A study on the invasion of alien plants species in Nong Bong Khai non-hunting area, Ramsar site, Chiang Rai, Thailand

〔タイ、チェンライ、ノン・ボン・カイ禁漁区ラムサール湿地における外来植物種の侵入に関する研究〕

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A study on the invasion of alien plants species in Nong Bong Khai non-hunting area, Ramsar site, Chiang Rai, Thailand

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by

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Declaration

The thesis is submitted for the degree of Doctor of Philosophy at the United Graduate School of Agricultural Sciences, Tottori University. This dissertation is the result of my own work and has not been and is not being, in part or wholly, submitted for another degree, diploma, or similar qualification.

Chitapa WONGSUPATHAI

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List of Abbreviation

cm	: Centimeter
DO	: Dissolved Oxygen
ha	: Hectare
m	: Meter
m^2	: Square meter
mg/L	: Milligram per liter
mm	: Millimeter
m/s	: Meter per second
NH_3-N	: Ammonia-Nitrogen
NO_2^-	: Nitrite
NO_3^-	: Nitrate
PO_4^{3-}	: Phosphate
RGB	: Red, Green, Blue
TP	: Total phosphorus
TN	: Total nitrogen
UAV	: Unmanned aerial vehicle
µS/cm	: Microsiemens per centimeter

CHAPTER 1
Introduction

1.1 Research background

Thailand is located in Southeast Asia in Indo-pacific between latitude 5° 37´N and 20° 28´N and longitude 97° 21´E and 105° 37´E, the east boundary is close to Laos and Cambodia. The west boundary is close to Burma. The north boundary is close to Burma and Laos. And the south boundary is close to Malaysia. The total covering area is 513,120 square kilometers. According to natural features, Thailand is divided into 6 regions: Northern, Southern, Central, Eastern and Western. The total population of Thailand is amounted to 66.5 million people (National Statistical Office, 2019).

The climate of Thailand is under influenced by two types of monsoons: 1) Southwest monsoon which blow over Thailand between the middle of May and the middle of October. It is originated from high pressure areas in the Indian Ocean in the Southern hemisphere. This monsoon will bring humid air masses from the Indian Ocean to Thailand causing a lot of rain especially along the coast. 2) Northeast monsoon begins to blow around the middle of October. It prevails over Thailand until the middle of February. This monsoon is originated from high pressure regions in the Northern hemisphere; Mongolia and China, which blows cold and dry air masses to cover Thailand. It causes of cold and dry weather, especially in the Northeastern. And it also causes of heavy rains in the Southern as it carries the moisture from the Gulf of Thailand especially in eastside of the Southern. The average rainfall throughout the year is more than 1,500 mm and the most rainfall is during August and September. The average relative humidity throughout the year is about 73-75%. The season in Thailand can be divided into 3 seasons: (1) Dry season during the middle of February to the middle of May. The average temperature is between 35.0°C -39.9 °C with the highest temperature at 40.0 °C. (2) Rainy season is between the middle of May and the middle of October. The average temperature is 27 °C. And (3) winter season is between the middle of October and the middle of February. The average temperature is 23.0°C (The Meteorological Department, Thailand ,2021).

The Office of Natural Resources and Environmental Policy and Planning reported wetland in Thailand consisted of mangrove forest, bog, swamp, march, lake and rivers scattered throughout the country. The total area of wetland in Thailand is approximately 36,616.16 square kilometers. It covers around 7.5% of total area of Thailand where can be categorized to 44.8% of freshwater areas and 55.2% of saltwater areas. Thailand was ratified to participate in the Ramsar Convention on 13th September 1998. In the Ramsar Convention, wetlands can be categorized as follow: 15 International important wetlands (Ramsar sites), 69 International important wetlands and 47 national important wetlands.

