indicate the organic pollution and high ammonia content can determine the anoxic condition in the waterbody (Chapman and World Health Organization, 1996).

Two reservoirs were involved in this study; Durian Tunggal reservoir and Jus reservoir. The main reason for the selection of the catchment under study is because both water catchments were listed in as eutrophic reservoirs in the Desk Study on the Eutrophication Lakes of Malaysia by National Hydraulics Research Institute of Malaysia (NAHRIM) in 2005. However, the classifications were made only using the land-use classification without assessing the water quality. Moreover, both water catchments are the main source of water supply for the Municipality of Malacca.

5.2 Methodology

A field sampling has been conducted from June until August 2013 and February until March 2014 in two different reservoirs in Malaysia. Two reservoirs were involved in the sampling: Durian Tunggal reservoir and Jus reservoir. A day before the sampling event, a site visit was conducted to identify the precise sampling point locations. The samples were taken from a boat. Five sampling points had been selected for each reservoir in the Durian Tunggal reservoir (DT) and Jus reservoir (Jus) for the study. The reason of having five sampling points is because DT has longitudinal shape while Jus has multiple arms. This is based on the recommendation made by Ryding, Rast and Unesco (1989) which state that the water bodies that are of a longitudinal shape, multiple arms or sub-basin it is critical to have several sampling point to characterize the average water quality. There are a few characteristic that influences the determination of the locations of the sampling points. For instance, the sampling points selected were near the inlet, in the middle of the reservoir and water outlet because these areas will have difference in constituent concentrations due to water dilution. Sampling of water inflow and outflow also recommended by Walker Jr (1987) which suggest that samples should be collect near the input and output of the waterbody because the area is where the most of the volume can be found and greatest change usually occur due opportunity to be completely mix. Besides that, sampling points that is isolated from flow and sunlight also been selected because the productivity of stagnant water is usually different from flowing water. This because stagnant water can be thermally or chemically stratified which make particulate materials of differing densities tend to distributed heterogeneously (Ryding, Rast and Unesco, 1989). A Global Positioning System (GPS) from Tomstrails GPS version 1.4.2 was used to identify the coordinates for each sampling point and to re-confirm the location of the stations during subsequent sampling periods.

5.2.1 Study area

5.2.1.1 Durian Tunggal reservoir

Durian Tunggal reservoir is the second largest drinking water reservoir in Malaysia, situated at Latitude 2° 21'N and Longitude 102° 19'E. It is located in the southern region of the Malay Peninsula, next to the Straits of Malacca (refer Appendix 4). The climate of the area is tropical rainforest climate (Af) with very little monthly variation in temperature. The average annual temperature is 28^{o}C with the minimum temperature of 22^{o}C and maximum temperature of 34^{o}C. The catchment area of this dam is affected by the monsoon systems i.e, the northeast monsoon and the southwest monsoon. Northeast Monsoon (NE) usually takes place from November until March whilst the Southwest Monsoon (SW) commences in June and lasts until September. Durian Tunggal receives an inlet from the Malacca River system and it has a catchment area of 41.4 km^2 with a maximum depth of 28.4 meters.

There were five sampling points selected in Durian Tunggal reservoir (Figure 5-1). Sampling point 1 was located approximately 2 meters from the inlet. Granite rocks were stacked at the water gate to slow down the water flow rate. Illegal fishing activities are normally carried out near the water gate. Rubbish such as paper and plastics are usually left behind as a result from the fishing activities. Sampling point 2 was located approximately 1 meter from the draw off tower. The draw off tower is the structure that was built to control the level of the reservoir by releasing some of the water to the nearest river. There was no activity found near the sampling point. Sampling point 3 was located in the middle of the reservoir. There was also illegal fishing activities at this point as there are a few fish net installed across the reservoir. Sampling point 4 is located near an abundance of emergent macrophytes. Dragon fruit farms, palm oil estates and rubber estates were observed surrounding this sampling point. Last but not least, sampling point 5 is located in the area where there is no current and protected from the wind. This sampling point also has an abundance of floating macrophytes. There were a few residential buildings and a private mini zoo observed surrounding this sampling point.

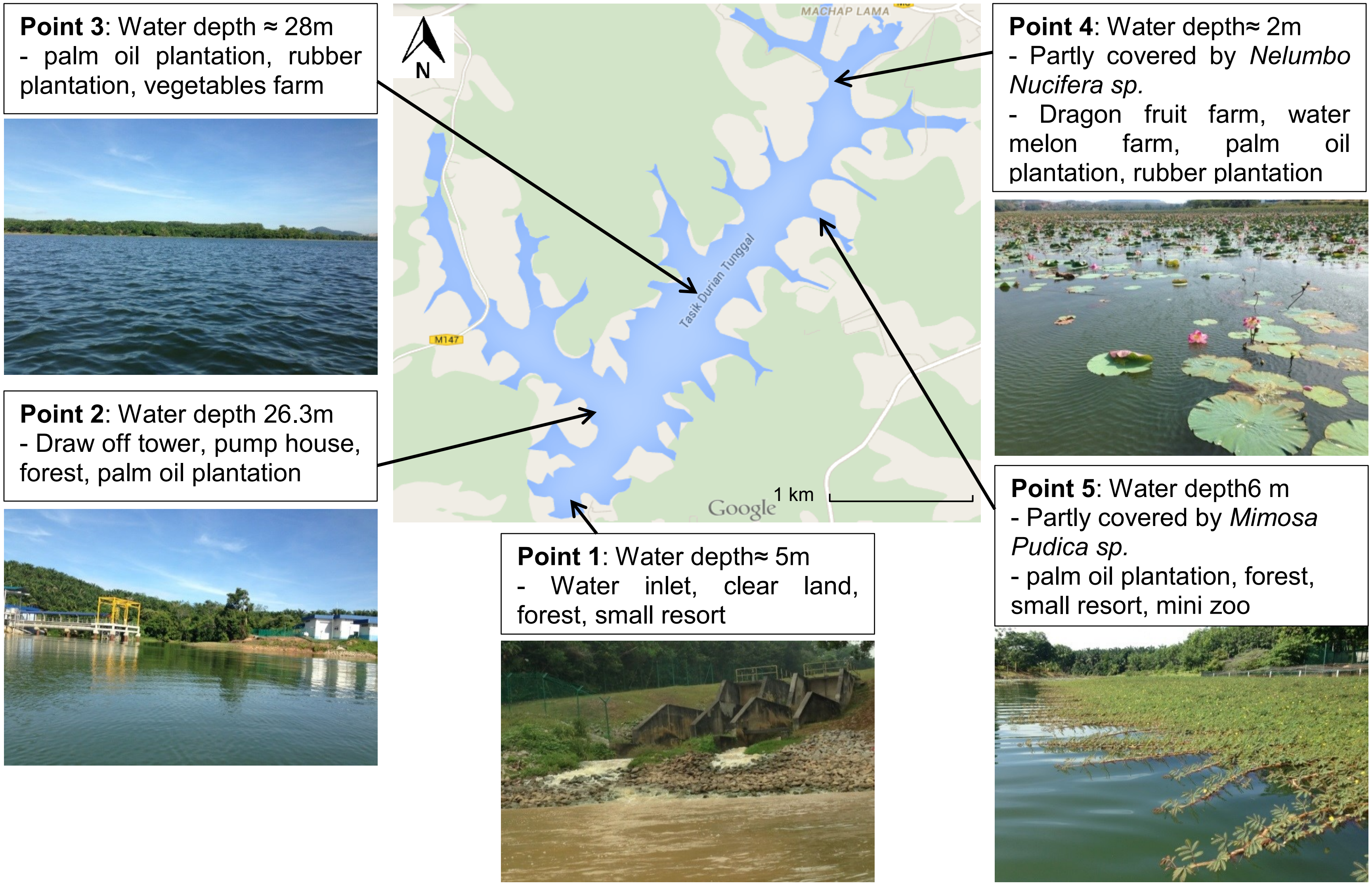

Figure 5-1: Durian Tunggal reservoir sampling map

5.2.1.2 Jus reservoir

Jus reservoir is a man-made reservoir located at Latitude 2° 27'N and Longitude 102° 25'E. It is an earth fill type of reservoir which was built in 2001. It only receives an inlet from surface runoff from its catchment area. It also falls within the same climate area as Durian Tunggal reservoir which is a tropical rainforest climate (Af) according to Koppen-Geiger climate classification (Rubel and Kottek, 2010). The catchment area is only half of that of the Durian Tunggal Reservoir which is 23 km^2; however, the maximum depth is up to 75 meters.

There were five sampling points selected in Jus reservoir (Figure 5-2). Sampling point 1 was located near the water inlet. The land covered along this sampling point has a few residential areas and some bushes. Sampling point 2 was also at the water inlet. However the land use area was a road and some bushes. Sampling point 3 was located in the middle of the reservoir and the land use was monopolised by the palm oil estates. Next, sampling point 4 is located at the arm of the reservoir. The lands used have a mixture of forest and palm oil estates. There has also been as aboriginal settlement observed near the sampling point. Lastly, sampling point 5 is located 1 meter from the draw off tower. The land use area nearby is palm oil estates. The morphometric of both reservoirs and the land use areas data were provided by Malacca Water Corporation (MWC) and displayed as in Table 5-1 and Table 5-2.

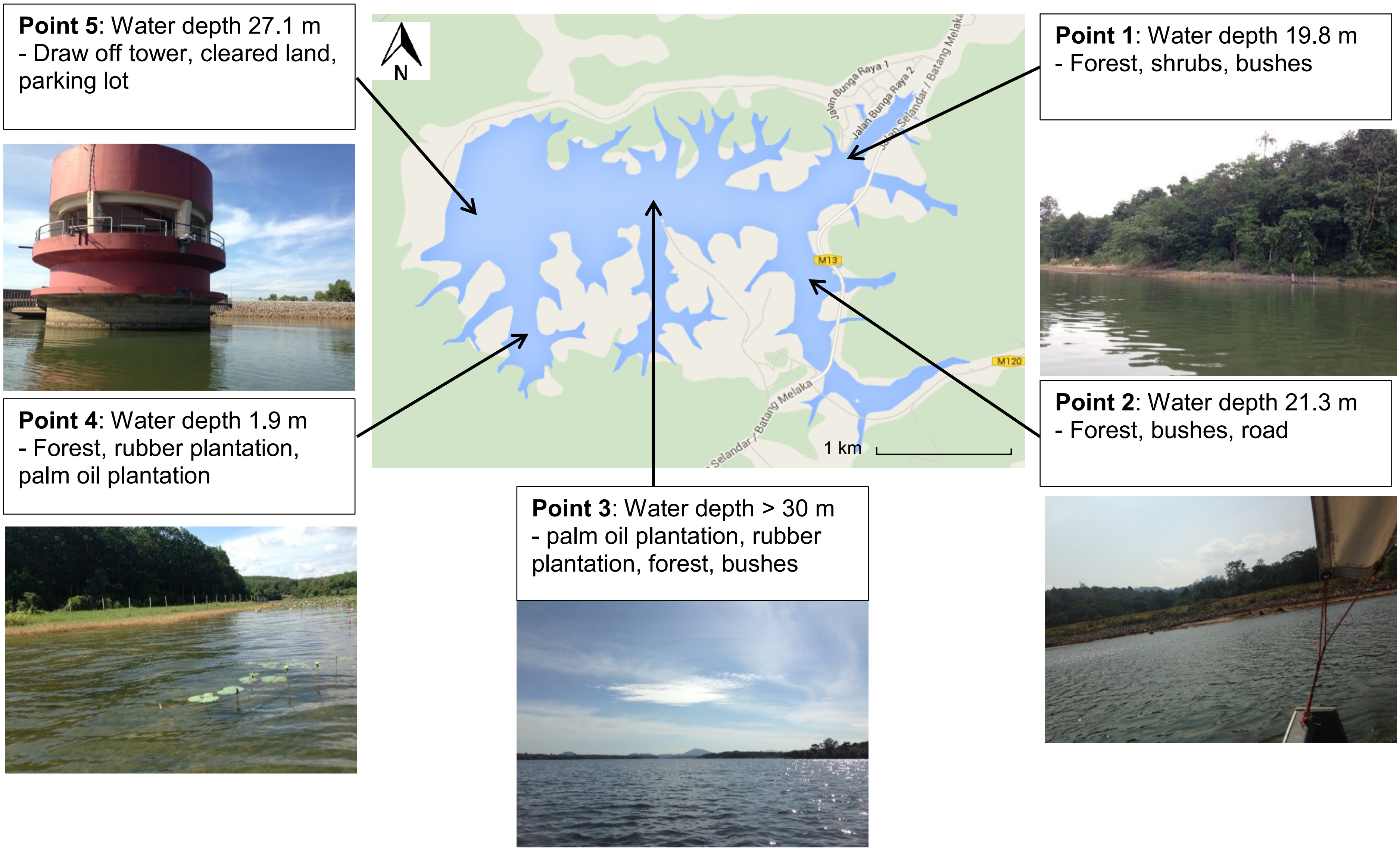

Figure 5-2: Jus reservoir sampling map

Table 5-1: Morphometric characteristic DT and Jus reservoir

	Durian Tunggal	Jus
Year built	1974	2001
Elevation	37 m	71 m
Catchment Area	41.4 km^2	23 km^2
Surface Area	5.8 km^2	5.35 km^2
Maximum Depth	28.41 m	75 m
Volume	32.6 Mm^3	48 Mm^3
Type	Earth fill	Earth fill

Table 5-2: Land use area in DT and Jus catchment area

Land use type	Area (%) DT	Area (%) Jus
Agriculture	75	50
Forest	3.5	15.4
Residential	20.3	25.7
Others	1.2	8.9

5.2.2 Sample collection, handling and preservation

The samples were collected from 11 am to 1 pm during 14 sampling events. Water samples were collected at depths of 1 metre (epilimnion) and 20 metres (hypolimnion) and duplicated using a grab water sampler with a capacity of 1.5 L which is equipped with a simple pull-ring that allowed sampling at the epilimnion and hypolimnion layer (Figure 5-3). In-situ profiling of pH, turbidity, dissolved oxygen and water temperature were taken at all sampling point using YSI 6820 multi-paramater sonde while the inlet water discharge was measured by using Global Water flow probe. In addition to that, rainwater samples were also collected for analytical analysis. The reason of rainwater sampling is to estimate the concentration of atmospheric deposition. Rainwater samples were collected in a clean plastic bottle was attached to a funnel tied to a stick and placed in a field nearby the reservoir and left overnight. The samples were collected as soon as possible on the next day to avoid water loss by evaporation.

All sampling bottles were acid-washed, cleaned and dried before use for sample collection to avoid contamination of the samples. Water samples were placed in an ice box and transported to the laboratory for immediate analysis. The samples were preserved as suggested in APHA (2012) when it was impossible to conduct the testing immediately.

Figure 5-3: Water sampler (left); Samples in opaque plastic bottles (right)

5.2.3 Analytical procedure

All analyses were conducted in the Environmental Science Laboratory in University Kuala Lumpur. The work were done according to standard procedures for water analysis in triplicate unless otherwise mentioned (APHA, 2012). Concentrations of Chl-a were determined from adequate samples filtered through 0.7 μm Whatman GF/F filters and extracted using 90 % (v/v) methanol and measured by ultraviolet-visible spectroscopy at 663 nm and 750 nm. The filtered water samples also used to determine N and P concentrations. Inorganic P was determined by the vanadate-molybdate method and measured by ultraviolet-visible spectroscopy at 400 to 490 nm, while TP was determined as inorganic P after potassium persulfate digestion of samples. Organic P was calculated as the difference between TP and inorganic P. A five-point calibration curve was constructed for each element. Blank and standard solutions were treated in a similar way as the samples. Ammonium nitrogen (NH3-N) and total kjeldahl nitrogen (TKN) were determined by the Kjeldahl method. NH3-N was determined by titration after the distillation of the samples while TKN was determined as NH3-N after acid digestion of the sample. Organic N was calculated as the difference between TKN and ammonium nitrogen. Water quality parameters, their units and methods of analysis are summarized in Table 5-3.

Table 5-3: Water quality parameters, units and analytical methods used during sampling

Parameters	**Abbreviation**	**Units**	**Methods**
pH	pH	pH unit	In-situ using YSI Sonde 6820v2
Turbidity		NTU	In-situ using YSI Sonde 6820v2
Dissolved Oxygen	DO	mg/L	In-situ using YSI Sonde 6820v2
Water Temperature	WT	oC	In-situ using YSI Sonde 6820v2
Phosphate	PO4	mg PO43- P/L	Vanadate Molybdate
Organic phosphate	Org-P	mg P/L	Calculation
Total phosphorus	TP	mg/L	Acid digestion + Vanade Molybdate
Ammonium nitrogen	NH3-N	mg NH3-N/L	Kjeldahl
Organic nitrogen	Org-N	mg N/L	Calculation
Total nitrogen	TKN	mg/L	Acid digestion + Kjeldahl
Chlorophyll-a	Chl-a	µg/L	Spectrophotometric

5.2.4 Secondary data collection

Secondary data such as air temperature, evaporation, rain intensity and wind velocity was collected from Malaysia Meteorological Department and Department of Irrigation and Drainage Malaysia (DID). Meanwhile, lands cover classes' data was obtained from Malacca Water Corporation (MWC) (Table 5.4). The data received from MWC was in report format which stated that the land cover classes were derived by Remote Sensing Malaysia for MWC.

Table 5-4: Land cover classes in DT and Jus

Land cover classes	DT		Jus	
	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)
Agriculture (mixed crop)	43.7	18.1	11.5	2.65
Agriculture (oil palm)	31.3	12.96	38.5	8.86
Forest	3.5	1.45	15.3	3.52
Residential	20.29	8.4	25.7	5.91
Vacant/Grassland	1.2	0.5	8.9	2.05

5.2.5 Data treatment

Spearman's rank correlation and t-test analysis were employed, in order to evaluate prevalent relationships between tested water quality variables and Chl-a as dependent variables and to compare the distribution of SE monsoon and NE monsoon. The epilimnion and hypolimnion data from both reservoirs and both seasons were used in the test.

5.3 Result

5.3.1 Trophic state index

Trophic state index (TSI) for the reservoirs was determined using Carlson's Trophic Status Index (Carlson, 1977). Carlson's TSI was used because it requires minimum data and is generally easy to understand. The adoption of the TSI has been tested by Bouvy et al. (2000), and they concluded that the adoption of the ecological apect from temperate is necessary. This is because the TSI was derived by log (base 2) transformation of secchi disk transparency and concentration of phosphorus and chl-a. Higher TSIs indicate higher productivity in the waterbody (Binford et al., 1987).The indicator also has been used extensively in other tropical climates such as used by Omar (2010), Sheela, Letha and Joseph (2011), Te and Gin (2011) and Oliveira et al. (2014a) to predict the condition of the water bodies even though it was developed based on the condition of a temperate lake. By using the mean value of the variables and TSI were estimated using equations below;

$$\text{TSI (SD)} = 60 - 14.4 \ln (\text{SD}) \quad (5\text{-}1)$$

$$\text{TSI (TP)} = 14.42 \ln \text{TP} \quad (5\text{-}2)$$

$$\text{TSI (Chl-a)} = 9.81 \ln (\text{Chl-a}) + 30.6 \quad (5\text{-}3)$$

Where;

TSI = Trophic State Index
SD = Secchi depth, m
TP = Total Phosphorus, µg/L
Chl-a= Chlorophyll-a, µg/L

TSI values during SE monsoon for DT and Jus are presented in Table 5-5. Based on TSI (SD), the productivity in both reservoirs can be categorized as eutrophic with the reading of secchi depth between one and two meters. According to Straskraba and Tundisi (1999), TSI values more than 50 indicate eutrophic productivity in tropical waterbodies. Different TSI numbers were obtained when TSI was evaluated by using TP and Chl-a concentration which shows some of TSI (TP) is double the number of TSI (SD) and TSI (Chl-a). Even though there are some large differences between TSI (TP), TSI (SD) and TSI (Chl-a), the productivity is still in eutrophic condition. The condition will only change to hyper-eutrophic once the TSI reaches 200 (Straskraba and Tundisi, 1999).

Table 5-5: Trophic state index (TSI) for DT and Jus during SE monsoon

Location	DT					Jus				
	SD	Epilimnion		Hypolimnion		SD	Epilimnion		Hypolimnion	
		TP	Chl-a	TP	Chl-a		TP	Chl-a	TP	Chl-a
Point 1	73	98	70	123	68	58	114	55	113	52
Point 2	55	95	64	108	51	57	110	61	112	61
Point 3	49	92	65	105	61	56	114	57	113	60
Point 4	50	116	64	105	67	56	108	55	115	59
Point 5	49	119	68	114	62	56	113	61	115	67

Table 5-6: Trophic state index (TSI) for DT and Jus during NE monsoon

Location	DT					Jus				
	SD	Epilimnion		Hypolimnion		SD	Epilimnion		Hypolimnion	
		TP	Chl-a	TP	Chl-a		TP	Chl-a	TP	Chl-a
Point 1	77	138	58	133	56	60	116	52	106	45
Point 2	57	130	56	122	55	58	113	50	109	36
Point 3	51	120	55	110	55	57	110	44	109	36
Point 4	51	137	59	110	59	57	117	57	109	48
Point 5	50	129	58	108	59	57	113	55	107	47

Table 5-6 shows the TSI values in DT and Jus during NE monsoon. During this season, TSI (SD) values were found to be higher than the values estimated during the SE monsoon. This might related to the high turbidity measured during NE monsoon where the average of the epilimnetic layer is 20.69 NTU in DT and 1.76 NTU in Jus. Compared SE monsoon, the turbidity was measured 15.44 NTU in DT and 4.01 in Jus. However, the productivity of both reservoirs remained unchanged. The increment of TSI values was also observed when TSI was measured using TP. TSI (TP) in both reservoirs increased compared to TSI (TP) during SE monsoon except for TSI (TP) values in the Jus hypolimnion layer which were slightly low compared to TSI (TP) measured during SE monsoon. On the other hand, TSI (Chl-a) was found to be low in the NE monsoon compared to the value estimated during SE monsoon which shows some improvement especially in the hypolimnion layer in Jus where the TSI (Chl-a) found to be in a mesotrophic state.

5.3.2 Variation in Chl-a and water quality in two difference monsoon

The data sets are based on 360 water samples in the SE Monsoon (5 sampling sites x 2 layers x triplicate samples x 6 days) and 180 water samples in the NE Monsoon (5 sampling sites x 2 layers x triplicate samples x 3 days) for two reservoirs. The selected water quality parameters include pH, turbidity, DO, water temperature, P, TP, NH_{3}-N, TN and Chl-a.

Mean and standard deviation (SD) of Chl-a and 8 key environmental parameters of water quality in two reservoirs are shown in Table 5-7. The highest mean concentration of Chl-a was found in the epilimnion layer in DT during the SE monsoon which is 38.15 µg/L and 28.73 µg/L in the hypolimnion layer. Chl-a concentration during the SE monsoon shows a huge variation between sampling points and sampling days compared to a small variation during the NE monsoon. For instance in the epilimnion layer, Chl-a mean concentration variation in DT during the SE monsoon is 16.71 µg/L and 12.27 µg/L in Jus but the variation is small in the NE monsoon where it is 2.67 µg/L in DT and 3.92 µg/L in Jus. During the NE monsoon, mean concentration of Chl-a in DT epilimnion layer is 15.08 µg/L and 9.23 µg/L in Jus which is lower than Chl-a measured in epilimnion layer during the SE monsoon. However, the mean concentration of Chl-a in the epilimnion layer is slightly higher than measured in hypolimnion layer for both reservoirs during the NE monsoon where the Chl-a concentration was 14.39 µg/L in DT and 3.88 µg/L in Jus.

Table 5-7: Monsoonal variations in chlorophyll-a and water quality parameters in Durian Tunggal reservoir (DT) and Jus reservoir (Jus)

	SE Monsoon		**NE Monsoon**	
	DT	**Jus**	**DT**	**Jus**
Chl-a epi (µg/L)	38.15 ± 16.71	16.04 ± 12.27	15.08 ± 2.67	9.23 ± 3.92
Chl-a hypo (µg/L)	28.73 ± 19.74	21.73 ± 17.83	14.39 ± 3.43	3.88 ± 2.60
DO epi (mg/L)	4.77 ± 0.63	5.42 ± 0.76	7.16 ± 0.97	9.01 ± 0.44
DO hypo (mg/L)	2.96 ± 1.37	3.58 ± 0.85	6.59 ± 1.19	6.40 ± 0.60
pH epi	7.01 ± 0.15	7.25 ± 0.21	6.68 ± 0.23	7.27 ± 0.27
pH hypo	6.84 ± 0.22	7.20 ± 0.20	6.67 ± 0.28	7.12 ± 0.41
Temp epi (^{o}C)	30.76 ± 0.35	29.54 ± 0.32	28.47 ± 0.47	28.62 ± 0.56
Temp hypo (^{o}C)	30.27 ± 0.26	29.43 ± 0.25	28.22 ± 0.55	28.32 ± 0.70
Turbidity epi (NTU)	4.01 ± 6.88	2.43 ± 0.85	21.80 ± 31.74	1.42 ± 0.42
Turbidity hypo (NTU)	15.44 ± 21.81	4.01 ± 1.69	20.69 ± 28.51	1.76 ± 1.0
TP epi (mg/L)	1.83 ± 2.06	2.38 ± 1.27	9.50 ± 4.07	2.69 ± 0.52
TP hypo (mg/L)	2.26 ± 1.89	2.65 ± 1.50	3.93 ± 3.26	1.79 ± 0.18
PO4 epi (mg/L)	0.65 ± 0.57	1.03 ± 0.96	8.72 ± 3.87	1.30 ± 0.24
PO4 hypo (mg/L)	0.91 ± 0.74	1.09 ± 0.95	2.58 ± 2.66	0.82 ± 0.12
TN epi (mg/L)	0.85 ± 0.75	0.68 ± 0.53	2.64 ± 0.95	1.41 ± 0.27
TN hypo (mg/L)	0.59 ± 0.50	1.35 ± 1.22	1.08 ± 0.31	1.01 ± 0.31
NH3 epi (mg/L)	0.35 ± 0.25	0.36 ± 0.23	1.74 ± 0.92	0.86 ± 0.25
NH3 hypo (mg/L)	0.32 ± 0.27	0.42 ± 0.25	1.74 ± 0.92	0.45 ± 0.23

From the graph in Figure 5-4, Chl-a concentration was found to be at a maximum in sampling point 1 for both layers in DT during the SE monsoon. The Chl-a concentration varies between 32.57 µg/L to 72.44 µg/L in the epilimnion layer and 15.78 µg/L to 80.25 µg/L in the hypolimnion layer. This result may be explained by the location of the sampling point which is situated near the water inlet. The inlet water was drawn from the Malacca River system and the mean turbidity measured during the sampling event was up to 12.10 NTU in upper layer and 41.20 NTU in bottom layer of the reservoir. The inlet from the river might have brought pollutant into the reservoir which increases the Chl-a concentration. The minimum concentration of Chl-a was found in sampling point 2 for both layers with the average concentration of 29.24 µg/L in epilimnion and 7.94 µg/L in the hypolimnion. It seems possible that this result is due to its location near to the draw off tower. The water was diluted until it reached the draw off tower. Contrast to Chl-a distribution during NE, the highest Chl-a concentration distribution is in sampling point 4 for epilimnion layer with the concentration between 16.49 µg/L to 19.39 µg/L and sampling point 5 for hypolimnion layer where the Chl-a concentration is between 15.19 µg/L to 19.09 µg/L. On the other hand, the lowest Chl-a concentration was measured at sampling point 3 for both layers where the concentration is between 10.17 µg/L to 13.73 µg/L in the epilimnion and 11.30 µg/L to 12.60 µg/L in the hypolimnion layer.

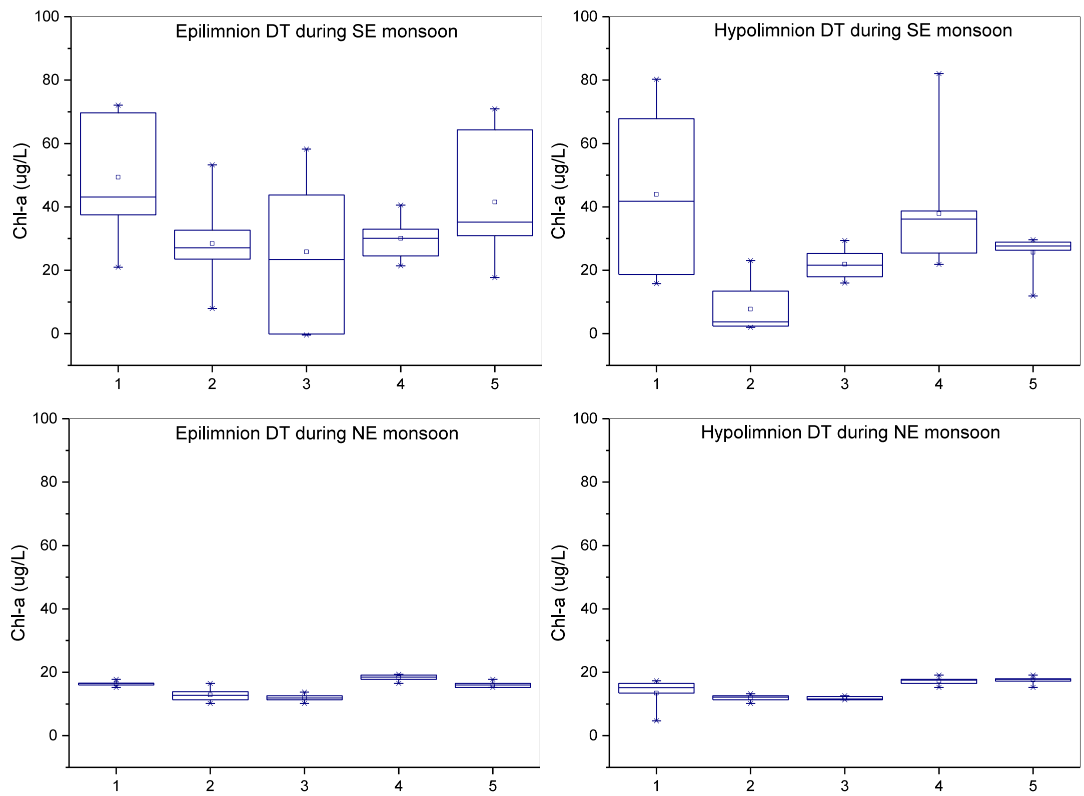

Figure 5-4: Chl-a distribution in 5 sampling points in DT during SE monsoon versus NE monsoon

Figure 5-5 shows Chl-a concentration distribution in Jus during SE monsoon and NE monsoon. From the graph, it can be observed that during SE monsoon, sampling point 5 contributed to the highest amount of Chl-a in the whole reservoir. Half of the Chl-a concentration distribution in epilimnion layer in sampling point 5 is between 15.33 µg/L to 24.63 µg/L while in the hypolimnion layer, half of the Chl-a concentrations are between 52.25 µg/L to 63.31 µg/L. The lowest Chl-a concentration was found in sampling point 1 for both layers. The average concentration is 11.44 µg/L in epilimnion layer and 9.19 µg/L in hypolimnion layer. On the other hand, the highest Chl-a concentration during NE monsoon was found in sampling point 4 and the lowest Chl-a concentration was in sampling point 3 for both layers. Chl-a concentration in sampling point 4 is between 11.60 µg/L to 17.46 µg/L in the epilimnion layer and 1.30 µg/L to 9.09 µg/L in the hypolimnion layer. While in sampling point 3, Chl-a concentration varies between 3.3 0µg/L to 4.60 µg/L in the epilimnion layer and 1.30 µg/L to 2.70 µg/L in the hypolimnion layer.

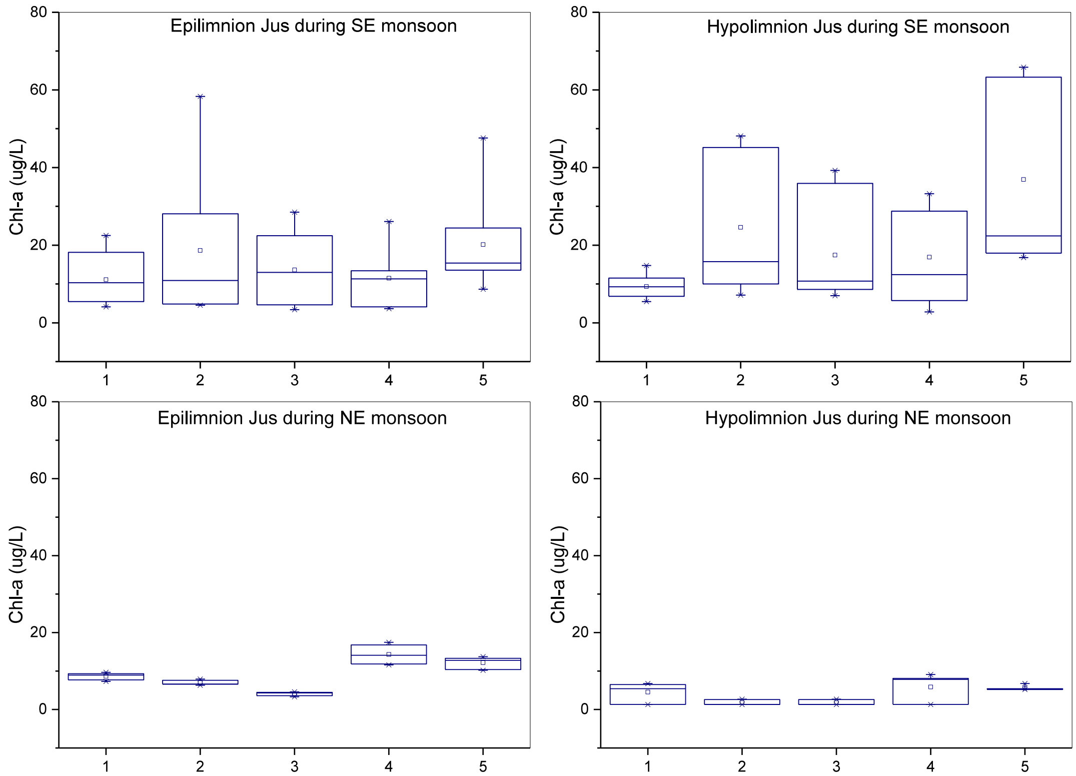

Figure 5-5: Chl-a distribution in 5 sampling points in DT (above) and Jus (bottom) during NE monsoon

During the SE monsoon, DO concentration was at the minimum that can support aquatic life (Figure 5-6). The hypolimnion layer has always been lower than the epilimnion layer in both seasons. This might be influenced by the depth because the hypolimnion is deep enough that little light reaches it. With little or no photosynthesis, respiration and microbial decomposition predominates in this layer, oxygen might be consumed completely. The highest DO concentration distribution is in sampling point 1 for both layers. However DO concentration in hypolimnion; 5.23 mg/L is slightly higher than the concentration in epilimnion ; 4.98 mg/L. DO level at the bottom layer is slightly higher might resulted from the well mixed water creates by the turbulent mixing. Meanwhile, during NE monsoon, both layers are well oxygenated with the mean of DO concentration in the epilimnion and hypolimnion is 7.16 mg/L and 6.59 mg/L.

The highest DO concentration distribution is in sampling point 1 for both layers. In the epilimnion layer, more than fifty percent of DO concentration contribution is between 8.01 mg/L to 9.06 mg/L, while in the hypolimnion layer, more than fifty percent of DO concentration distribution is between 7.79 mg/L to 8.63 mg/L. The high concentration of DO might be influenced by the turbulent flow of the water inlet. More oxygen dissolves into water when turbulence caused by the stacked granite at the water gate brings more water into contact with the air.

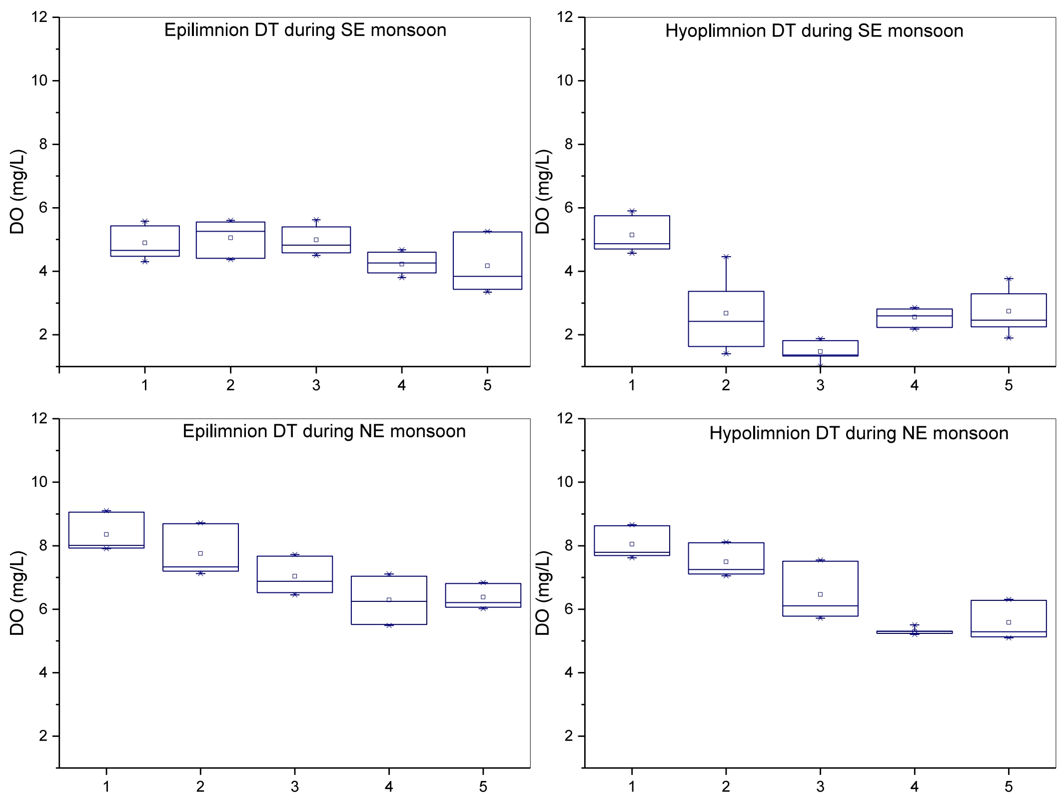

Figure 5-6: DO distribution in 5 sampling points in DT during SE monsoon versus NE monsoon

DO concentrations can be observed to be high during NE monsoon compared to SE monsoon (Figure 5.7). This is probably during SE monsoon the waterbody does not disturb by rainy event or by strong wind which resulted in more productive water. Besides that the decomposition of the dead organisms also more efficient and the continued microbial decomposition eventually results in oxygen deficient water. The highest DO measured during SE monsoon was in sampling point 2, where the concentration in epilimnion is 5.83 mg/L and 4.40 mg/L in the hypolimnion. This is probably because sampling point 2 is located near the water inlet. The flowing water at the inlet may results the point of sampling to have high dissolved oxygen content than the other sampling points because the turbulence that resulted by the flowing water bring the air and water into contact. In contrast, the high concentration of DO during NE monsoon might be influenced by the series of rainy event that caused turbulence in the water body due to flushing from water inlet and surface water runoff. The highest DO during NE monsoon was measured in sampling point 3 for the epilimnion layer; 9.24 mg/L and sampling point 2 for the hypolimnion; 6.96 mg/L.

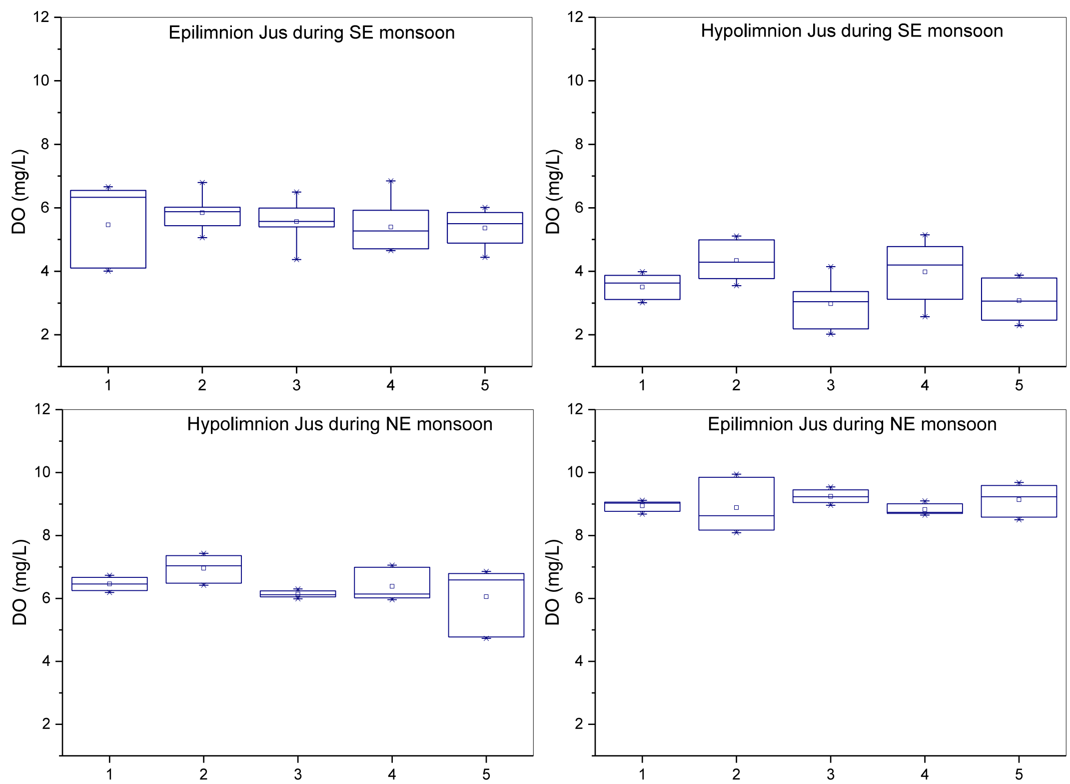

Figure 5-7: DO distribution in 5 sampling points in DT (above) and Jus (bottom) during NE monsoon

TP concentration distributions during the SE monsoon and NE monsoon for DT are shown in Figure 5-8. TP concentration distribution during NE monsoon was observed to be slightly higher than TP concentration distribution during SE monsoon. During SE monsoon, TP was found to be at a maximum in sampling point 5 for the epilimnion layer. The concentration distribution was between 1.28 mg/L to 8.25 mg/L. Sampling point 5 was located near the neighbourhoods which possesses a mini zoo. Animal wastes were believed to be one of the major contributors of high TP concentration at this sampling point. However, there was no physical discharge into the reservoir found during the sampling activities. It was believed that surface water runoff is the major source of nutrient loading that carries the nutrient to the water column during rainy events in addition to infiltration. On the other hand, the highest TP concentration distribution in hypolimnion was found in sampling point 1. The minimum TP concentration in the sampling point was 3.74 mg/L while the maximum concentration was 8.27 mg/L. The high amount of PO4 was believed to come from the sediment. Inlet water that creates turbulent water may be one of mechanisms which releases dissolved phosphate from sediment into the water column. In contrast, during the NE monsoon, the maximum of TP concentration distribution was found in sampling point 1 for both layers. More than half of the distributions are between 14.01 mg/L to 16.99 mg/L in epilimnion while in the hypolimnion; the concentration varies from 9.51 mg/L to 10.33 mg/L. The water inlet might contain high concentrations of TP which contributes to the maximum of TP content in this sampling point.