In 1971, wetland ecosystems were first acknowledged for their significant in the global level at the Ramsar Convention, the oldest intergovernmental environmental agreement, in Ramsar, Iran. Wetlands in over 160 countries were identified for the value they bring to humanity as a whole (Ramsar, 2014). Refer to the Ramsar Convention, wetlands include all inland aquatic habitats (permanent or temporary, whether fresh, brackish, or saline, and including lakes, streams, rivers and inland seas), coastal systems shallower than 6 m depth at low tide (lagoons, estuaries, marshes, mangroves, seagrass beds, mud flats and coral reefs), and human-made systems such as reservoirs (6,000–7,000 km^3 according to recent estimates) and rice paddies. Wetlands are greatly determined by water levels, and so fluctuation of climatic conditions that affect water availability will highly influence its structure and function (IPCC, 2001; José and Pérez, 2008). Water is an important element of wetland. Change in wetland's water bodies, in term of level or quality, can influence the distribution and the productivity of vegetations, and also ecosystems in wetland. Wetland's water is varied by various factors such as land utilization and climate. During the 20th century, a main cause behind the loss of wetlands and associated ecosystem services was land use/land cover changes which have potentially large impacts on hydrologic processes (De Fries et al., 2004; Foley et al., 2005; Gagne and Fahrig, 2007; MA, 2005; Stonestrom et al., 2009; Anand et al., 2018). Particularly in limited water availability regions, land use/land cover changes could result in the deterioration in water quality and also in an increase of water scarcity. Additionally, land use/land cover changes effect to generate changes in plant species composition and habitat loss (Kingsford and Thomas, 2002; Van Asselen et al., 2013). Not only land use/land cover change are a main cause of wetland loss, but climate change also effects to the loss of wetlands and associated ecosystem services. Climate change is recognized as a major factor to determine the survival of species and integrity of ecosystems worldwide (Hulme, 2005). The changes in climate tend to affect wetlands significantly, in their spatial extent, distribution and function (IPCC, 1992, 2001). Changes in precipitation will alter water availability and stream flows affecting ecosystem productivity with lower summer water availability reducing water quality. Populations of aquatic organisms are sensitively impacted from floods, droughts and other extreme weather events as well as to water temperatures, which are likely to increase as caused by climate change (Jefferson and Grice, 1998), because their physiology is dominated by the delicate balance between the rainfall, temperature and evapotranspiration. Hydrological fluctuation is a major disturbance that influences wetland ecosystems (McGowan et al., 2011; Nielsen et al., 2013; Raulings et al., 2010). In addition, rivers, lakes and waterways are threatened by aquatic invasive through displacement of native species, alteration of hydrological cycles, affecting nutrient cycles and altering food web dynamics, introducing new diseases and parasites and hybridization with native species (Bartley et al., 2005; Poulos et al., 2012). Besides, their invasion, which impacts on ecosystems and biodiversity, results in large economic loss (Pimentel et al., 2000). Global Invasive Species Program (GISP) stated that there are several ways; including changing the density, diversity and distribution pattern of the native species, invasive species affect the ecosystems.

Nowadays, most of the wetlands in Thailand are degraded and destroyed from various causes, mainly are the conversion of wetlands into community, agricultural and industrial areas, the discharge of wastewater from those areas into water bodies, climate change, and also invasion of alien plants especially *Eichhornia crassipes* and *Mimosa pigra*. In 2017, Thailand institute of scientific and technological research reported that Nong Bong Khai wetland, registered as Ramsar site, tended to be degraded from 3 core causes 1) elution of fertilizers and insecticides from agricultural areas into water bodies 2) highly increasing in *Eichhornia crassipes* and 3) changes of climate resulted in the fluctuation of the amount of water in the lake. If those causes are not mitigated, the wetland will continuously be degraded and may finally loss.

Remote sensing is one of the tools used in wetland assessment. Remote sensing provides significant data to delineate, explain and predict changes in wetland ecosystems especially where a high spatial resolution is needed (Zweig et al., 2015). Unmanned aerial vehicles (UAVs) can improve the mapping and monitoring of biomass and productivity in coastal wetlands. UAVs have the ability to provide the suitable spatial resolution needed to adequately identify and assess ecosystem change (Whitehead, 2014; Klemas, 2015; Manfreda, 2018). UAVs have high potential in discriminating and mapping a variety of vegetation classes and species (Klemas, 2015). A map from photogrammetry using UAV has proved a cost effective and efficient alternative to traditional remote sensing techniques (Shabazi et al., 2014). High resolution orthophotos acquired from low-altitude UAV photogrammetry can generate information of physiological and ecological characteristics of plant communities such as texture and color (Li et al., 2010). Complex wetland vegetation information at a community scale can be identified (Li et al., 2010; Lechner et al., 2012), delineated and classified.

Wetland loss can have major consequences for biodiversity and the ecosystem services that wetlands provide (Zedler and Kercher, 2005). Wetlands offer a variety of ecosystem services such as storage and purification of water, filtration of agricultural pollutants, flood buffering, fixation of carbon, and the provision of protein via hunting and fishing, among others (Brander et al., 2006; Mitsch and Gosselink, 2007). They also provide critical habitat for flora and fauna, and often represent highly diverse ecosystems (Dudgeon et al., 2006). Processes of wetland loss and degradation undermine the capacity of wetlands to provide these valuable services to humanity (Zedler and Kercher, 2005). Hence, wetlands are ecosystems of global and local importance, which lends support for their conservation (Keddy, 2010). Assessing the wetland's conditions for acknowledge the current situation is importance for future management plan of sustainable wetlands.