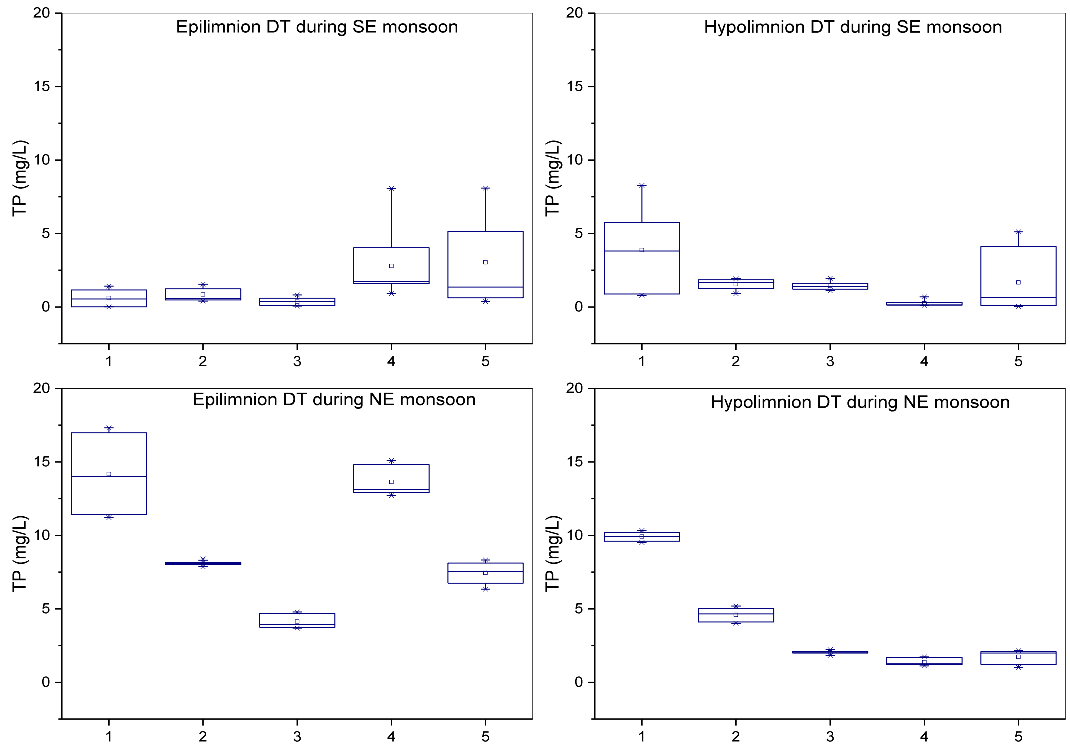

Figure 5-8: TP distribution in 5 sampling points in DT (above) and Jus (bottom) during SE monsoon

TP concentration distribution trend in Jus in both seasons more or less is the same (Figure 5-9). However, TP concentration distribution during SE monsoon was observed to be slightly higher than TP concentration distribution during NE monsoon. This may be due to the release of phosphate from the sediments into the water as can be seen from previous section that mention DO concentration was low during SE monsoon. The depletion of DO in hypolimnion layer will result in anoxic condition that leads to the release of TP from the sediments. During this season, TP was found to be maximal in sampling point 1 for the epilimnion layer with the concentration distribution of 1.29 mg/L to 5.16 mg/L whilst in sampling point 5 the hypolimnion layer with the concentration between 1.03 mg/L to 4.50 mg/L. Meanwhile, during NE monsoon, the highest TP concentration was found in sampling point 4 in both layers where more than 50 percent of the concentration distribution is between 3.32 mg/L to 3.60 mg/L in epilimnion and in the hypolimnion, the concentration distribution varies between 1.77 mg/L to 2.02 mg/L.

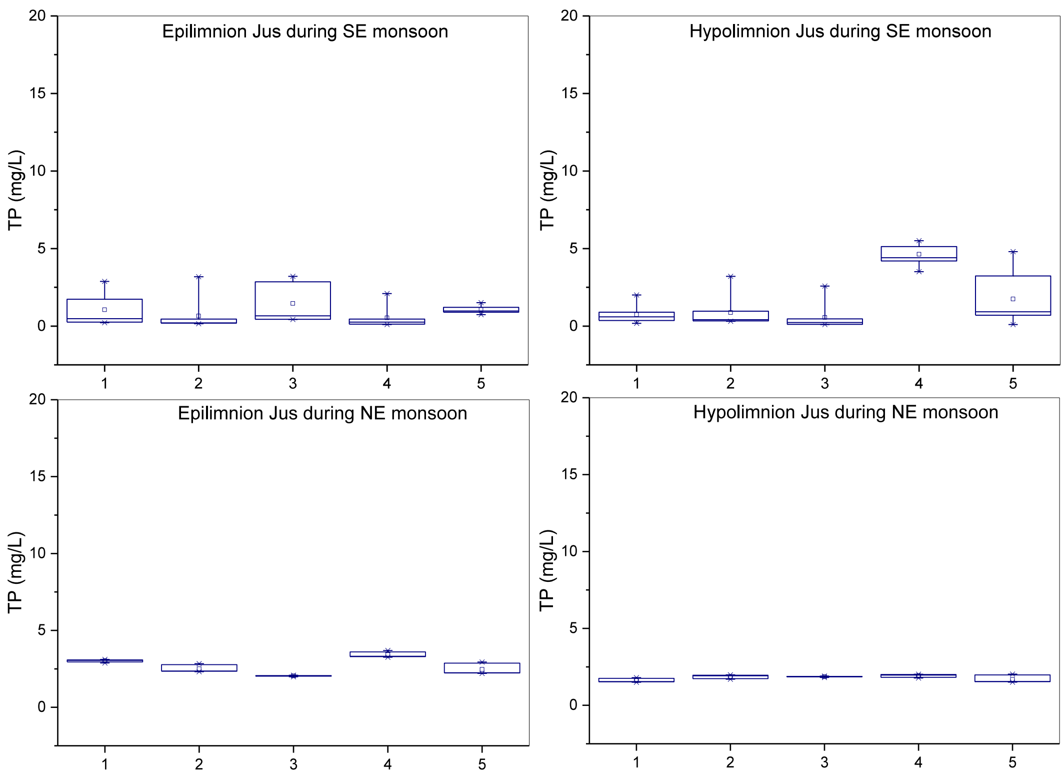

Figure 5-9: TP distribution in 5 sampling points in DT (above) and Jus (bottom) during the NE monsoon

Concentration distribution of TN for Jus during the NE monsoon was slightly higher than measured in SE monsoon as can be seen in Figure 5-10. During SE monsoon, sampling point 3 was found to contain the highest amount of TN in the upper layer of the reservoir with a mean concentration of 1.71 mg/L. However, it contains the lowest mean concentration in its bottom layer which is 0.26 mg/L. The low TN concentration might be caused by the denitrification process in the bottom layer which has the potential of N losses (Lewis, 2002). During the NE monsoon, the highest mean concentration of TN for both layers was in sampling point 1 which was 3.17 mg/L of TN in the epilimnion and 1.43 mg/L of TN in the hypolimnion. The concentration was high compared to the TN concentration measured at the same sampling point during the SE monsoon as the average concentration was 0.45 mg/L for both layers.

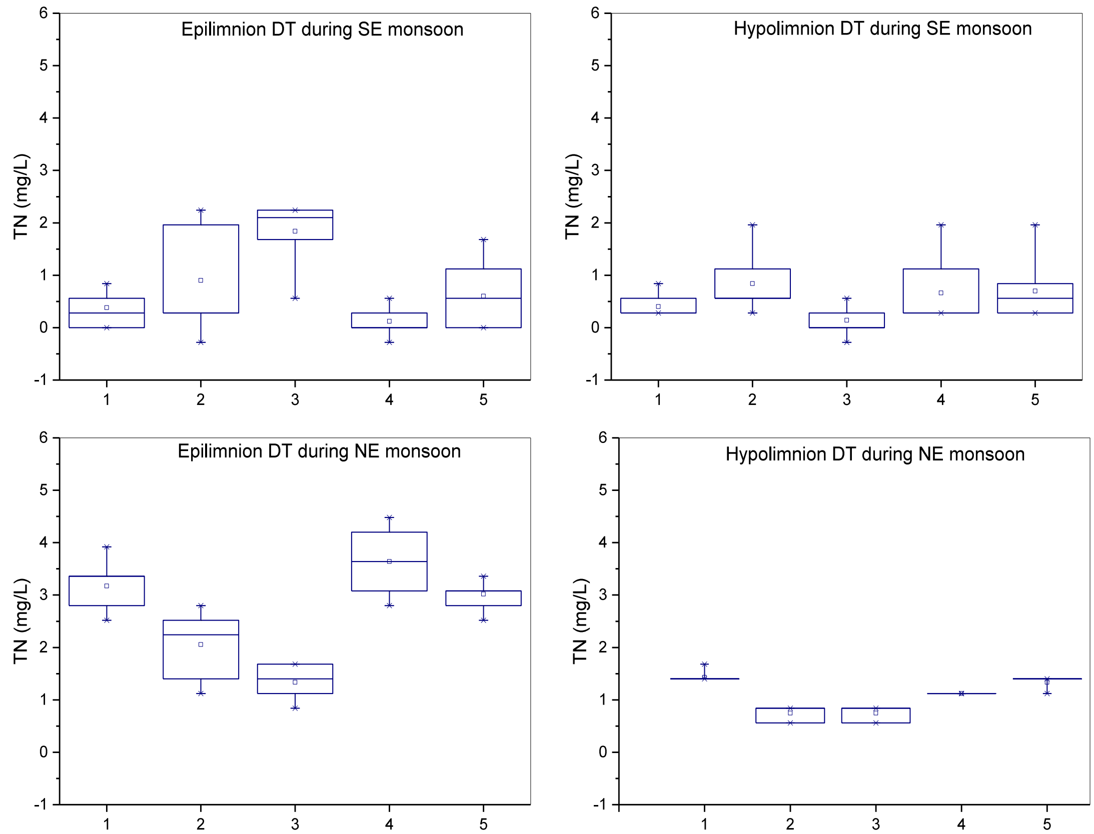

Figure 5-10: TN distribution in 5 sampling points in DT (above) and Jus (bottom) during SE monsoon

As been observed in DT, the trend of TN concentration distribution in Jus was high in NE monsoon compared to SE monsoon (Figure 5-11). This is presumably because the increased TN from the surface runoff water from the surrounding area. The highest TN concentration during SE monsoon was found at the epilimnion layer in sampling point 4 with an average concentration of 1.06 mg/L. The sampling point is located at the arm of the reservoir where the land uses of surrounding area are the mixture of forest and palm oil estates. Meanwhile hypolimnion layer in sampling point 5 contain the highest concentration of TN with an average concentration of 2.61 mg/L. During NE monsoon, the highest TN concentration was found in sampling point 1 for both layers. The average concentration was 1.49 mg/L of TN in the epilimnion and

1.28 mg/L of TN in the hypolimnion. The source of TN was suspected from the external source because sampling point 1 was located near the water inlet.

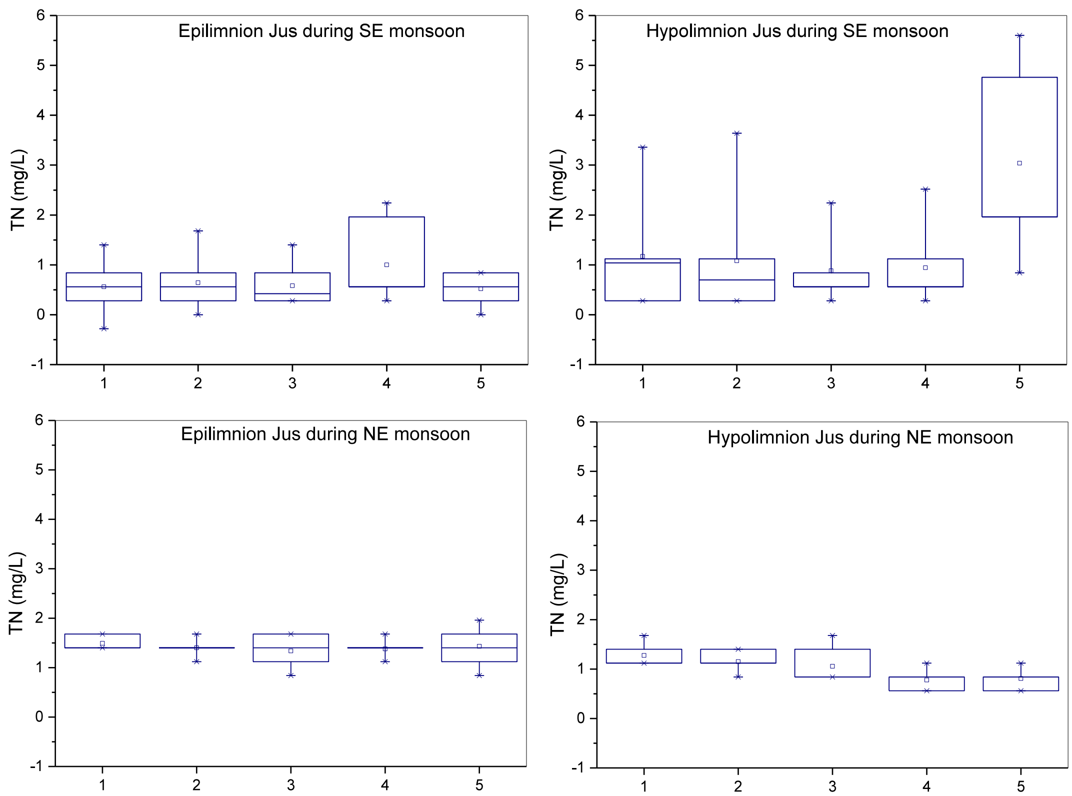

Figure 5-11: TN distribution in 5 sampling points in DT (above) and Jus (bottom) during NE monsoon

5.3.3 Water quality difference in SE monsoon and NE monsoon

An independent samples t-test was conducted to compare several parameters during SE monsoon and NE monsoon (Table 5.8). From the result, can be seen that there was a significant differences in the scores for Chl-a and DO for both reservoirs during SE monsoon and NE monsoon where the t-test is significant at $P < 0.01$. From the positive value show on the t-test, Chl-a was high during SE monsoon compared to NE monsoon. It is possible that these results are due to the calm weather which makes the waterbody undisturbed thus resulted in high productivity of the algal biomass. Meanwhile, the negative t-value on t-test indicates the direction of the differences which shows that DO was high during NE monsoon compared to SE monsoon. The series of rainy event during this season might result in flushing that cause turbulence in the waterbody thus increased dissolved oxygen concentration. Significant differences also been observed in TP, PO_4, TN and NH_3-N for DT reservoir between SE monsoon and NE monsoon but not in Jus reservoir. It seems possible that these results are due to the difference in morphology and the land use category between both reservoirs. Overall, these results indicate that more differences were observed between SE monsoon and NE monsoon rather than similarities which conclude that climate are one of the important factors in the development of algal biomass in the waterbody.

Table 5-8: Difference between SE monsoon and NE monsoon

	SE		**NE**		**T-test**	**P-value**
	Mean	**SD**	**Mean**	**SD**		
Chl-a DT	33.44	13.37	14.74	2.60	4.31	0.000
Chl-a Jus	19.14	9.11	6.56	4.14	3.97	0.001
DO DT	3.86	1.34	6.87	1.04	-5.61	0.000
DO Jus	4.50	1.06	7.70	1.40	-5.78	0.000
TP DT	2.04	1.59	6.72	4.75	-2.95	0.009
TP Jus	2.51	0.33	2.23	0.60	1.27	0.220
PO_4 DT	0.78	0.60	5.65	4.68	-3.26	0.004
PO_4 Jus	1.06	0.41	1.06	0.31	0.02	0.987
TN DT	0.72	0.43	1.86	1.06	-3.18	0.005
TN Jus	1.02	0.61	1.21	0.26	-0.92	0.372
NH_3-N DT	0.34	0.11	1.21	0.84	3.27	0.004
NH_3-N Jus	1.02	0.61	0.68	0.26	1.64	0.118

5.3.4 Relationship between Chl-a and water quality parameters

Table 5-9: Spearman's rank correlation coefficient between variables in DT and Jus during SE monsoon and NE monsoon (* p=0.05; ** p=0.01)

	pH	Turbidity	DO	Temp	PO4	TP	NH3	TKN
Chl-a DT SE	-0.112	-0.74	0.415**	0.151	0.55	0.327**	-0.159	-0.172*
Chl-a Jus SE	0.103	0.089	0.195*	0.230*	0.295**	0.285**	-0.074	-0.196*
Chl-a DT NE	-0.224	-0.351	0.375*	-0.577	0.314*	0.307*	0.458**	0.547**
Chl-a Jus NE	0.165	0.03	0.440**	0.17	0.631**	0.711**	0.551**	0.348**

The results reported in Table 5.9 indicate the strength of the correlation between Chl-a dynamics with the measured parameter in DT and Jus at a significant level of 0.01 and 0.05. The correlation between Chl-a and the nutrient is important in order to support the hypothesis four as it can determine whether N is more feasible to be managed. Based on the results shown, Chl-a during the SE monsoon and the NE monsoon had a different response when compared with water quality. There was no single correlation between Chl-a, pH, turbidity and temperature found in both reservoirs for both seasons except for temperature in Jus during the SE monsoon which positively correlated with Chl-a. However the correlation was weak with the correlation coefficient of 0.230. TP was observed to be correlated positively with Chl-a in both seasons which means increasing TP will increase Chl-a concentration. The correlation was weak in both reservoirs during the SE monsoon (where correlation coefficient for DT is 0.327 and Jus 0.285) but strong in Jus (correlation coefficient; 0.711) during the NE monsoon. Weak correlation between TP and Chl-a was found in DT during NE monsoon with the correlation coefficient 0.307 which is lower than the correlation found in DT during the SE monsoon. Besides

TP, positive correlation also found between DO and Chl-a in both seasons where the increase of Chl-a resulted in the rise of DO concentration. Contrast with TKN which only shows positive correlation with Chl-a in the NE monsoon but negatively correlated with Chl-a during the SE monsoon.

5.3.5 Nutrient loading

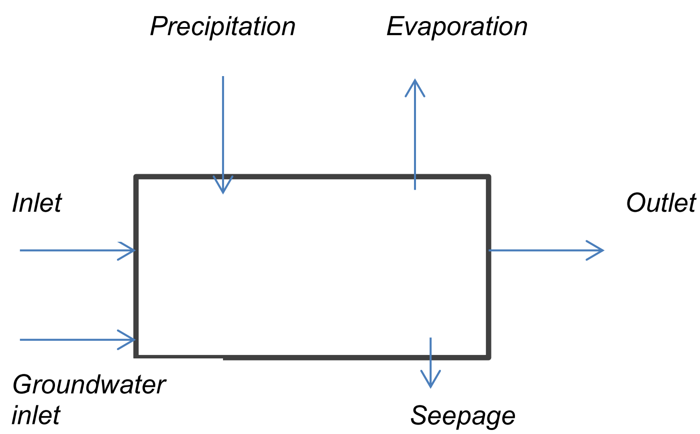

Figure 5-12: Water budget of DT and Jus

Both reservoirs only depend on one direct inflow (i.e.; DT was drawn from Malacca River system) and few indirect intakes such as surface runoff and precipitation. The inlet and outlet water discharge were measured using Global Water Flow Probe and water sample also collected for P and N analysis. The water budget for both reservoirs is shown in Figure 5-12. Direct nutrient input or output was estimated by utilizing the discharge and chemical concentration that collected at the water inlet (L_i) and water outlet (L_o). The general equation (equation 5-4) is as follow (Ismail and Najib, 2011);

$$L = C \times Q \qquad (5\text{-}4)$$

Where;

C = concentration of pollutant (mg/L)
Q = water inlet discharge (m^3/s)

On the other hand, non-point source nutrient loading was estimated from consideration of P and N export coefficients (kg/ha.yr) from soils, atmospheric deposition and per capita discharge of sewage. Because of the limited information for nutrient export rates, data from other literatures from Malaysia as shown in Table 5-10 were used. P and N export coefficient from agricultural land (mixed crop) and vacant land were adopted from Eisakhani et al. (2009). This is because the nutrient export coefficient was derived from mixed vegetables and tea planted land have the similarities with DT and Jus land cover that having planted with mixed vegetables and fruits. Besides that, P and N export coefficient for oil palm also taken from Corley and Tinker (2008). The coefficients were derived from the study of nutrient loss from oil palm through surface runoff in Malaysia. Nutrient export coefficient of dissolved and undissolved nutrient from forested catchment in Peninsular Malaysia was also used in this study (Yusop, Douglas and Nik, 2006). Meanwhile, the nutrient export from residential areas is adopted from domestic sewage characteristics which are expressed in gram per capita per day (g/ca.d). The population in the residential area was estimated by multiplying the population per square kilometer with the residential area. The population per square kilometer data was retrieved from the World Bank database which use spatial resolution of 100 m^2 (The World Bank, 2014). The atmospheric deposition was calculated by using equation 5-5 (Sundarambal et al., 2010). The concentration of P and N were measured from the collected rainwater near the reservoir. Meanwhile, the precipitation rate (m/day) and the total of rainy days data were obtained from Malaysia Meteorological Department.

$$F_{wet} = 1000 \times C_{rain} \times P_{rate} \qquad \text{(equation 5-5)}$$

Where;

F_{wet} = Wet deposition ($mg/m^2/day$)
C_{rain} = Concentration of nutrient (P and N) (mg/L)
P_{rate} = Precipitation rate (m/day)
1000 = Unit conversion

The equation used to calculate the nutrient input which includes point source and non-point source is as equation 5-6 (Reckhow, Beaulac and Simpson, 1980);

$$M_{in} = (Ec_{ag} \times Area_{ag}) + (Ec_{f} \times Area_{f}) + (Ec_{o} \times Area_{o}) + (Ec_{a} \times Area_{b}) + (N_{p} \times Area_{r}) + L_{in} \quad (5\text{-}6)$$

Where;

Ec_{ag} = Export coefficient for agricultural land (kg/ha/yr)
Ec_{f} = Export coefficient for forest land (kg/ha/yr)
Ec_{o} = Export coefficient for others type of land (kg/ha/yr)
Ec_{a} = Export coefficient of atmospheric precipitation (kg/ha/yr)
N_{p} = Export coefficient from sewage (g/ca.d)
$Area_{ag}$ = Area of agricultural land (ha)
$Area_{f}$ = Area of forest land (ha)
$Area_{o}$ = Area of other types of land (ha)
$Area_{b}$ = Area of basic (ha)
$Area_{r}$ = Area of residential (ha)
L_{in} = Direct nutrient input

Table 5-10: Nutrient export coefficient

Land cover	**P export (kg/ha.yr)**	**N export (kg/ha.yr)**
Agricultural (mixed crop)*	12.11	41.02
Agricultural (oil-palm)**	0.7 - 1.1	4.5 - 7.2
Forest***	0.1	8.1
Atmospheric deposition	0.038	0.094
Others (vacant land/grassland)*	1.02	12.91
	P export (g/cap.d)****	**N export (g/cap.d)******
Sewage	1-3	2-15

*Adopted from Eisakhani et al. (2009)
** Adopted from Corley and Tinker (2008)
***Adopted from Yusop, Douglas and Nik (2006)
****Adopted from The World Bank (2014)

To obtain the nutrient loading for residential, the average of P or N export (g/cap.d) was multiplied by population in the residential area (ca). Nutrient loading for direct water inlet was calculated by multiplying inlet water discharge with P or N concentration. On the other hand, nutrient loading for agricultural (mixed crop) was calculated by multiplying the nutrient export coefficient (refer Table 5-9) with the land cover area (refer Table 5-4). The same calculation also applies to obtain nutrient loading for agriculture (oil palm), forest and others (vacant land/grassland). Meanwhile nutrient loading for atmospheric deposition can be calculated by multiplying the P or N export coefficient with the area of DT and Jus reservoir.

Nutrient retention in the reservoir can be estimated by subtracting the total input and total output and the equation is as equation 5-7 (Ismail and Najib, 2011);

$$R = M_{in} - M_{out} \qquad (5\text{-}7)$$

Where;
R = Nutrient retention (kg/month)
M_{in} = Nutrient in (kg/month)
M_{out} = Nutrient out (kg/month)

The results of nutrient loading and nutrient retention for both reservoirs during the SE monsoon and the NE monsoon are shown in Table 5-11 and Table 5-12. The nutrients output were calculated by using equation 5-4. The data of nutrient concentrations and flowrate output were measured at the intake in the water treatment plant. From the results, both reservoirs seem to receive high TP input from the point source which draws from the river basin. In contrast with TN loading, diffuse sources especially agricultural land contributed to high TN in both reservoirs. Because of the limited data, the estimation of diffuse sources for both nutrients is the same between the SE monsoon and the NE monsoon. However, the difference of the nutrient loading can be observed from point source which shows both reservoirs received high nutrient loading in the NE monsoon compared to the SE monsoon. The total input for both reservoirs in both seasons was higher compared to total output which retained a large amount of nutrient monthly.

Table 5-11: Nutrient loading and retention in DT during SE monsoon and NE monsoon

Nutrient	SE		NE	
	TP (kg/month)	TN (kg/month	TP (kg/month)	TN (kg/month)
Residential	46.03	195.61	46.03	195.61
Direct water inlet	5688.63	1022.18	5821.95	1377.71
Total nutrient input from point source	**5734.66**	**1217.79**	**5867.98**	**1573.32**
Agriculture – mixed crop	1826.59	6187.18	1826.59	6187.18
Agriculture – Oil palm	97.2	631.8	97.2	631.8
Forest	1.21	97.88	1.21	97.88
Atmospheric deposition	1.84	4.54	1.84	4.54
Others	4.25	53.79	4.25	53.79
Total diffuse nutrient input	**1931.09**	**6975.19**	**1931.09**	**6975.19**
Nutrient output	4482.29	3955.37	5555.3	4266.47
Nutrient retention	3183.46	4237.61	2243.77	4282.04

Table 5-12: Nutrient loading and retention in Jus during SE monsoon and NE monsoon

Nutrient	SE		NE	
	TP (kg/month)	TN (kg/month)	TP (kg/month)	TN (kg/month)
Residential	32.38	137.62	32.38	137.62
Direct water inlet	1328.16	184.1	1591.6	591.75
Total nutrient input from point source	**1360.54**	**321.72**	**1623.98**	**729.37**
Agriculture – mixed crop	267.43	905.86	267.43	905.86
Agriculture – Oil palm	66.45	431.93	66.45	431.93
Forest	2.93	237.6	2.93	237.6
Atmospheric deposition	1.69	4.19	1.69	4.19
Others	17.43	220.55	17.43	220.55
Total diffuse nutrient input	**355.93**	**1800.13**	**355.93**	**1800.13**
Nutrient output	973.11	736.4	1643.76	1091.46
Nutrient retention	743.36	1385.45	336.15	1438.04

The measured mean annual lake P concentration also been compared with Vollenweider model that has been modified by Foy (1992) as shown in Table 5-13. Vollenweider model was developed by the assumption that the changes in P concentration in lake is equal to the P concentration added to lake minus the loss through sedimentation and outflow (Jorgensen and Fath, 2011). However, the equation was then improved by Foy (1992) to be able to be used by the lakes that have water retention less than 1 year. Water retention for DT and Jus is less than a year where 72 days for DT and 102 days for Jus. Thus, equation 5-8 was used to calculate the value in Table 5-13;

$$Mean\ annual\ lake\ P\ concentration\ (\mu g.L^{-1}) \quad = \frac{P_{in}}{1+\sqrt{t_w}} \qquad (5\text{-}8)$$

Where;

P_{in} = Mean inflow P concentration (µg/L)
T_w = Water retention time (years)

Table 5-13: Measured Annual P concentration versus Vollenweider model

Reservoirs	Mean Annual P concentration (µg/L)	
	Measured (µg/L)	Vollenweider model (µg/L)
DT SE	1830	886.52
DT NE	6715	907.30
JUS SE	1840	660.50
JUS NE	1545	791.29

5.4 Discussion

From the Carlson's Trophic State Index (TSI), both reservoirs are undergoing a eutrophication process whereas DT shows a higher degree of water contamination compared to Jus. Both reservoirs can be categorized as eutrophic during the SE monsoon and the NE monsoon on the basis of secchi depth, Chl-a concentration and TP concentration. There was no significant relationship between TSI (SD) and TSI (Chl-a) observed in both reservoirs because when secchi depth is at a minimum, Chl-a can sometimes be minimal or maximal. The results disagree with findings in other tropical waterbodies such as those reported by Janjua, Ahmad and Akhtar (2009) and Offem et al. (2011) which found that when secchi depth was at a minimum level, the highest Chl-a was recorded. This suggested that the minimum secchi depth in both reservoirs might be due to non-algal turbidity which probably is controlled by the phytoplankton population since the abundance of macrophytes from the group of *Nelumbo nucifera sp.* (Figure 5-13) and *Mimosa pudica sp.* (Figure 5-14) were observed in DT during the sampling event. This result showed that secchi disk visibility may not always be acceptable as an index of high productivity because other factors such as primary production, the amount of suspended material and the amount of colored matter in the lake might influence the secchi depth value (Hakanson and Boulion, 2001). Besides that, TSI (TP) is always greater than TSI (Chl-a) which means algae will not response rapidly with the increasing or decreasing of P because P are in excess of demands by phytoplankton. According to Carlson (1991) which interpret the relationships between trophic state variables, they noted that P will be limiting nutrient to algal growth when TSI (Chl-a) is equal to or greater than TSI (TP). However, when TSI (Chl-a) is significantly lower than TSI (TP), this indicates that algae does not solely depends on the availability of P. Therefore, it can be concluded that some factor other than P is limits the algal biomass in both reservoirs.

Agricultural land such as dragon fruit farms, oil palm plantations and rubber estates dominate the catchment area in DT; whilst, the combination of oil palm plantations and forest were the major land cover surrounding the water catchment in Jus. The design of the land use is believed to be the main contributor that resulted in high TP concentration in DT and Jus because nutrient contamination from agriculture is the second most important contributor to freshwater pollution (Puckett, 1995). P which is generally bound to soil particles may enter waterbodies through surface runoff, therefore, increasing the TSI (TP) values during the NE monsoon (Dodds, 2002a). Besides the increment of the TP during high intensity of rainfall event, the rainfall also flushes away the phytoplankton which results in low TSI values for Chl-a.

Figure 5-13: *Nelumbo nucifera sp*. in DT

Figure 5-14: *Mimosa pudica sp.* in DT

Seasonal variation in the distribution of Chl-a in the surface water of the study area was found to be maximal during the SE monsoon. Based on the results shown in the previous section, Chl-a in DT and Jus had different responses towards the water quality variables during the SE monsoon and the NE monsoon. Variations in the water quality variables were commonly associated with the fluctuation in algal biomass as reflected by the Chl-a concentration data. Supersaturated concentrations of DO corresponds to maximum concentration of Chl-a and vice versa because of the oxygen production as a result of photosynthesis by the algae. This was manifested by the regression result for both reservoir during NE and SE monsoon where DO concentration was found to be increased correspond to the increase of Chl-a. However, mean Chl-a concentration is higher in the SE monsoon compared to the NE monsoon but contrasted with mean of DO concentrations which are lower in the SE monsoon compared to the NE monsoon. This situation probably occurred because of the rapid rate of bacterial decomposition in tropics reduce the DO level in SE monsoon as more algae and plants grow, the more will die (Osborne, 2012). Moreover, measurements were carried out in the morning for both seasons when oxygen production by algal biomass has not yet compensated its nocturnal consumption (Wang et al., 2007). Nevertheless, high DO level in NE monsoon which was caused by strong winds might be one of the reasons that differentiate the DO level with the SE monsoon. This is because strong winds no doubt will create turbulence on the surface water and result in more oxygen being absorbed into the water.

During the wet season, the rainfall intensity was abundant. Water enters the water body directly by wet deposition and indirectly by surface runoff. The inflow of high volumes of water during rain events can lead to a reduction of algal biomass due to high flushing rates. The effect of the rainy season on annual rain off patterns is significant in tropical settings, since the period of maximum algal production in tropical lakes and reservoirs often takes place one or two months after the rainy season (Ryding, Rast and Unesco, 1989). Thus it is expected that the peak of eutrophication in both reservoirs appears during dry season. This has been demonstrated in this study when Chl-a was found to be high compared the amount measured during wet season.

The measurement of epilimnion and hypolimnion were made because both reservoirs are categorized as deep reservoirs which have the potential to be stratified. Epilimnion layer was measured because this is where most of the primary production happens. Meanwhile samples taken from the hypolimnion are necessary to access hypolimnetic oxygen depletion and phosphorus regeneration from the bottom sediments. In this study, there is not much difference between mean concentration of the parameters in epilimnion and hypolimnion layer except for Chl-a and DO. Chl-a concentration was high in epilimnion layer compared to hypolimnion layer because the light penetration was abundant on the surface of the water as light was the primary factor affecting the photosynthesis productivity. DO in epilimnion higher in concentration compared to hypolimnion due to the high amount of Chl-a in the epilimnion as oxygen was the product from the photosynthesis process.

DT and Jus have the same condition in the way they receive light, the average temperature and mean rain intensity caused by the same climatic conditions. Thus the factor that differentiates them is the reservoir morphology and its catchment area. The higher catchment area to reservoir ratios, the higher the nutrient concentrations in the reservoir which leads to more productivity inside the water bodies (Nõges, 2009). This finding is consistent with the statement that catchment area to reservoir ratio in Durian Tunggal reservoir (7:1) is higher than Jus reservoir (4:1). Thus it can be observed from the results in the previous section which found that more productivity was occurring in the DT compared to the Jus. This is because more land is draining into the water body. When watersheds are disturbed, they will transport more sediment, nutrients and other pollutants to the water body.

A positive relationship between Chl-a and TP in both seasons showed the dependence of algal biomass on this nutrient. However, the TP concentration in the NE monsoon is higher than in the SE monsoon. The increase of TP concentration especially in the epilimnion layer during the NE monsoon could be due to the intense rainy event from October 2013 to January 2014 that washes off the nutrients from the land into the waterbodies. The high loading of

TP could be attributed to the agricultural land alongside the lake. Conversely in the SE monsoon, the TP was high in the hypolimnion layer especially in the area where there was an abundance of macrophytes from the group of *Nelumbo nucifera sp.* and *Mimosa pudica sp.* observed. Low DO concentration in the hypolimnion during SE monsoon might be the reason for high in-lake TP because low DO concentration stimulates the P in bottom sediment especially under dense macrophytes beds to release and diffuse back to the water column (Harper 1992).

A more complex relationship was found between algal biomass and N species – i.e., a positive and significant correlation between both variables was found during the NE monsoon, but on the contrary, a negative correlation was found during the SE monsoon. Lower concentrations of TN in the water column during the SE monsoon can be correlated with a higher primary productivity and the subsequent biological N uptake. During the NE monsoon, biological N uptake was less evident, which contributes to maintain higher concentrations of N species in the water column and to a lower accumulation of N in the sediments from dead biomass. However, TN concentration in both seasons was relatively lower when compared with TP, which may suggests that TN is acting as the limiting nutrient. The conclusion is drawn based on the Liebig's minimum law which states that the growth rate of plant is determined by scarce nutrients (Jorgensen and Fath, 2011). On the other hand, the ratio of TN to TP in both Durian Tunggal reservoir and Jus reservoir is below the ideal ratio of 7.2:1 by mass cited in Ryding, Rast and Unesco (1989).

The possible explanation of the N limitation is low external supply of N as tropical rainforests climate export very little N into stream waters because of the losses of N from nitrification and denitrification (Houlton, Sigman and Hedin 2006). Besides that, high internal loss of N due to denitrification at the bottom layer also might be the reason for N limitation. This is because higher temperatures contribute to the rapid rate of bacterial decomposition in the tropics which is much faster than temperate water (Bot and Benites, 2005). N limitation occurs due to largely or greater application of phosphate fertilizers to the pastures as can be seen in both reservoirs where most of the land use was used for agriculture purposes. The P that is deposited as sediment during the wet season is resuspended during the dry season resulting in decreasing TN:TP ratios.

The point source of nutrient that is estimated from the river discharge to the reservoir was enriched with TP compared to TN. This suggested that the intensive human impact on the river basins such as disposal of domestic and industrial wastewater leads to high inputs of phosphorus to the river which then contributed in nutrient enrichment in the reservoir. This is because for domestic loads, the resident only need to comply with Water Act, 1920 (Amendment 1989) which states that all house need to have their own sewage system or engage with the third party to treat their sewage (Waters Act, 2006). There is no parameter limits that need to be comply by the resident because the discharge limits only enforce to the industrial discharge. Household products such as cleaning products (laundry, dishwashing and bathroom) and personal care product (e.g., shampoos, shower gel and toothpastes) are the main source of TP in the domestic wastewater (Tjandraatmadja et al., 2010). This might reflect on inadequate wastewater treatment facilities for many areas near the river basin. Moreover, there is no regulation restricting the P content in the detergent as well as limiting the discharge of P in Malaysia receiving water.

In contrast, high amounts of TN loading was coming from diffuse sources compared to direct sources where agricultural land contributed the most. TN from agricultural land usually comes from chemical fertilizers or animal manure which is commonly applied to crops to add nutrients (Bothe, Ferguson and Newton, 2006). The high TN input that estimated from agricultural land in DT and JUS might be a result of improper agricultural management practices and the failure to incorporate the fertilizer with the soil which later permits the exposure of the fertilizer to the surface runoff. Direct point source which comes from the river basin also contributed to high amount of TN input to both reservoirs. However the amount is much lower compared to

TP generated by these sources. This is might because N accounted to less in domestic and industrial wastewater near the river basin.

Nutrient retention is the amount of the nutrient that is retained within the waterbodies without being exported by the outflow (Kronvang et al., 2004). TP retention in lakes determined by the water residence time where long hydraulic residence time, trap less P than the short hydraulic residence time (Prairie, 1989; Brett and Benjamin, 2008). Water residence time (Ʈ) can be calculated by dividing the volume of water stored in the reservoir (V) by the volumetric flowrate (Q) (Rueda, Moreno-Ostos and Armengol, 2006). In this study, water residence time in Jus (102 days) was much longer compared to DT (72 days) which might have resulted in high TP retention in DT compared to Jus. Besides that, TP retention in both reservoirs is high during the SE compared to TP retention during the NE monsoon which corresponds with earlier findings by Brett and Benjamin (2008) which state that TP retention is at peak when the lake is stratified. This is because when the lake is undisturbed, more TP is settling down on the sediment which means less TP is transported with the outflow. High TP concentration in lakes also was influenced by non-point source TP loading. This is because the measured mean annual TP in the lakes also does not balance with the calculated Vollenweider model. In this study, the Vollenweider model was calculated based on the TP concentration in lake is equal to TP concentration added to lake through direct water inlet. Therefore, the excess TP in the measured value is probably comes from the non-point source which the amount is not included in the calculation.

On the other hand, TN retention seems to be high during the NE monsoon compared to the SE monsoon. This is because N retention increases with N loading in waterbodies as has been documented by Jansson et al. (1994); Fleischer et al. (1994); Saunders and Kalff (2001). In contrast with TP retention, longer hydraulic residence time in lakes promotes TN retention processes such as denitrification and sedimentation. With shorter residence time, the loss of organic N via outlet will increase resulting in a decrease of TN retention (Windolf et al., 1996; Berge et al., 1997). This might be the reason for high TN retention in Jus.

5.5 Conclusion

This study took place in two different seasons, the Southeast Monsoon (dry season) and the Northeast Monsoon (wet season) in order to monitor the effect of the changing season on the water quality. From the study, the results collected in DT and Jus shows that both reservoirs are currently undergoing a eutrophication process which is expected will be severe if there is no action been taken. The trophic state shows that both reservoirs have eutrophic productivity. In this study, the relationship of Chl-a concentration is directly proportional to turbidity, DO, organic P and TP. The nutrients found to be high during the NE monsoon compared to the SE monsoon which might be related to the high intensity of rainfall that carries the land nutrient to enter the reservoirs. Besides that, the algal growth in both reservoirs appears to rely upon N rather than P as the N:P ratio found was lower than 7:1. Therefore, this study reports evidence towards the hypothesis that freshwater reservoirs in tropical regions do not respond in a similar way to those in temperate climate regions. It also can be concluded that the high nutrient loading to both reservoirs is caused by the human activities nearby the water catchment. As a consequence the nutrient retention was also high which resulted in high productivity in the reservoirs.

As nutrient loading to the reservoirs increases as a result of human activities, the need to mitigate the resulting impact is becoming more and more important especially for the drinking water reservoir. Because most of the nutrient loading in both reservoirs comes from the point source, it is much easier to control. However, agricultural land near the water catchment also contributed to the high nutrient loading and unfortunately it is well known that nutrient coming from this source is difficult to control. Hence, the selection of mitigation measures that are most suitable to reduce the nutrient loading and eutrophication for both reservoirs will be suggested in next chapter.

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CHAPTER 6

Evaluation of eutrophication management framework

Chapter 6 : Evaluation of eutrophication management framework

6.1 Introduction

The observations from the reservoirs in previous chapters indicated that immediate steps had to be taken to reduce the concentration of nutrients entering the DT and Jus. The investigation revealed that the major contributing factor causing this condition comes from the inlet river (Malacca River system) that goes into the reservoirs based on the measured water inlet in DT and Jus which found high in P and N concentration. The drainage had caused high nutrient in the reservoirs which resulting in eutrophic productivity according to trophic state index. Macrophytes were observed to dominate the surface of the reservoirs where epilimnion layer is situated. Decomposition of organic matter from the macrophytes might increase the available nutrients in the hypolimnion layer. Because both reservoirs are drinking water reservoirs, the management goal must be to aim to reduce the trophic state to at least mesotrophic conditions to be tolerable for use. This is because eutrophic water increases the cost of water treatment due to frequent filter backwashing, frequent clarifier desludging and additional treatment for odour and taste removal.

Extensive attempts in reducing eutrophication and algal blooms in waterbodies have been trialled in developed countries for the past few decades. A few management tools to support decision making were developed by the researchers and organizations in question, generally aiming to reduce the eutrophication and algal bloom problem especially for temperate systems. A few of the recognizable tools that are widely used to support decision making are modelling, Decision Support System (DSS) and Cost Benefit Analysis (CBA). Models are built to encompass the entire knowledge about the system from synthesis, rationalisation and observation of the behaviour of the system under controlled conditions (Jorgensen and Fath, 2011). There are many studies that used modelling to support the management of the aquatic system by using different types of model such as physical models, empirical models and computational models. The modelling of the aquatic system gives at least three good reasons which are better understanding of the system, improved management and prediction of the incidence of algae (Atanasova et al., 2006).

Another useful tool that was popular between the researcher and decision maker are Decision Support Systems (DSS). DSS are information systems that are designed to interactively support all phases of the user in the decision making process (Forgionne, 2002). A few examples of support that are provided by DSS are high level programming languages, simulation languages, database management, financial modelling, and statistics (VanSchaik and Sol, 1990). Another important tool that helps in decision making processes is Cost Benefits Analysis (CBA). CBA provides better understanding of the implications of a decision by estimating the overall benefits and the cost by comparing all the positive and negative elements of the proposed methods or techniques (Arrow et al., 1996). Therefore, the selection of the most preferable option can be made either by; a) comparing the cost benefit ratios of the proposed programme and level of expenditure; b) comparing the absolute values of the expected benefits of the programme using a fixed level of monetary and other resources; and c) determining the minimum cost for the proposed programme for achieving a specific water quality goal (Jorgensen et al., 2005). A few examples of using CBA in decision making are the calculation of cost of damage caused by eutrophication in England and Wales (Pretty et al., 2003), the costs and benefits from P reduction to the Baltic Sea (Gren, Söderqvist and Wulff, 1997), cost efficiency in eutrophication control in a Dutch shallow lake (Hein, 2006), cost of N abatement in wetlands (Byström, 1998), cost of mitigation non-point source pollution (Carpenter et al., 1998a) and others.

However, these types of tools are often too costly to be considered by developing countries. For instance, DSS requires an investment in information systems in order to collect data from many sources and some of the analysis needs advanced data analysis, statistics and econometrics which are expensive to hire. Therefore, multiple criteria analysis was introduced in Chapter 4 to translate the scientific and technical knowledge into a form that can be readily used by any level of decision makers and water managers in order to protect their surface water. Meanwhile, the main objective of this chapter is to evaluate the use of multiple criteria analysis (MCA) as a supporting tool in selecting the suitable management techniques for eutrophication and algal bloom formation in tropical freshwater bodies.

6.2 Methodology

Information such as water quality, trophic status and source of pollution of the reservoirs that was gathered from fieldwork data in Chapter 5 was used in the pre-selection step. From there, the reservoirs' conditions were evaluated and whether eutrophication control or eutrophication prevention needed to be implemented. The selection of the control techniques took place after the pre-selection step. In order to select the best option for the DT and Jus reservoirs, multiple criteria analysis (MCA) was developed. Next, a scenario based approach was adopted to evaluate the MCA framework.

A scenario based approach is a technique to describe the possible future under different conditions. Scenarios are different from forecasts or predictions, as they provide a dynamic view of the future by exploring "what if" questions to explore the consequences of uncertainty (Mahmoud et al., 2009). Scenario approaches have been used by many decision makers including the US Air Force to foresee their opponent's actions in World War II (Schwartz, 1996), corporate companies such as Shell to predict the uncertainty in oil prices (Ringland and Schwartz, 1998), and even environmentalists to explore environmental impact (Sonesson and Berlin, 2003; Basset-Mens and Van der Werf, 2005; Duinker and Greig, 2007). The scenario approach used in this study works as an aid to support the MCA by providing the weight for the criteria in order to select the best control techniques in managing the eutrophication problem in the DT and Jus reservoirs.

6.2.1 Scenario development

The scenarios were developed to represent the decision of the decision maker on the specific situation. In this study, five criteria were used in the MCA. These were efficiency (C1), longevity (C2), confidence (C3), potential negative impact (C4) and cost (C5). The weight of each criterion was dependent on the decision maker because not all the criteria were always going to be equally important. The decision maker may find that one or more criteria are less important than the other. Seven scenarios with a projection time of ten years were generated in this study based on three driving forces: population growth, economic growth and land use change. The scenarios were developed to represent the potential decisions that may be made by the decision maker under the driving forces for DT and Jus reservoirs.

a) Population growth

According to data from The World Bank (2015), the population growth in Malaysia increased two percent per annum from the year 2000 to 2014. However, there was a decrease in population growth compared to 10 years before the year 2000 which shows the population growth was three percent per annum. Therefore under population growth, three scenarios were assumed in order to reduce uncertainty.

Scenario 1 assumes that the population growth near the DT and Jus reservoirs water catchment will increase more than two percent per annum. As population grows, the demand for water will increase as well as the level of waste discharge to the environment which will decrease economic growth. When the country's income that is low, the budget that is allocated for environmental conservation will also be reduced. Thus, in this scenario, it is assumed that the cost of the control techniques is the most important criterion in selecting the best option for managing the water quality problem in DT and Jus reservoirs. Besides that, the efficiency of the control techniques is also one of the most important criteria to protect the water from the growing amount of pollutant loading.

Scenario 2 assumes that when the pollutant loading to DT and Jus reservoirs increased, the eutrophication will become worse which then requires efficient techniques while at the same time low cost as suitable for a low income country. Besides that, confidence that the control technique can feasibly applied to both reservoirs is also important in order to avoid financial loss resulting from the installation of unsuitable control techniques.

Scenario 3 assumes that the population growth near DT and Jus reservoirs water catchment will remain unchanged. Therefore it is assumed that the amount of nutrient loading in DT and Jus reservoirs is the same and the eutrophication state in DT and Jus reservoir remains eutrophic. Even though the amount of pollutant loading will remain unchanged, but the eutrophication in the reservoirs will continue to grow as a result of internal nutrient loading. Therefore in this scenario it is assumed that the control techniques must produce long term effects so that they will not require reapplication which will increase operation cost. Besides that, the cost of the treatment also needs to be suitable to a low income country.

Economic growth

Economic growth in a country is measured by the country's gross domestic product (GDP) per capita per year (Auty, 2001; Cheng, 2003). GDP is the total value of all the goods and services produced in that country in one year. GDP growth can either be achieved by increasing the inputs to production such as increasing production from natural resources, increasing the productivity of the human capital and investing in capital goods (Nakicenovic and Swart, 2000). The relationship between economic growth and environmental quality is often described by the Environmental Kuznets Curve (EKC) (Everett et al., 2010). The inverted U-shape curve shows that as the GDP per capita rises with the rapid development of manufacturing, agro-based industries and other resource extraction, the rates of waste generation increases in quantity. At higher levels of development, the waste generation decreases in quantity as a result of better technology, higher environmental expenditure and increased environmental awareness through the enforcement of environmental regulations (Stern, 2004; Everett et al., 2010; Halkos, 2011). Under economic growth, two scenarios were developed;

Scenario 4 assumes that an increased in GDP growth in Malaysia will increase the pollutant loading in the DT and Jus reservoirs as a result of rapid production in the manufacturing sector and agro-based industries. As the income of Malaysia increases, the budget that can be allocated for environmental protection and conservation will also increase. Therefore, the cost of control techniques is no longer a problem for the stakeholder. In this scenario, it is assumed that high efficiency and long term techniques are the most important criteria preferred in order to handle the increased pollutant loading in DT and Jus reservoirs in the future.

Scenario 5 assumes that the GDP growth in Malaysia will remain unchanged but the pollutant loading to DT and Jus reservoirs increases as a result of rapid manufacturing and agro-based development. Therefore in this scenario, high efficiency and long term control techniques are preferred in order to reduce the pollutant loading entering the reservoirs. At the same time, the cost of control techniques is also important because of budget constraints as a result of low GDP.

b) Land use changes

Changes in land use were mainly influenced by economic development and population growth (Houghton, 1994). For example, an increase in the world's population will increase the world's food demand. Thus, this will induce the transformation of land from forest to cropland and plantations such as in Malaysia, where forest land has been reduced by 868 km^2 each year (The World Bank, 2015). The increase in agricultural activities will induce a similar incremental trend of fertilizer consumption to improve crop production which will also lead to the degradation of water quality (Johnes, 1996; Forney et al., 2001;

Foley et al., 2005). Therefore, under land use changes, two scenarios were built;

Scenario 6 assumes that there is a change in the land use pattern near the DT and Jus reservoirs' water catchment which shows increased land use for agriculture and human settlement. This no doubt will increase the pollutant loading to the DT and Jus reservoirs. Therefore, in this scenario, the longevity of the control techniques is the most important criteria for the eutrophication management in order to protect the reservoir from a high amount of pollutant loading in the future. Besides that, control techniques that have low environmental impact are important in order to minimize the side effects for the people and livestock living near to the water catchment area.

Scenario 7 assumes that there are no changes in the land use pattern near the DT and Jus reservoirs' water catchment area but that the pollutant loading keeps increasing because of increasing pesticide and fertilizer usage due to the existing agricultural land combined with climate change. In this scenario, it is assumed that the control techniques are feasible for the Malaysian climate so that they will work effectively in reducing the eutrophication in the DT and Jus reservoirs while being low cost control options.

The weight of each criteria assigned to a scenario represents the potential decision that may be made by the stakeholder according to the conditions of that future scenario. This is a linguistic variable which is then converted to a fuzzy number so as to be used in the calculation by the MCA matrix. The most important criteria selected in each scenario were weighted as 'most important' while the unselected criteria were weighted as 'fair' which then convert to 1 (most important) and 0.6 (fair) in the MCA matrix. The criteria weighted in each scenario were summarized in Table 6-1.

Table 6-1: Scenario description

Driver	Scenario	Criteria				
		C1	C2	C3	C4	C5
Population	Scenario 1	1	0.6	0.6	0.6	1
	Scenario 2	1	0.6	1	0.6	1
	Scenario 3	0.6	1	0.6	0.6	1
Economic	Scenario 4	1	1	0.6	0.6	0.6
	Scenario 5	1	1	0.6	0.6	1
Land Use	Scenario 6	0.6	1	0.6	1	0.6
	Scenario 7	0.6	0.6	1	0.6	1

6.2.2 Calculation of MCA matrix

Fifteen alternatives to control external and internal nutrient loadings were used in the MCA matrix as shown in Table 6-2.

Table 6-2: Alternatives for eutrophication and algal bloom management

Alternative	Measures	Alternative	Measures
A1	AWT	**A9**	Dilution and flushing
A2	Diversion	**A10**	Hypolimnetic withdrawal
A3	Pre-dam	**A11**	Destratification
A4	Constructed wetlands	**A12**	Dredging
A5	Law and regulations	**A13**	Sediment cover
A6	Algaecides	**A14**	Biomanipulation
A7	Nutrient inactivation	**A15**	Doing nothing
A8	Harvesting		

The MCA matrix was calculated based on equation 6-1 which was derived from the general additive value function as used by Roy (1990) and Hobbs et al. (1992) as below. Examples of the MCA matrix are shown in Table 3;

$$A_i = \sum_{j=1}^{n} S_{ij}\left(W_j\right) \qquad (6\text{-}1)$$

Where;

A_i = measures alternative;
S_{ij} = performance score of the alternative for criteria j, i=A1, . . . , n; and
w_j = weighting factors for the criteria, j=1, . . . , n;

Table 6-3 is the example of the MCA matrix calculation for Scenario 1. The MCA matrix table consists of the control techniques in the row and criteria in the column. Using equation 6-1, the total performance score was calculated by multiplying the performance score by the weight. The performance score was developed based on the systematic review in Chapter 3 and the development of the performance score was discussed in Chapter 4. The example of the calculation of total performance score is as below;

Total score for A1 = (1x1) + (1x0.6) + (0.5x0.6) + (1x0.6) + (0.25x1)
= 1 + 0.6 + 0.3 + 0.6 + 0.25
= 2.75

The alternatives are then sorted and ranked from the most feasible to the least feasible. The highest total performance score is the most feasible option while the lowest total performance score is the least feasible option.

Table 6-3: Example of a MCA matrix for Scenario 1

	1	0.6	0.6	0.6	1	Weight	Overall rank
	C1	C2	C3	C4	C5	Total	
A1	1	1	0.5	1	0.25	2.75	4
A2	0.75	0.75	0.75	0.5	0.50	2.45	9
A3	0.75	1	0.75	0.75	0.50	2.75	4
A4	1	0.75	0.75	0.75	0.75	3.10	2
A5	1	1	0.75	1	1.00	3.65	1
A6	0.75	0.25	0.75	0.25	0.75	2.25	12
A7	1	0.75	0.5	0.5	0.75	2.80	3
A8	0.75	0.25	0.75	0.75	0.75	2.55	7
A9	0.5	0.5	0.5	0.5	0.50	1.90	13
A10	0.75	0.75	0.5	0.5	0.50	2.30	11
A11	0.5	0.5	0.75	0.25	0.50	1.90	14
A12	0.25	1	0.5	0.75	0.75	2.35	10
A13	0.75	0.75	0.5	0.5	0.75	2.55	7
A14	0.75	0.75	0.75	0.5	0.75	2.70	6
A15	0.25	0.25	0.25	0.25	0.25	0.95	15

6.3 Result

6.3.1 Pre-selection

Pre-selection steps have been carried out in DT and Jus to identify the current conditions of the reservoirs. The result from the pre-selection steps will be able to help select the suitable mitigation measures for both reservoirs in the selection steps. As a result from Carlson's Trophic State Index (TSI) measurement, both reservoirs are undergoing a eutrophication process which can be categorized as eutrophic during both seasons (Southeast Monsoon and Northeast Monsoon) on the basis of secchi depth, Chl-a concentration and TP concentration. Because both reservoirs are drinking water reservoirs, the management goal should be to reduce the trophic state to at least mesotrophic conditions to be tolerable for use. This is because eutrophic water increases the cost of water treatment due to frequent filter backwashing, frequent clarifier desludging and additional treatment for odour and taste removal.

Chl-a concentration in drinking water reservoirs should be less than 15 μg/L in order to achieve a high quality of water. This is because beyond 30 μg/L of Chl-a an algal nuisance is created (Hart and Allanson, 1984; Walker, 1985; Raschke, 1993). Therefore, keeping the Chl-a concentration to a minimum is the best option to achieve high water quality and to reduce treatment costs in water treatment plants. However, observations done on DT and Jus show that Chl-a concentration in both reservoirs is more than 15 μg/L Chl-a during the Southeast (SE) monsoon, and less than 15 μg/L Chl-a during the Northeast (NE) monsoon. The limiting nutrient can be assessed by comparing the TN and TP mass ratio. If the mass ratio is less than 7.2N:1P, N is the potential limiting nutrient and if the calculated ratio is greater than 7, P is the potential limiting nutrient. TN concentration in both reservoirs is always low compared to TP which leads to a mass ratio less than 7. This may suggest that TN is acting as the limiting nutrient in both reservoirs for both seasons.

The investigation revealed that the major contributing factor causing this condition in DT and Jus was drainage from the Malacca urban area and in particular the sewage effluents which contained high concentrations of N and P. Sewage is known as the major polluter for the Malaysian river (Daud, 2009). The drainage had caused rapid eutrophication in both reservoirs resulting in a typical eutrophic lake with phytoplankton activity confined exclusively to the epilimnion which might increase the available nutrients in the hypolimnion. The summary of the pre-selection is shown in Figure 6-1.

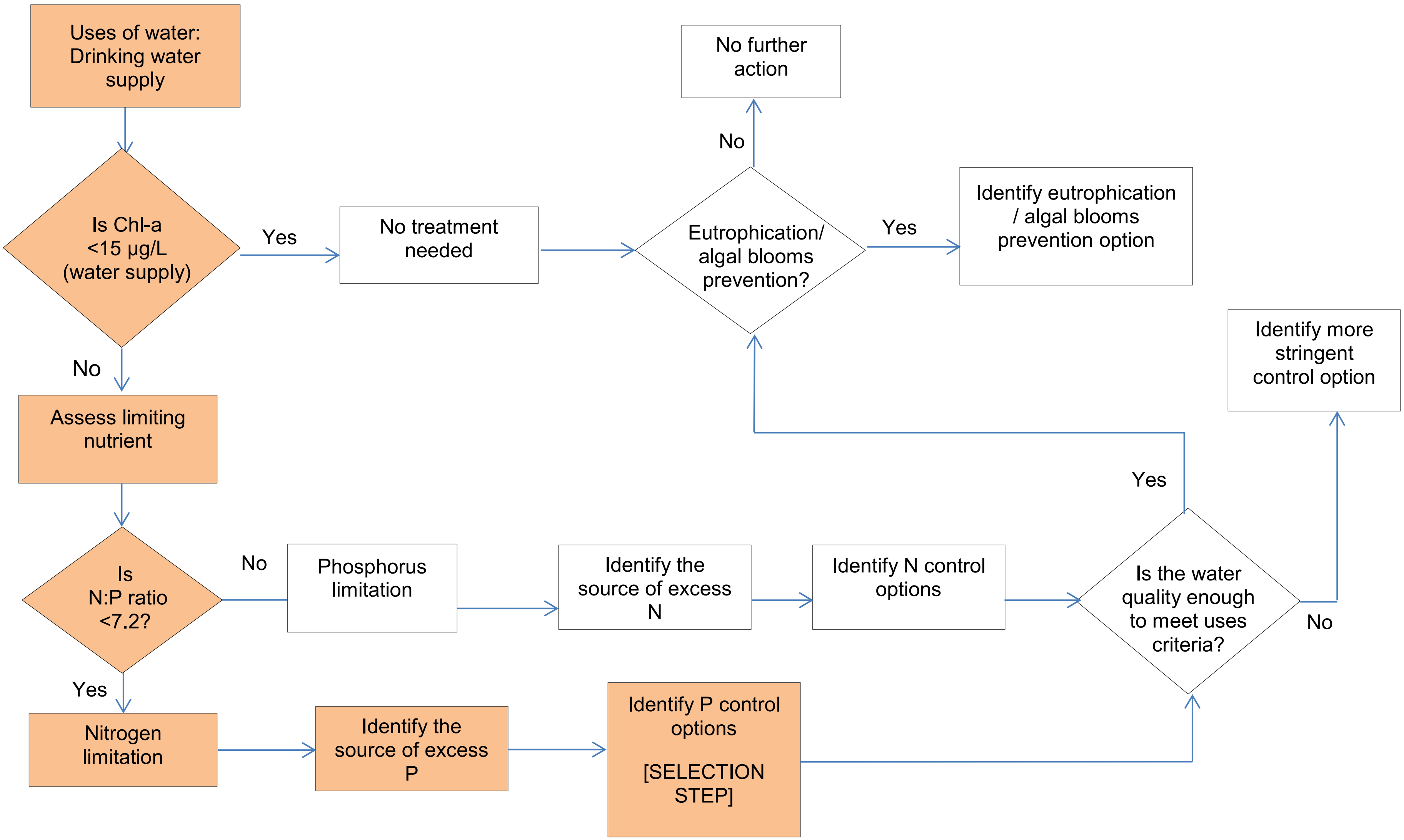

Figure 6-1: Pre-selection decision tree for DT and Jus reservoir

6.3.2 Selection

Based on the result from the pre-selection stage, both reservoirs do not meet the water quality criteria derived from other studies in tropical countries. Therefore, suitable techniques in controlling the nutrient level need to be evaluated and the selection stage will help in the decision making process. Fifteen alternatives in controlling external and internal nutrient loading were introduced in the MCA matrix to determine the best option in improving water quality in the DT and Jus reservoirs. The alternatives were divided into two groups; external nutrient control techniques and internal nutrient control techniques. Table 6-4 presents the summary of the results from the MCA matrix for the prevention techniques.

Table 6-4: Ranking for the external nutrient control techniques

Driver	Scenario	Alternative rank					
		1	2	3	4	5	6
Population	Scenario 1	LR	CW	AWT	Pre-dam	Diversion	DN
	Scenario 2	LR	CW	Pre-dam	AWT	Diversion	DN
	Scenario 3	LR	CW	Pre-dam	AWT	Diversion	DN
Economic	Scenario 4	LR	CW	AWT	Pre-dam	Diversion	DN
	Scenario 5	LR	CW	Pre-dam	AWT	Diversion	DN
Land Use	Scenario 6	LR	AWT	CW	Pre-dam	Diversion	DN
	Scenario 7	LR	CW	Pre-dam	AWT	Diversion	DN

LR= Law & regulation
AWT = Advanced wastewater treatment
CW = Constructed wetland
DN = Doing nothing

From the results, it can be seen that the implementation of regulatory approach to reduce the sewage discharge directly to the waterbody is the best choice in controlling the N and P loading to the reservoirs for all scenarios. The second best choice is constructed wetland except for Scenario 6 which shows that advanced wastewater treatment (AWT) is better than constructed wetland. The other choices in controlling the external nutrient loading according to high to low rank are pre-dam, AWT, wastewater diversion and doing nothing. Even though the rank for all the scenarios is almost the same, the total performance score for each alternative is different as shown in Figure 6-2. For example, though the ranking for regulatory approach in all scenarios are the same, according to the total performance score, regulatory approach was highest in Scenario 5 with a score of 4.05. This shows that regulatory approach might be the best to fit in Scenario 5 compared to the other scenarios. On the other hand, total performance score for the option of doing nothing is always the lowest in all scenarios with an average score of 0.98. It also can be observed that there is a big difference between the total score for doing nothing technique to the other 5 techniques. For instance, in Scenario 1, the percentage difference between doing nothing and AWT is 65.45%, diversion (61.22%), pre-dam (65.45%), constructed wetland (69.35%) and law and regulation (73.97%). Hence, doing nothing technique should be considered as a last resort when all alternative techniques are impossible or difficult to be implemented in the reservoirs.

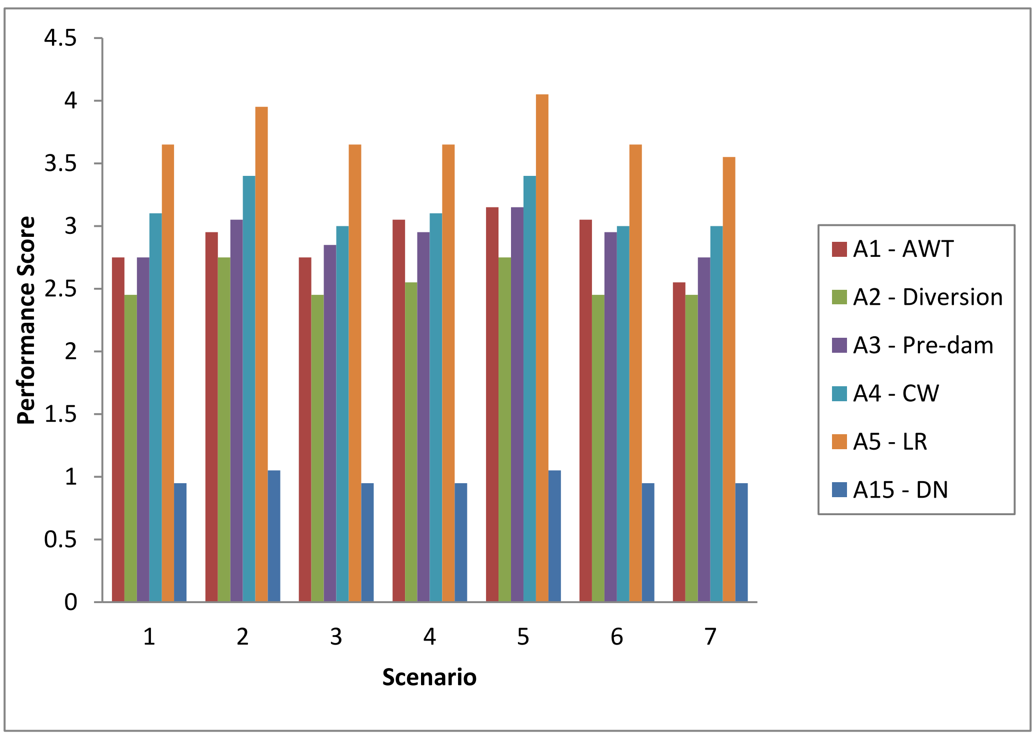

Figure 6-2: Total performance score for external nutrient loading control techniques

For internal nutrient control, nutrient inactivation technique was found to be the best technique to be applied in all scenarios except for Scenario 6 where dredging is the best technique and in Scenario 7, biomanipulation is the best technique as shown in Table 6-5. The highest performance score for nutrient inactivation is in Scenario 5 where the efficiency, longevity and cost are the most important criteria selected in the scenario. Meanwhile biomanipulation is the second best technique for all the scenarios except for; Scenario 6 where biomanipulation is the third best technique, and Scenario 7 where biomanipulation is the best technique to suit with selected criteria in the scenario. In the case that nutrient inactivation and biomanipulation are not feasible for the reservoir, it can be replace by harvesting for Scenario 1, Scenario 2 and Scenario 7, dredging for Scenario 3 and sediment cover for Scenario 4 and Scenario 5. On the other hand, option of doing nothing is always placed as the last option for all scenarios. This shows that these techniques were not as good as other options and should be considered as a last resort when all other options are either impossible or difficult to implement in the reservoirs. The performance score for each alternative for each scenario shown in Figure 6-3.

Table 6-5: Ranking for the internal nutrient control techniques

Driver	Scenario	Alternative rank									
		1	2	3	4	5	6	7	8	9	10
Population	Scenario 1	NI	BM	HA	SC	DR	HW	AL	DF	DS	DN
	Scenario 2	NI	BM	HA	SC	DR	AL	HW	DS	DF	DN
	Scenario 3	NI	BM	DR	SC	HA	HW	AL	DF	DS	DN
Economic	Scenario 4	NI	BM	SC	DR	HW	HA	AL	DF	DS	DN
	Scenario 5	NI	BM	SC	DR	HA	HW	AL	DF	DS	DN
Land Use	Scenario 6	DR	NI	BM	SC	HA	HW	DF	AL	DS	DN
	Scenario 7	BM	NI	HA	DR	SC	AL	HW	DS	DF	DN

AL = Algicides
BM = Biomanipulation
DF = Dilution & flushing
DN = Doing nothing
DR = Dredging
DS = Destratification
HA = Harvesting
HW = Hypolimnetic withdrawal
NI = Nutrient inactivation
SC = Sediment cover

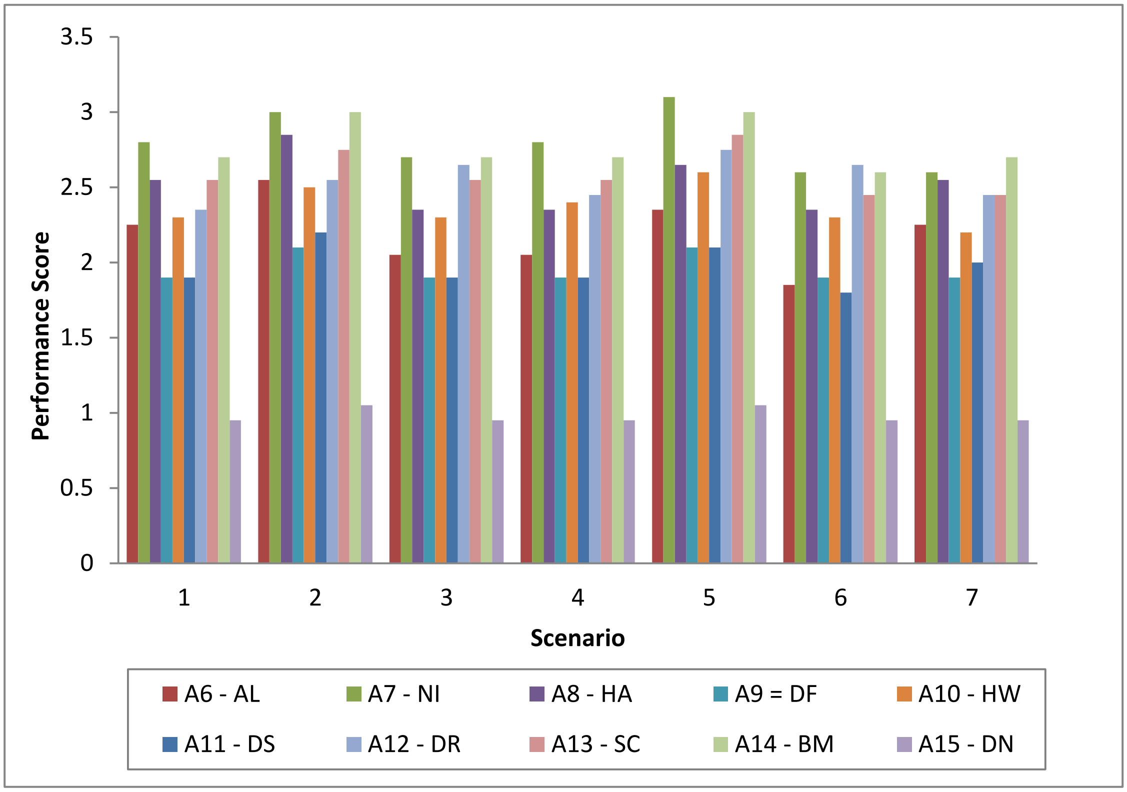

Figure 6-3: Total performance score for in-lake nutrient control techniques

6.4 Discussion

The results from the pre-selection stage reveal that both reservoirs need to go through the selection step in order to determine the best option for eutrophication reduction. In the selection step, MCA was introduced to help to identify the best technique by creating a ranking system from best to the least effective technique. Scenario analysis was incorporated in the MCA to evaluate the MCA framework by providing possible outcomes when certain weights were applied to the MCA matrix. From there, it can help the water managers in selecting the suitable mitigation measures tailored to their needs and preferences. The proposed integration of a scenario based approach and MCA framework provides a clear picture to water managers on the options that are available and how to choose the suitable ones when different criteria are considered. Unlike other models and rules in decision analysis, which are too technical and complex, this approach is easily understood and implemented while suiting different skill levels and backgrounds. In this study, direct alternatives to the eutrophication and algal bloom control techniques are shown when manipulated by a given scenario. However, the most feasible option will vary depending on the location and morphology of the catchment area and other circumstances such as public willingness to pay or accept.

From the investigation done in DT and Jus, there are some significant differences between the reservoirs especially in their morphology and land setting. The difference in the catchment area and surface area in DT and Jus resulted in the different of catchment area to reservoir ratio. For instance, the catchment area to reservoir ratio in DT is 7:1 which is higher than Jus which have a ratio of 4:1. This resulted in higher degree of water contamination in DT compared to Jus because more land is draining into the water body. Besides that, both reservoirs were also found to be N limited because they have low in TN:TP mass ratio. The TN:TP mass ratio in waterbody is important as it can be used to diagnose the types of algae likely to exist under different nutrient conditions. For instance, under low TN:TP mass ratio (N limited), blue-green algae tends to dominate the waterbody but the presence is rare when the TN:TP mass ratio was greater than 29:1 (Smith, 1983). Other algae such as green algae and diatoms will replace the blue-green algae dominance when TN:TP mass ratio more than 7.2 (P limited) (Dokulil and Teubner, 2000). A few studies suggested that even though N is the limiting nutrient, to mitigate the eutrophication, P is the only element that needs to be controlled (Schindler et al., 2008; Wang and Wang, 2009; Ganoulis, Aureli and Fried, 2013). A study done by Schindler et al. (2008) found that reducing N alone rapidly favored N_2 fixing cyanobacteria as a consequence of extreme N limitation. This is because N_2 fixing cyanobacteria can survive under low dissolved nitrate and ammonium concentration by fixing the atmospheric nitrogen. Furthermore, N_2 fixing cyanobacteria also may alleviate their nitrogen deficiency and thus become limited by another nutrient (Wurtsbaugh et al., 1985). Besides the problem of N_2 fixing cyanobacteria, N is also relatively difficult to control due to that fact that most N is derived from non-point sources such as agriculture and atmospheric deposition. The high solubility of the nitrate makes it rapidly escapes to underneath the root zone and further to the groundwater (Fields, 2004). Even though N is difficult to control, in the case of DT and Jus, it is necessary to do so if the critical concentration for healthy drinking water is not to be exceeded. Therefore both nutrients should be considered in the nutrient management plan as suggested by Elser, Marzolf and Goldman (1990) and Fields (2004).

Besides that it can be observed that external nutrients play an important role in supporting high productivity in DT and Jus. Point source loading is the main supply of high TP loading while non-point source loading is responsible for high TN loading in the reservoirs. The most feasible control option in a given situation is to control the external nutrient inputs as this is believed to be the most effective, long-term strategy for controlling eutrophication in reservoirs. Nevertheless, it is also important to be realistic in selecting specific control measures, both in terms of how much reduction in the external P loads can be expected and how much such control measures will likely cost. This is because unrealistic management plan can undermine popular support for P control efforts if it is observed that a given plan will not achieve the desired P control goals or that it is inappropriate from the point of view of cost effectiveness (Ryding, Rast and Unesco, 1989). In this case, each scenario represents the possible criteria that might be preferred by the water managers and tested in a MCA matrix to rank the best alternatives in managing eutrophication problems in the DT and Jus reservoirs.

At the moment, harvesting macrophytes using a hand pulling technique is used in shallow area in DT and Jus where emergent macrophytes occupied. This technique works best especially in softer sediment since it pulls the entire root system which gives immediate effect in improving the reservoir water quality. However, according to Cooke et al. (2005) this technique may result in re-suspension of the bottom sediments and nutrients which contribute to the already high in-lake nutrients. For the deep area in the DT and Jus, a cutting technique was used because floating macrophytes was usually occupied this area. The technique works by cutting the plant stems where it is visible. However, according to the DT and Jus water manager, the regrowth of the macrophytes is more frequent compared to using a hand pulling technique. This is possibly because the leaf fragments may re-root. The advantages of a cutting technique compared to a hand pulling technique is that it does not create re-suspension of bottom sediments and nutrients as in the case of hand pulling techniques.

6.4.1 Prevention of eutrophication

Control of external nutrient loading is the first step that needs to be considered in improving the quality of eutrophic or hypertrophic lakes and reservoirs. This is because this type of treatment has been discussed to be the most feasible control option providing efficient and long term results (Ryding, Rast and Unesco, 1989). However, this technique should be excluded if the main problem of the lakes or reservoirs comes from internal nutrient loading. In this study, the techniques in managing eutrophication and algal bloom problems were divided into two categories; 1) external nutrient control; and 2) internal nutrient control.

For external nutrient control, regulatory approaches are the best solution for controlling point source and non-point source nutrient loading including atmospheric N deposition in DT and Jus regardless of any criteria that might be preferred by the water managers. Even though a regulatory approach is the best solution according to the MCA ranking, it is difficult to implement in the DT and Jus because the success of regulatory approaches are dependent on effective governance and the participation of the stakeholder. The enforcement of law and regulations is still poor in Malaysia because some of the law was formulated before independence (i.e; Water Act, 1920) and needs to be revised to tailor to the current land use design, population and types of pollutant. Since Malaysia achieved its independence in 1957, water policies have been made by different authorities and organizations. There are no centralized and standardized water policies or guidelines for the states to adopt because of the overlap of water management between federal and state governments. For instance, the Water Act, 1920 is an act to provide for the control of rivers and streams covering the property of rivers, restoration, prohibition of diversions and pollution, licensing, penalties and compensation (Waters Act, 2006). There is no regulation that address about the pollutant resulted from N deposition. However, this act only applies to seven states out of thirteen states in Malaysia. Besides that, the policy is too general, without any specific details as to which department or agency should implement them. Some are even unaware of its existence, which results in the inefficient management of those rivers and streams (Saimy and Yusof, 2013).

Several acts were enacted to protect water resources from being polluted in the country. The legislation that is related to the control of water pollution or the control of any activities that might give rise to water pollution problems includes the following:

1. Mining Enactments and Mining Rules, 1934;
2. Forest Enactments, 1935;
3. Environmental Quality Act, 1974 and its related Regulations/Order;
4. Town and Country Planning Act, 1976;
5. Water Act (Amendment) 1989.

Out of these five Acts, the Environmental Quality Act, 1974 has been the most important piece of legislation which addresses specifically the subject of pollution and environmental quality. Eight out of twelve of the Regulations under the Environmental Quality Act, 1974 are directly related to water pollution control for water quality improvements including the standard for sewage effluent discharge. There are three standards for sewage effluent that are most widely used from the Environmental Quality Act, 1974: (a) Standard A for discharges upstream of raw water intake (Table 6-6); (b) Standard B discharges downstream of raw water intake (Table 6-6); and (c) for effluent other than Standard A and Standard B (Table 6-7). These standards are interpreted as absolute standards, which are not be exceeded at any point and enforcement would be based upon grab samples only.

Table 6-6: Parameter limits for Standard A and Standard B discharge (Law of Malaysia, 2012)

THIRD SCHEDULE
ENVIRONMENTAL QUALITY (SEWAGE AND INDUSTRIAL EFFLUENTS) REGULATIONS, 1979
Regulation 8(1), 8(2), 8(3)

	Parameter (1)	Unit (2)	Standard A (3)	Standard B (4)
(i)	Temperature	°C	40	40
(ii)	pH Value	-	6.0-9.0	5.5-9.0
(iii)	BOD_5 at 20°C	mg/l	20	50
(iv)	COD	mg/l	50	100
(v)	Suspended Solids	mg/l	50	100
(vi)	Mercury	mg/l	0.005	0.05
(vii)	Cadmium	mg/l	0.01	0.02
(viii)	Chromium, Hexavalent	mg/l	0.05	0.05
(ix)	Arsenic	mg/l	0.05	0.10
(x)	Cyanide	mg/l	0.05	0.10
(xi)	Lead	mg/l	0.10	0.5
(xii)	Chromium, Trivalent	mg/l	0.20	1.0
(xiii)	Copper	mg/l	0.20	1.0
(xiv)	Manganese	mg/l	0.20	1.0
(xv)	Nickel	mg/l	0.20	1.0
(xvi)	Tin	mg/l	0.20	1.0
(xvii)	Zinc	mg/l	1.0	1.0
(xviii)	Boron	mg/l	1.0	4.0
(xix)	Iron (Fe)	mg/l	1.0	5.0
(xx)	Phenol	mg/l	0.001	1.0
(xxi)	Free Chlorine	mg/l	1.0	2.0
(xxii)	Sulphide	mg/l	0.50	0.50
(xxiii)	Oil and Grease	mg/l	ND	10.0

Note: ND - Not Detectable

Table 6-7: Parameter limits for other than Standard A and Standard B discharge (Law of Malaysia, 2012)

SIXTH SCHEDULE
ENVIRONMENTAL QUALITY (SEWAGE AND INDUSTRIAL EFFLUENTS) REGULATIONS, 1979
Regulation 11(5)(b)

	Parameter	Unit	Limit
(i)	Temperature	°C	40
(ii)	pH Value	-	5.0-9.0
(iii)	BOD_5 at 20°C	mg/l	400
(iv)	COD	mg/l	1000
(v)	Suspended Solids	mg/l	400
(vi)	Mercury	mg/l	0.10
(vii)	Cadmium	mg/l	1.0
(viii)	Chromium, Hexavalent	mg/l	2.0
(ix)	Arsenic	mg l	2.0
(x)	Cyanide	mg/l	2.0
(xi)	Lead	mg/l	2.0
(xii)	Chromium, Trivalent	mg/l	10
(xiii)	Copper	mg/l	10
(xiv)	Manganese	mg/l	10
(xv)	Nickel	mg/l	10
(xvi)	Tin	mg/l	10
(xvii)	Zinc	mg/l	10
(xviii)	Iron (Fe)	mg/l	50
(xix)	Phenol	mg/l	5.0
(xx)	Sulphide	mg/l	2.0
(xxi)	Oil and Grease	mg/l	100

In Malaysia, the control of heavy metals from effluent discharge is stricter than the control of nutrients discharge. As can be seen in Table 1 and Table 2, most of the parameters listed were strictly focussed on heavy metals instead of chemical nutrients. However, it does not mean that there is no control of chemical nutrients but the control is not stringent enough as there are no specific limits set for chemical nutrients within effluent discharge as can be seen in Table 6-8.

Table 6-8: List of parameters the limits of which to be specified (Law of Malaysia, 2012)

FIFTH SCHEDULE ENVIRONMENTAL QUALITY (SEWAGE AND INDUSTRIAL EFFLUENTS) REGULATIONS, 1979 Regulation 8(4)	
(i)	Ammoniacal Nitrogen
(ii)	Sulphate
(iii)	Chloride
(iv)	Cobalt
(v)	Colour
(vi)	Detergents, Anionic
(vii)	Fluoride (as F)
(viii)	Molybdenum
(ix)	Nitrate Nitrogen
(x)	Phosphate (as P)
(xi)	Polychlorinated Biphenyls
(xii)	Selenium
(xiii)	Silver
(xiv)	Beryllium
(xv)	Vanadium
(xvi)	Radioactive Material
(xvii)	Pesticides, fungicides, herbicides, insecticides, rodenticides, fumigants or any other biocides or any other chlorinated hydrocarbons.
(xviii)	A substance that either by itself or in combination or by reaction with other waste or refuse may give rise to any gas, fume or odour or substance which causes or is likely to cause pollution.

At the moment, there is no specific national water quality standard which requires stringent control of parameters such as nutrients, formulated for lakes and reservoirs. Only Putrajaya Lake has its own specific water quality standard. This is because of the separation powers in terms of management for different types of water bodies are based on their use. For instance, lakes in Malaysia are under the responsibility of the Drainage and Irrigation Department (DID). Dams and reservoirs which were created for the water supply are governed by the various water supply departments or agencies. Meanwhile, the dams and reservoirs that are created for electricity generation are managed by the National Electricity Board (Sharip and Zakaria, 2007). Because of the overlap in the responsibilities and duties among federal and state governments in managing water resources, the public is confused on which agency is in charge of certain matters. The level of awareness and participation of the public in environmental issues, especially in water, is still low (Sharip and Zakaria, 2007). Therefore possible actions to take in order to control point source pollution in both reservoirs need to be within the jurisdiction of the Malacca Water Corporation (MWC).

After regulatory approaches, constructed wetland and AWT are the second and third best choice to reduce the external nutrient loading in DT and Jus. Where cost is the biggest constraint in mitigating external nutrient loading to the reservoirs, constructed wetland is the best choice because constructed wetland is the cheap version of AWT (Kivaisi, 2001; Sim et al., 2008b). In contrast with AWT which is normally installed as a last stage in a wastewater treatment plant, constructed wetland can be installed at the upstream catchment before entering the reservoirs. This technique successfully removed TP and TN in a few tropical countries as shown in Table 6-9. Therefore, if this method was put in place, it might be successful in reducing the excess nutrients in the river as was the case in Putrajaya Lake where constructed wetland successfully removed 82.11% TN and 84.32% TP in the upstream catchment area before entering the lake (Sim et al., 2008b). Table 6-10 shows the prediction of minimum and maximum TP and TN in DT that can be reduced by the constructed wetland if it is installed in the water catchment. The calculation was made using the minimum and maximum percentage values in Table 6-9 as a reference. From the results it shows that, even the minimum percentage removal may reduce the amount of nutrient retention in DT. This method is suitable for developing countries because the cost of installing and maintaining constructed wetland is less expensive than other treatment options.

Table 6-9: Efficiency of removal of TP and TN by constructed wetland

Studies	TP reduction (%)	TN reduction (%)
Sim et al. (2008b)	84.32	82.11
Farahbakhshazad, Morrison and Filho (2000)	93.0	78.0
Kurniadie and Kunze (2000)	68.59	90.54
Juwarkar et al. (1995a)	35.57	69.15
Boonsong, Piyatiratitivorakul and Patanaponpaiboon (2003)	22.6-65.3	44.8-54.4
Schulz and Peall (2001)	54.0-75.0	70.0-84.0

Table 6-10: Prediction of minimum and maximum TP and TN reduction by constructed wetland in DT

Nutrient sources	Current (kg/month)		Predicted (kg/month)			
			After minimum reduction		After maximum reduction	
	TP	TN	TP	TN	TP	TN
Point source nutrient input	5688.63	1022.18	4402.99	564.24	398.51	96.70
Agriculture	452.81	3648.38	350.47	2013.91	31.7	345.14
Residential	46.03	195.61	35.63	107.98	3.22	18.5
Forest	1.99	50.15	1.54	27.68	0.14	4.74
Atmospheric deposition	96.67	58.00	74.82	32.02	6.77	5.49
Others	1.75	26.50	1.35	14.63	0.12	2.51
Diffuse nutrient input	599.25	3978.64	463.81	2196.21	41.95	376.38
Nutrient output	4482.29	3955.37	3469.29	2183.36	313.76	276.88
Nutrient retention	1805.59	1045.45	1397.51	577.09	126.39	98.9

Meanwhile, AWT might be difficult to implement in the DT and Jus catchment area because it needs participation from the public especially at willingness to pay for the improved water quality. This is beyond the jurisdiction of the DT and Jus water manager and the water corporation unless there are national rules and regulations which require every house near the catchment area to treat their wastewater. However, to overcome this issue, MWC can alarm the public about the importance of domestic wastewater treatment by raising the public awareness through environmental campaigns, educational programs, media coverage and other informational products that will encourage the public to make more sustainable choices. This can also serve to inspire the Malaysian government to review the laws and regulations regarding wastewater discharge. According to recent reports, a few countries have actively worked to raise the environmental awareness of individuals in professional, administrative and political sectors. For example, the Japanese government used mass media coverage such as newspapers and television to raise public awareness to reduce greenhouse gas emissions and this has successfully increase public concern for the issue (Sampei and Aoyagi-Usui, 2009). Another example is in the European Union where a project was initiated to increase environmental awareness near the Baltic sea water catchment in order to prevent further deterioration of the Baltic Sea (Kreft-Burman, 2002).

Pre-dam is only suitable when all the above techniques are difficult or impossible to implement in DT and Jus. This method is not widely used except in Europe and especially Germany (Paul, 1995; Pütz and Benndorf, 1998; Paul, 2003). However, it could be possible to apply this technique in Malaysia because; 1) this method is not climate dependent and 2) was successfully applied once in Hartbeespoort Dam, South Africa as reported by Twinch and Grobler (1986). It is not feasible to apply pre-dam technique to DT because the land area in DT has been occupied by 20.3% of human settlements and 75% of agricultural land. Pre-dam have better chances to be applied to Jus because the land setting of Jus area is still covered by 15.4% of forest and the reservoir was built far from human settlements. The availability of space is the main disadvantage of the pre-dam technique as it might be impossible to retrofit an existing reservoir unless there is enough space or otherwise the pre-dam is constructed at the same time as the reservoir.

Last but not least, diversion of wastewater is the last option to be selected in preventing eutrophication in DT and Jus. This method can only be applied with great care due to the high nutrient content carried by the canal which may create water quality problems in the downstream water. Unless the downstream storage is built as a stabilization pond, this method is expected to give similar results as nutrient removal through advanced wastewater treatment (Cooke et al., 2005). In the DT and Jus case, the high nutrient loading has come from the inlet water that is supplied mainly by the river. Therefore if diversion was selected, the cost will be high because it will have to be installed before the pollutant enters the river which might include the whole city.

6.4.2 Treatment of symptom

Nutrient inactivation appears to be the best option in managing eutrophication and to control the in-lake nutrient level in terms of cost, efficiency and longevity. It works using the same principle as chemical coagulation in treatment plants by forming flocs after the application of alum which absorbs the dissolved P. The flocs accumulate on the bottom and absorb P that has leached out of sediments. However, this technique has a limitation in that it is not feasible for use in waterbodies that are overgrown with macrophytes and waterbodies that have a retention time of less than a year but high P loading (Straskraba and Tundisi, 1999). Considering this limitation, the technique might not suitable to be used in both reservoirs because the average retention time for DT is 72 days while Jus is 102 days. Besides that, both reservoirs are partly covered by macrophytes from the *Nelumbo nucifera sp.* and *Mimosa pudica sp*. Even if the macrophytes were removed, nutrient inactivation still might not work because of the high nutrient loading that comes from the inlet water and non-point sources especially from agricultural runoff.

Biomanipulation is also one of the best techniques for controlling eutrophication after nutrient inactivation. It is the best technique for the individual or company with a tight budget as it low cost due to no needs for chemicals or machinery. The main principle of this technique is to increase zooplankton populations to promote heavy grazing of algae (Carpenter et al., 1995). To date, there has been no biomanipulation history in Malaysia, and limited successful examples using biomanipulation were recorded in tropical regions such as Lake Paranoa (Starling, 1993; Jeppesen et al., 2007a), and the Americana Reservoir (Arcifa, Northcote and Froehlich, 1986). This might be due to the difference in temperature which results in an elevated primary production of algae, thereby reducing the grazing effect (Jorgensen et al., 2005). The DT and Jus reservoirs can be classified as deep reservoirs as the depth of both reservoirs is more than 20 metres. Meanwhile, the P concentrations in the DT and Jus reservoirs were strongly related to external loading. A study by Mason (2002) suggested that biomanipulation is likely to be more effective in small and shallow waterbodies even though there are a few successful cases in deep lakes such as in London Reservoir (Duncan, 1990), Lake Mendota (Lathrop, Carpenter and Rudstam, 1996) and Bautzen Reservoir (Benndorf, 1990). This is because in shallow water, the ecosystem can be inhabited by macrophytes and the removal of fish is more feasible. This also agrees with a study by Mehner et al. (2002) which finds that the most important criteria in biomanipulation are shallowness, the presence of macrophytes and a low amount of P loading. Therefore reduction of external loading is a pre-requisite in the DT and Jus reservoirs before commences any biomanipulation technique can be implemented. This is exemplified in the work undertaken by Benndorf et al. (2002) which states that one of the factors that contributes to the success of biomanipulation is the lower external and internal P loading and this is because biomanipulation will only occur if P loading (external and internal) is lower than the sum of all P losses. Even though this technique is cheap, various interactions on the food web, sediments, physical-chemical and biological components of the reservoir need to be taken into consideration. Besides that, caution also must be considered in introducing foreign species into the DT and Jus reservoirs because they might lead to new problems such as increasing the appearance of cyanobacteria as was the case in the Paranoa Reservoir where the introduction of a Tilapia species and a Tambaqui species enhanced the dominance of the blue-green algae from *Cylindrospermopsis Raciborskii sp*. and reduced the presence of silver carp (Starling and Rocha, 1990).

Hypolimnetic withdrawal is the technique that is mostly used when dealing with eutrophication in deep lakes. Hypolimnetic withdrawal works by discharging the water from the bottom layers which reduces the nutrients in the lake and eventually improves the dissolved oxygen. A high cost will be incurred when it is necessary to construct a hypolimnetic withdrawal system in existing reservoirs such as the construction of the new outlet in Upper Yarra Dam in Australia which cost AUD 13 million (McMahon and Finlayson, 1995). In the DT and Jus case, this technique involves nearly zero cost because both reservoirs have a built-in draw-off tower. For example, DT has two draw-off levels which are at 16.37 metres and 23.08 metres deep. The function of the draw-off towers in both reservoirs is for the augmentation of low flows of the downstream river when required (Basiron, 2014b). It is expected that the discharge of water to regulate the downstream river will indirectly reduce the size of the hypolimnion. This in turn will result in the reduction of the bottom nutrients concentration and therefore reduce the phytoplankton productivity. However, there are a few considerations before this technique can be implemented in DT and Jus such as the effect to the water quality after the changing of the outlet and the possible negative impact to the downstream water users. This is because the amount of external nutrient loading in DT and Jus is bigger than internal nutrient loading. The discharge water will be replaced by water from surrounding areas which includes the inlet water and differing water quality.

Dredging is the best option when longevity of the treatment is the most important criteria preferred by the stakeholder. This is because this technique gives relatively long-lasting effects such as shown in Lake Trummen in Sweden where there has been a consistently low P concentration over the past nine years (Peterson, 1981). The other advantages of this technique include removing the entire nutrient rich layer of sediment, reducing P release from the sediment, increasing the lake depth and volume and controlling macrophytes. However, the cost of dredging is high. The figure given by Peterson (1981) for dredging alone amounted to between USD0.23 to USD15.00 per square metre, and the cost can be converted to 2015 costs by applying a 2.58 inflation factor (http://www.bls.gov/data/inflation_calculator.htm) to the 1981 costs. Dredging is unlikely to be successful in DT and Jus reservoirs when considering the depth of both reservoirs and that the main pollution source of both reservoirs comes from external nutrient loading. This technique is more suitable for use in shallow lakes with high internal nutrient loading.

Meanwhile, sediment cover is definitely not suitable for DT and Jus. It is only suitable for newly built reservoirs or shallow lakes. This is because the water needs to be drawn out before the sediment can be covered. In the case of DT and Jus, both are reservoirs that can be categorized as deep reservoirs where the depth of both reservoirs is more than 10 meters. Thus, it is impossible to drain reservoirs with such large capacity in order to cover the sediment because this will involve a high cost including the cost of the loss of the withdrawn water. Another technique that is not suitable to be applied to DT and Jus is the application of algaecides. This is because both reservoirs are used for drinking water supply and the application of copper sulphate may release toxins contained in the algae species which can cause human illness (Kenefick et al., 1993). Moreover, in tropical conditions where the regrowth of algae and macrophytes is rapid, frequent reapplication is necessary. The application of algaecides in the long run will cause copper to accumulate in the sediment and may harm other aquatic life such as occurred in the Minnesota lakes (Hanson and Stefan, 1984).

One of the earliest methods used to combat algae bloom in lakes was using copper sulphate. It has been widely used and the experience has been documented in literature. The primary advantage of the method is that it works rapidly. However, it has more disadvantages than advantages such as the short duration of its effects, accumulation of copper sulphate in the bottom sediment that may harm other aquatic life and the possible release of toxins contained in the algae species (Holdren, Jones and Taggart, 2001; Jorgensen et al., 2005; Cooke et al., 2005). It is not safe to use copper sulphate in DT and Jus reservoirs because both are drinking water reservoirs. However, there is a natural algaecide which is the addition of barley straw to the waterbody (Schrader et al., 1998). Barley is widespread and occurs in most temperate areas in the world (Ullrich, 2010). However, it is not suitable to be used in Malaysia as barley is not a common plant cultivated in Malaysia. Besides that, decomposition of the barley straw is temperature dependent. It may take 6-8 weeks for the straw to become active when water temperatures are below 10^oC. At water temperatures above 20^oC, the decomposition process is even faster so the straw will not last long and will need to be reapplied which involves additional cost of the barley straw and man power. Apart from that, the long exposure of barley straw in water bodies during hot weather in Malaysia may also increase the risk of deoxygenation through the combined effect of dying algae and rotting straw (Centre for Ecology and Hydrology, 2004).

Dilution and flushing is one of the least feasible techniques according to the MCA ranking. However, very few documented case histories of dilution and flushing exist because this technique requires a readily accessible source of low-nutrient water (Olem and Flocks, 1990; Cooke et al., 2005; O'Sullivan and Reynolds, 2008). The best documented case of dilution is in Moses Lake, Washington where chlorophyll-a was reduced by almost 80 percent and TP declined 50-60 percent after the treatment which lasted no longer than three weeks (Welch and Patmont, 1990). In the case of the DT and Jus reservoirs, it is impossible to dilute the entire reservoir waterbodies because the clean water situation in Malaysia has gone from abundant to scarce due to the growing demands and pressure on good quality water (Azhar, 2000). However, if dilution and flushing is the only available technique that can be used for the DT and Jus reservoirs, the water must be toxin free because the DT and Jus reservoirs are drinking water reservoir. Besides that, to apply this technique, MWC must be capable of handling the discharged water because it might result in a negative effect to the downstream users as a result of flushing the high nutrient content from the reservoir

Destratification is the second to last technique to be considered if all the techniques proposed above are impossible to implement. The principle of destratification is to prevent anaerobic conditions in the hypolimnion layer so that less nutrients are released from the sediments under the such conditions. Thus, it is more suitable for deep lakes with stable stratification. However, destratification is unlikely to be successful in reducing the eutrophication in DT and Jus. As previously mentioned in the description of hypolimnetic withdrawal, the external nutrient loading should be the main concern in managing eutrophication in DT and Jus. Even though Jus has a high level of nutrients in the hypolimnion layer, the condition only happens during the Southeast monsoon. Therefore, this technique will work inefficiently if installed in DT and Jus. For the successful application of this technique, the total oxygen demand of the lake, the depth between the thermocline and hypolimnion layer and the P-binding capacity of the bottom sediments must be correctly estimated before installing the aerator. This will involve a high cost of installation, operation and maintenance of equipment. Full guidance in implementing destratification is shown in Lorenzen and Fast (1977) or Ashley (1985).

6.4.3 Combined methods

Because the efficiency of management methods varies for different situations, there is good reason to combine different approaches. This is because external or internal nutrient control alone is often not sufficient to achieve the desired objectives of lake restoration. Few examples of cases that used only external or internal control only were addressed by Mason (2002) and one of them is a case from the Vaal River in South Africa. P controls on sewage treatment was used to overcome the algal bloom problem in the reservoir. The technique was successful in reducing the P concentration at the reservoir inlet; however, there was no reduction in chlorophyll level. On the other hand, a combination of watershed and in-lake methods gives the best result. For example, Lago Paranoa, a highly eutrophic urban reservoir in Brazil, was restored by the construction of AWT in the city of Brasilia to control the external nutrient loading and complemented by the internal measures of biomanipulation and reduction of residence time (Mudroch, 1999). Using the MCA matrix, the best option for external control and the best option for internal control can be used simultaneously to get the best result in managing the eutrophication and algal bloom problem in the lake and reservoir. In the DT and Jus reservoir cases, water managers have only used harvesting techniques to reduce the eutrophication in both reservoirs. If the water managers were to implement a combined technique by implementing the external nutrient control technique, the water quality of the reservoirs might be better than current conditions.

For example, if the constructed wetland were implemented before the DT reservoir water inlet, the external P loading can be decreased by a minimum of 126.39 kg/month and maximum of 1397.51 kg/month. This assumption was made based on successful case studies from other tropical countries including Malaysia as presented in Table 10. Therefore, when the external P loading in DT is reduced by up to half the amount, the frequency of macrophytes harvesting in DT might be reduced from three times annually to two or one times annually which might also reduce the cost of the operation. For instance, the cost of macrophytes harvesting using the hand pulling technique in DT is approximately USD1500 annually which includes the cost of local labour, rental of cutting tools and boat fuel (Basiron, 2014a). This cost can be reduced up to fifty percent if the constructed wetland is installed before the water inlet.

In the case of DT and Jus reservoir, both reservoirs were found to be N limited which indicates that the reservoirs has been over-fertilised with P. Lewis and Wurtsbaugh (2008) analyse the question on which nutrient should be control in the input to manage lakes, they concluded that even though N limits the biomass accumulation, restoration of the polluted lakes is most feasible by restriction of P supply. This decision also agreed by Welch (2009) which found the same evidence from his study in Moses Lake. The long-term dilution of Moses Lake with low nutrient water has turned the lake into N limited lakes and dominated by the cyanobacteria. This is because reduction of the N supply may cause extreme N limitation that might promote the dominance by cyanobacteria (Schindler, 2012). Hence from the observation of previous studies, control of P is more important and the most effective way in reducing phytoplankton biomass in eutrophic lakes even in the N limited lakes.

6.4.4 Option of doing nothing

The option of doing nothing is selected as the least effortful method in managing eutrophication. For the option of doing nothing, it was assumed that no action is taken and that effluent volumes would increase in the future, but P concentrations in the effluents would remain at their present levels. This option will create costs over the long term because the water quality in the basin will deteriorate as a consequence of the increase in human settlement near the water catchment (Cooke et al., 2005). In this case, the default state of DT and Jus is before the water managers apply the harvesting technique in both reservoirs to reduce the eutrophication problem. In this case, the doing nothing option will simply further the existing state of the reservoir which will make the water more difficult to treat at the drinking water treatment plant. This is the last option that should be taken if all of the other options are unsuitable.

6.5 Conclusion

The results of this study clearly indicate great potential for scenario analysis and MCA in developing the framework for eutrophication and nutrients loading reduction in tropical surface water. The framework that is proposed using MCA as a decision support tool allows for the selection of robust investments management in eutrophication and algal bloom. The integration of scenario analysis can provide complementary insights into sustainability and cost efficiency for eutrophication management and policy for developing countries by giving the best available techniques according to the selected criteria. Unlike other models and supporting tools in decision analysis, this approach allows the water manager or stakeholder to view the future result as a consequence from the decisions made.

The most feasible control option varies depending on the selected criteria and it also varies from location to location, depending on the circumstances. For example, some control techniques may be suitable for Jus but may not suitable to DT because of the morphology and the land setting of the reservoir. Even though it is generally believed that the control of external nutrient inputs represents the most effective, long-term strategy for attempting to control eutrophication of lakes and reservoirs, not all surface water has the same problems. Therefore, the combination of external and internal nutrient control is recommended to improve water quality. No matter the condition, the option of doing nothing needs to be avoided because it creates a cost over the long term by ignoring lake or reservoir water quality and will likely result in the situation becoming worse, thereby requiring an even more expensive and frequent control programme at a later date. Complete validation of the framework procedure such as that described in the previous section would take many years of observation though the individual steps are largely based on the techniques that are well established. Therefore, more research of conditions in tropical and developing countries is needed to further validate and improve this framework in the future.

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CHAPTER 7

General conclusion

Chapter 7 : General conclusion

This concluding chapter evaluates the research achievements in relation to the aims and objectives set at the beginning of the study. Based on the findings, this chapter highlights possible directions for future research in eutrophication and algal bloom management in tropical countries.

7.1 Research achievement

The primary aim of this study was to develop a framework that could be used in supporting decision making in the tropics in order to solve eutrophication and algal bloom problems. This aim led to five objectives which were achieved in the study and are discussed below;

7.1.1 To update to the latest eutrophication and algal bloom control techniques that are scientifically established

To develop an eutrophication management framework requires information on past and present techniques used in reducing and preventing eutrophication and algal bloom. This led to the development of the first research objective which is to update the eutrophication and algal bloom control techniques. To achieve this objective, a systematic review was used as presented in Chapter 3. The findings clearly show that many attempts were made to control the proliferation of eutrophication and algal blooms from the 1960s to 2014. Most of the control techniques have been introduced since the 1960s. However, the materials or chemicals used are changing with time. For instance, copper sulfate ($CuSO_4$) was used extensively as an algaecide to control algal blooms in lakes and reservoirs until it was found to give negative side effects to human health as well as aquatic life. After this, many other chemicals were introduced to substitute $CuSO_4$ such as potassium permanganate (Fitzgerald, 1966; Chen and Yeh, 2005), hydrogen peroxides (Barroin and Feuillade, 1986; Drábková, Admiraal and Maršálek, 2007; Barrington and Ghadouani, 2008) and chlorine (hypochlorous acid) (Nicholson, Rositano and Burch, 1994; Rodríguez et al., 2007). The findings show that the systematic review approach was able to update the development of control techniques used up until 25th May 2014.

7.1.2 To evaluate and compare possible mitigation measures from temperate systems that can be applied to tropical water bodies

The finding from the systematic review was also able to fulfill the second objective which is to identify the control techniques that are suitable to be used in tropical countries, by using two methods;

i) Extracting the techniques that come from the studies in tropical regions only; and
ii) Comparing the conditions in tropical regions with temperate regions.

It was observed that even though most of the literature comes from temperate countries, in some conditions the techniques may be suitable for tropical conditions. For example, most of the external control techniques do not need to have the same climate conditions as the temperate regions such as pre-dam, wastewater diversion and advanced wastewater treatment. Besides that, findings from the review also enabled the decision making process to become easier by providing the advantages and disadvantages of each of the measures.

7.1.3 To develop a mitigation management framework to support decision making in controlling the eutrophication and algal bloom problem in tropical developing countries

A management framework to manage the eutrophication and algal bloom problem was developed in Chapter 4 to achieve the third objective of the study. The framework provides the simplest and most economical way to diagnose and manage the eutrophication problem. It was developed towards allowing implementation by tropical countries' who' budget constraints and lack of technical expertise are often limiting factors. The framework consists of two stages; 1) a pre-selection stage which requires the decision maker to evaluate the condition of the waterbody, and 2) the selection stage which allows suitable control techniques to be identified based on Multiple Criteria Analysis (MCA). Using the findings from the systematic review, the MCA decision matrix was developed to rank the control techniques based on the weight of the selected criteria. This will enable the decision maker to select the best option in managing the eutrophication and algal bloom problems specific to the prevailing economic and technical situation.

7.1.4 To explore the problems of eutrophication and algal bloom in the Durian Tunggal reservoir (DT) and Jus reservoir (Jus) as drinking water supply sources

To explore the problems of eutrophication and algal bloom in the Durian Tunggal reservoir (DT) and Jus reservoir (Jus), a series of field studies to collect data were conducted during the Southeast Monsoon and Northeast Monsoon. Both the Durian Tunggal and Jus reservoirs were listed as eutrophic lakes in a previous study by the National Hydraulics Research Institute of Malaysia (NAHRIM, 2005). Since then, there has been no other follow up research concerning the development of eutrophication in these reservoirs. There is no data available from the Malacca Water Corporation except from the drinking water quality data and the morphology data for the reservoirs. Therefore the results in Chapter 5 gave extended knowledge concerning the current eutrophic condition of the Durian Tunggal and Jus reservoirs which were both found to still be undergoing the eutrophication process and which are expected to be severe if no action is taken. The chapter also revealed that both reservoirs were primarily N limited. This was calculated based on TN to TP ratio as suggested in the previous study by Tett, Droop and Heaney (1985) and Downing and McCauley (1992). Rainfall is an important element in nutrient transportation (Kleinman et al., 2006), which then reflected the result in the DT and Jus reservoirs where the nutrients level was found to be high during the Northeast Monsoon compared to the Southeast Monsoon. This might be related to the high intensity of the rainfall that carried the land nutrients to the reservoirs. It is also revealed that the main source of the nutrients is from point sources which are their rivers. Agricultural land near the water catchment also contributed to the high nutrient loading especially during rainfall events, again due to the surface runoff into the reservoirs.

7.1.5 To validate the framework by using the DT and Jus reservoirs as a case study

To achieve the fifth research objective, the actual condition and situation observed in the DT and Jus reservoirs was used to validate the framework developed in Chapter 4. The result of the study found that the framework was able to guide the decision maker in determining the most suitable control option to manage the eutrophication and algal bloom problem in these waterbodies. The finding from Chapter 6 confirmed that MCA was able to be used as a tool to support decision making in eutrophication and algal bloom management in tropical water bodies. The use of scenario analysis to assist the weighting of the criteria was able to rank the suitable control techniques to be used in the DT and Jus reservoirs. For example, the finding suggest that regulatory approach is the best solution for controlling point source and non-point source nutrient loading in DT and Jus reservoirs. However, this technique is depends on effective governance and stakeholder which was difficult to be implemented in Malaysia at the moment. Therefore, the MCA ranking suggest that the second best choice to reduce the nutrient loading to both reservoirs is by installing the constructed wetland at the upstream catchment. This technique seems to be the best technique for DT and Jus reservoirs because it has been successfully implemented in Putrajaya Lake, Malaysia in order reduce nutrient loading from the surface runoff caused by development and agricultural activities from an upstream catchment. At the moment, harvesting technique is used in DT and Jus reservoirs to control the eutrophication problem. However, the harvesting technique was only managed to solve the macrophytes problem for a short time and the process will be repeated once per three to four months. Therefore, the findings suggest the best technique to treat the symptom of eutrophication is by using hypolimnetic withdrawal after found that nutrient inactivation and biomanipulation were unsuitable to be implemented in both reservoirs. It is also suggested that the combination of control between external nutrient control and in-lake control will act better than single control. Without controlling the external nutrient loading to the reservoir, eutrophication in DT and Jus reservoirs will keep going even though in-lake control measure was implemented. This is because certain in-lake control technique is only suitable with low nutrient loading condition. Therefore, external nutrient loading need to be reduce to make the in-lake technique become efficient. Next, this framework will be proposed to MWC to provide them a guide to more systematic approach in eutrophication management and strengthen the current water management programme for the reservoirs.

To summarize, the most feasible control option in given situation varies from location to location, depending on the circumstances such as lakes morphology and land use setting. Therefore, as pointed by few study such as by Ryding, Rast and Unesco (1989); Bootsma, Barendregt and Van Alphen (1999); Kuo, Wang and Lung (2006); Kagalou, Papastergiadou and Leonardos (2008), the control of external nutrient inputs represents the most effective, long-term strategy for attempting to control eutrophication of lakes and reservoirs. Here, MCA plays important roles as an aid to the decision maker to rank the most suitable option for external nutrient control and internal nutrient control depending on the criteria preferred. Nevertheless, it is important to be realistic in selecting specific control measures, both in terms of how much reduction in the external nutrient load can be expected and how much such control measures will be likely cost.

7.2 Research contribution

The results of the study will contribute at three geographic scales. At a global scale, the study provides new approach to collect the retrospective information in eutrophication and algal bloom management by introducing the systematic review technique. This technique has been used extensively by medical researchers and policy makers as it provides data for rational decision making. However, to date, there is no systematic review approach used in the subject of eutrophication and algal bloom management. From the study, systematic review has demonstrated the ability to collect the control techniques that have been scientifically established. This method was also able to give an update to the latest technology in controlling the eutrophication and algal bloom problem. Besides that, the MCA model for the selection of the best control techniques was introduced to support the decision making process in improving water quality. The result obtained in the study displayed the great potential of MCA as a decision support tool because it was able to rank the control techniques according to the priority dependent on the criteria agreed by the stakeholder.

Meanwhile at the regional scale, the study makes a notable contribution by offering guidance in controlling eutrophication and algal bloom problems. The framework is specifically tailored to suit the tropical region in which normally having budget constraints and inadequate technology. Therefore, the framework only listed the most important parameters that are commonly used to determine and evaluate the eutrophication level and the presence of algae in waterbodies. This will help tropical developing countries minimize the cost from sampling and analyzing unrelated or unimportant parameters.

Last but not least, at a local scale the study provides a number of contributions such as;

i) Providing data for future reference;

   As mentioned before, the availability of water resource management data in Malaysia is still limited especially on the eutrophication and algal bloom subject. Therefore, the data from the study can be compiled into the existing Malaysian lake database to contribute for better water resource management in Malaysia.

ii) Updating the current situation in both reservoirs;

   The previous eutrophication and algal bloom study of Malaysia’s lakes and reservoirs took place in 2005. Since then, there has been no other attempt to update the current condition of the lakes and reservoirs. Therefore, the result of this study will help to provide information and updates about the current condition in the DT and Jus reservoirs. This will increase awareness of the water managers and the government regarding the importance of this issue such that they may take action.

iii) Policy extension;

The findings from the study can help in the establishment of many programmes that strengthen environmental planning and management in Malaysia and within many government agencies and private institutions. This will be the platform to inform the Malaysian government to revise current policy to support the growing human population and activities.

7.3 Research limitation

Several limitations to this study need to be acknowledged. First and foremost, because of time constraint, grey literature was excluded from the systematic review search which may have resulted in bias. However, the literatures that have been reviewed are from scientific publications which have undergone the peer review system. This assured that the published articles meet widely accepted methodological standards and may therefore be considered more robust. The search was also limited by the chosen keywords where poor combinations of key words might have resulted in some studies left unidentified. In addition, the study looked only at publications in the English language and might have created bias for publications in other languages.

The second limitation is that the framework was validated only using two reservoirs. This is because of the difficulty to gain access to other lakes and reservoirs due to the conflict of bureaucracy which has overlapping in the water bodies' ownership. Besides that, the water quality data is also not continuously monitored and there is a lack of data quality control by the data provider which in this case is government agencies. For instance, the water quality data for N was only measured once a month and the sample was only collected at the water inlet at the drinking water treatment plant instead of the reservoir. Moreover, the number of parameters was also limited which required the researcher to measure them herself. For example there is no chlorophyll-a, P and N data available for the DT and Jus reservoirs. Therefore, permanent water quality monitoring in the study area would certainly improve the rigour of research in the future with the ability to monitor the water discharge, nutrient patterns. According to Ryding, Rast and Unesco (1989), a water quality data of at least three years normally should be regarded as the minimum effort for the most accurate assessment of a waterbody. Others such as Chapman and World Health (1996); Chorus and Bartram (1999a); Cooke et al. (2005), however points out that minimum period of one year data is enough to assess the condition in the water bodies. Because of the inconsistency of the data, there are few parts in the study which use assumptions based on other literature that have the same climate and economy such as the nutrient export coefficient.

Last but not least, number of sampling campaigns carried out is only limited to SE monsoon and NE monsoon. Therefore it is might be difficult to extrapolate these case study findings to other condition in other tropical countries. Despite limitations, the finding of this study may valid to be as a reference to other countries which shares the same climate setting and have similar catchments characteristic. This research shows that there are lots of issues that can be improved in this field of study especially in Malaysian catchments. With this limitation, the information from other tropical water bodies is important in order to understand the processes and responses of the mitigation management framework. Hence, after highlighting the limitation of this research it is hope that the future researched can fill this gap or cover this limitation and develop this research further.

7.4 Recommendation for future works

Therefore, in continuation to this research, a few recommendations are suggested below;

- Improving systematic review findings;

  The systematic review findings can be improved by including the grey literature (e.g. unpublished research paper, institutional reports, and conference proceedings) and exploring wider databases. For example, Haig and Dozier (2003) listed out the advantages of grey literature and one of them is grey literature can have a strong effect on policy makers. Therefore, including grey literature as one of the medium of literature search might help to discover more control techniques from other perspective including from the government.

- Extending the MCA model by including more evaluation criteria and more control techniques;

  The study includes five criteria to evaluate the performance of fifteen control techniques. Hence, for a more robust MCA model, more criteria and more control techniques could be included. Besides that, a qualitative interview method can be incorporated to collect information on stakeholder opinions which can be converted into weighting of MCA criteria.

- Extending the management framework process;

  Various models such as total maximum daily load (TMDL), the watershed model and the P loading model can be incorporated into the framework process to thoroughly evaluate the waterbodies before concluding on suitable control options.

- Involving more lakes and reservoirs to evaluate the eutrophication management framework;

  The eutrophication management framework was demonstrated using two reservoirs in a specific region of Malaysia. Involving more lakes and reservoirs will refine the framework.

- Collecting continuous data or year-round data;

The data used in the study only covers two months over the Southeast Monsoon season and two months over the Northeast Monsoon season. Therefore, it is recommended to collect continuous data or year-round data including transition seasons which occur in between the monsoons. This would allow better understanding of the progression of the eutrophication and algal bloom problem in Malaysia.

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Appendix 1: Examples of performance score rating

4	Constructed wetland					
	No	**Journal**	**Effectiveness**	**Longevity**	**Confidence**	**Impact**
	1	Domestic wastewater treatment through constructed wetland in india	Removing BOD (67%-90%) and N (58%-63%)	N/A	tropical	
	2	The Use of a Mangrove Plantation as a constructed wetland for municipal wastewater treatment	Removing TP (39.19%-67.27%) and TN (29.75%-57.08%)	N/A	tropical	
	3	Nitrogen and phosphorus removal in substrate-free pilot constructed wetlands with horizontal surface flowing Uganda	Removing P (9.3%-11.2%) and N (15.7%-28.5%)	N/A	tropical	
	4	Nutrient removal in a pilot and full scale constructed wetland Putrajaya city, Malaysia	Removing TP (84.32%) and TN (82.11%)	4 years	tropical	
	5	Wetland projects developed in brazil	Removing P (93%) and N (78%)	N/A	tropical	
	6	Nutrient Removal in a Vertical Upflow Wetland in Piracicaba, Brazil	Removing P (93%) and N (78%)	N/A	tropical	
	7	The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review	N/A	N/A	tropical	
	8	Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater—a tropical case study	Removing NH4 (11.2%-25.2%)	6 years	tropical	
	9	Seafood wastewater treatment in constructed wetland: Tropical case	Removing TP (72%-77%) and TN (72%-92%)	N/A	tropical	
	10	Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with Canna and Heliconia	Removing N (12%-41%)	N/A	tropical	
	11	Wastewater treatment by tropical plants in vertical-flow constructed wetlands	Removing TKN (85%-88%) and P (32%-52%)	N/A	tropical	
	12	Water quality effectiveness of a detention/wetland treatment system and its effect on an urban lake	Removal of TP (75%)	5 years	temperate	
	13	Potential of constructed wetlands in treating the eutrophic water:evidence from Taihu Lake of China	Removal of TP (35%–66%) and TN (20%–52%)	N/A	temperate	
	14	Nutrient removal from eutrophic lake water by wetland filtration	Removal of TP (30%–67%) and TN (30%–52%)	2 years 4 month	temperate	
	15	Particulate phosphorus removal via wetland filtration: an examination of potential for hypertrophic lake restoration	Removal of TP (42%)	N/A	temperate	
	16	Stormwater runoff treatment in a wetland filter: effects on the water quality of Clear Lake	Removal of TP (54%)	6 years	temperate	
	17	Removal of nutrients in various types of constructed wetlands	Removal of TP (40-60%) and TN (40-55%)	4 - 6 years	temperate	
	18	Nutrient removal from polluted river water by using constructed wetlands	Removal of OP (52-85%) and NH4 (78-100%)	2 years	temperate	
	19	Agricultural pollutant removal by constructed wetlands: Implications for water management and design	NO3 (22-99%),	1- 3 years	mediteranean	1) provide habitats for pests 2) Odor and insects may be a problem due to the free water surface 3) some mosquitoes sp. can be harmful to human healts such as aedes
	20	Phosphorus and nitrogen removal from tertiary treated urban wastewaters by a vertical flow constructed wetland	TP (77%), NH4 (95%), TN (24.4%)	1 year	mediteranean	
	21	Treatment Efficiencies of Constructed Wetlands for Eutrophic Landscape River Water	TP (19.37-65.27%) , TN (21.56- 62.94%)	14 weeks	temperate	
	22	Nutrient removal from aquaculture wastewater using a constructed wetlands system	TP (32-71%) , NH4(86-98%), TN (95-98%)	8 months	temperate	
	23	Nutrient removal in tropical subsurface flow constructed wetlands under batch and continuous flow conditions	TP (25.5-69.6%), TN (95.2%)	3 years	tropical	
	24	Nitrogen Removal in Experimental Wetland Treatment Systems: Evidence for the Role of aquatic plants	TN (80%)	3 years	tropical	
	25	Artificial wetlands and water quality improvement	Efficiency of heavy metals removal	several years	temperate	
	26	Oxygen demand, nitrogen and copper removal by free water surface and subsurface flow constructed wetlands under tropical conditions	TN (22-26%), Cu (63-80%)	376 days (1 year)	tropical	
	27	Application of a constructed wetland for industrial wastewater treatment: A pilot-scale study	TP (35%), TN (56%)	1 year	temperate	
	28	Constructed wetlands as a sustainable solution for wastewater treatment in small villages	removed BOD, COD and TSS	2 years	mediteranean	
	29	Wetlands for wastewater treatment: Opportunities and limitation	N & P (50%)	10 years	temperate	
	30	A comparative study of Cyperus papyrus and Miscanthidium violaceum-based constructed wetlands for wastewater treatment in a tropical climate	TP (48.4-83.2%), TN (61.5-75.3%)	5 months	tropical	
	31	Plants for constructed wetland treatment systems — A comparison of the growth and nutrient uptake of eight emergent species	TP (79-93%), TN (65-92%)	2 years	temperate	
	32	Constructed wetlands in Queensland: Performance efficiency and nutrient bioaccumulation	TN(55-98%), TP (13%)	3 years	tropical	
	33	Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands	TP (90%), TN (90%)	7 years	temperate	
	34	Treatment of domestic and agricultural wastewater by reed bed systems	TP (80-99%), TN (80-99%)	N/A	temperate	
	35	Reed-Bed Treatment for Municipal and Industrial Wastewater in Beijing, China	TP (55.3%), TN (13%)	2 years	temperate	
	36	Removal of organic matter and nutrients from urban wastewater by using an experimental emergent aquatic macrophyte system	P (47-61%), N (56-62%)	N/A	mediteranean	
	37	The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines	P (90%), N(90%), BOD (95%)	N/A	temperate	
	38	Nutrient removals by 21 aquatic plants for vertical free surface-flow (VFS) constructed wetland	P (78-99%), N (80-99%)	N/A	temperate	
	39	Seasonal performance of a wetland constructed to process dairy milkhouse wastewater in Connecticut	TP (68%), TKN (53%)	5 years	temperate	
	40	Effect of hydraulic retention time on the treatment of secondary effluent in a subsurface flow constructed wetland	TN (90%)	4 months	tropical	
	41	Tropical application of floating treatment wetland	NH4 (90%)	2 months	tropical	
	42	Efficiency of aquatic macrophytes to treat Nile tilapia pond effluents	TP (82-83.3%), TN (46.1- 43.9%)	4 months	tropical	
	43	Landfill leachate treatment using sub-surface flow constructed wetland by Cyperus haspan	TP (59.8-99.7%), TN (33.8-67.0%)	21 days	tropical	
	44	Effect of operational and design parameters on removal efficiency of pilot-scale FWS constructed wetlands and comparison with HSF systems	TP (51.7-63.5%), TKN (60.4-70.4%)	2 years	temperate	
		excellent 24	54.50%	more than 5yrs	11.40%	
		good 12	27.30%	1-5yrs	38.60%	
		fair 6	13.60%	less than 1 yrs	34.10%	
		poor 2	4.50%	less than 1 yrs with rea	15.90%	

Appendix 2: Cost criteria rating

Method: Activity-Based Cost

Method	Capital				Operation		Maintenance		Cost summary			
	Construction	Equipment	Chemical	Material	Low	High	Low	High	C	O	M	RANK
AWT	X	X	X			X		X	high	high	high	**poor**
Pre-dam	X	X			X			X	fair	low	high	**fair**
Diversion	X	X			X			X	fair	low	high	**fair**
Constructed wetlands	X	X		X	X		X		fair	low	low	**good**
Law and regulations				X	X		X		low	low	low	**excellent**
Algicides			X		X		X		low	low	fair	**good**
Nutrient inactivation			X		X		X		low	low	fair	**good**
Harvesting		X			X		X		low	low	low	**good**
Dilution and flushing	X	X				X		X	fair	high	high	**fair**
Hypolimnetic withdrawal	X	X				X		X	fair	high	high	**fair**
Destratification	X	X				X		X	fair	high	high	**fair**
Dredging	X	X		X	X			X	high	fair	low	**good**
Sediment cover	X			X		X		X	fair	low	low	**good**
Biomanipulation				X	X		X		low	low	low	**good**
Do nothing	X	X	X	X	X	X	X	X	high	high	high	**poor**

Capital	**low**	chemical / material
	fair	construction + equipment
	high	construction + equipment + chemical / material
Operation	**low**	labour + material
	high	labour + energy (fuel/electricity) + material + chemical
Maintenance	**low**	small maintenance such as clean up
	high	equipment maintenance

i. Excellent – low capital cost, low operation cost, low maintenance cost
ii. Good – fair capital cost, low operating cost, low maintenance cost
iii. Fair – fair operating cost, low operation cost, high maintenance cost
iv. Poor – high capital cost, high operation cost, high maintenance cost

Capital cost (CC) – machinery and other equipment purchases, material and chemical purchases, building or place construction, equipment installation, licence application

Operating cost (OC) – labour, supplies such as chemical, equipment operating cost (eg: fuel, electricity)

Maintenance cost (MC): corrective maintenance (repairs made after the equipment has failed and cannot perform its formal function anymore) and preventive maintenance (provide periodic or schedule inspection and minor repair to reduce danger and anticipated breakdown)

Appendix 3: Template for decision makers

Weight						
	C1	C2	C3	C4	C5	Total performance score
A1	1	1	1	1	0.25	
A2	0.75	0.75	0.75	0.5	0.5	
A3	0.75	1	0.75	0.75	0.5	
A4	1	0.75	0.75	0.75	0.75	
A5	1	1	1	1	1	
A6	0.75	0.25	1	0.25	0.75	
A7	1	0.75	0.75	0.5	0.75	
A8	0.75	0.25	0.5	0.75	0.75	
A9	0.5	0.5	0.5	0.5	0.5	
A10	0.75	0.75	0.75	0.5	0.5	
A11	0.5	0.5	0.5	0.25	0.5	
A12	0.25	1	0.5	0.75	0.75	
A13	0.75	0.75	0.75	0.5	0.75	
A14	0.75	0.75	0.5	0.5	0.75	
A15	0.25	0.25	0.25	0.25	0.25	

Total performance score can be calculated as below;

$$A_i = \sum_{j=1}^{m} S_{ij} \left(W_j\right)$$

Where;

A_i = measures alternative;
S_{ij} = performance score of the alternative for criteria j, i=A1, . . . , n; and
w_j = weighting factors for the criteria, j=1, . . . , n;

Appendix 4: Location of DT and Jus reservoirs (marked in yellow)