1.2 Objectives

(1) Describe background of the increase of alien plants species by analyzing land use/land cover and water quality in the lake. And apply unmanned aerial vehicle (UAV) for non-submerged aquatic vegetation mapping to study their distribution especially *Eichhornia crassipes*.

(2) Describe impacts of water level fluctuation caused by decreased precipitation on the distribution of the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* by applying non-submerged aquatic vegetation and distribution maps based on images from UAV.

(3) Describe impacts of changes of the land use and land cover around the lake and the water level fluctuation to the increase of an alien plant species. And propose a measure to manage an alien plant species for improve the lake and maintain the sustainable ecosystem services.

CHAPTER 2

Theoretical and Conceptual Framework

2.1 Wetland

Wetlands, as defined by the Ramsar Site Convention, mean the areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters (Ramsar convention Secretariat, 2013). While the U.S. Fish and Wildlife Service (2019) specifies the definition of wetlands, in term of ecology, as a transition between terrestrial and aquatic systems, where water is the dominant factor determining development of soils and associated biological communities and where, at least periodically, the water table is at or near the surface, or the land is covered by shallow water. Wetlands are lands which have a predominance of hydric soils and which are inundated by surface water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas (Hammer, 1996). Wetlands are ecosystems that are important for human, plants and wildlife such as a habitat for fish, wildlife and plants, flood protection, shoreline erosion and recreation, education, and research.

Ramsar Site Convention is an international agreement specified a framework for members' co-operation of wetland conservation. Its objective is to conserve and restrain the disappearing of ecosystems in global wetland. This convention was certified in Ramsar, Iran on February 2, 1971 and was legally used in 2518. There are 152 countries participate in this convention. Under Ramsar Site Convention, a category of wetland can be divided, bases on a habitat, into 3 types (1) Coastal wetlands such as lagoon, brackish, water, beach, coral reef, tidal marsh, delta, mangrove forest, mud flat, and seagrass bed (2) Inland wetlands such as river, lake, pond, marsh, swamp, and bog (3) Human-made such as pond, dam, and reservoirs.

2.2 Threats to wetlands

The various causes such as habitat destruction, overexploitation of aquatic resources, pollution, tourism, change of climate, and the introduction of invasive exotic species are depleting wetlands and its biodiversity. In particular, the freshwater ecosystem is highly vulnerable to those pressures. In recent decades, invasive alien species are recognized as one of the major factors for the existing native aquatic diversity (Centre for Biodiversity Policy and Law, 2003). Threats of wetlands can be defined in 3 major causes.

2.2.1 Effect of land use and land cover change on wetland

Wetlands are affected by several surrounding land utilizing. Despite wetlands being known to be critical to providing of valuable ecosystem services, they are among the ecosystems suffering the greatest transformations worldwide (MA, 2005). Land use change caused by human activities has the potential to significantly affect food security and the sustainability of the world agricultural and forest product supply systems (Popp et al., 2014). Land use change is a feature of both rural and urban areas and occurs in both developed and developing countries (Galbraith et al., 2005). Especially in industrialized countries, the intensification of agriculture in fertile regions and the abandonment of farming in less favorable areas affect natural and cultivated ecosystems all over the world (Kristensen, 1999; Van Doorn and Bakker, 2007). During the 20th century, land use change was a main driver behind the loss of wetlands and associated ecosystem services (De Fries et al., 2004; Foley et al., 2005; MA, 2005; Gagne and Fahrig, 2007). In Spain, land use change from intensive agriculture and urbanization is a main cause of biodiversity loss and has led to the 60% conversion of the original wetland area over the last five decades. According to the Spanish sub global ecosystem assessment, 62% of the ecosystem services provided by wetlands have declined over the last fifty years, affecting regulating services in particular (EME, 2011). Also in Thailand, wetland has been a tendency of rapid decline. The area will be replaced by agricultural area, urban area and industrial area. Moreover, drainage wastewater of community, agricultural, and industrial areas into water bodies led to risk of water quality degradation of wetlands (Office of Natural Resources and Environmental Policy and Planning, 2018).

Wetlands in Thailand, especially those outside Ramsar area, are destroyed or altered the utilization. Ratanasermpong (2000) reported that the area of mangrove forest referred from satellite image in 2000 decreased from 1975 by 67,200 ha. Central and eastern of Thailand had the most invasion of mangrove forest which was mostly altered to be an aquaculture area. While the utilization of the area surrounding fresh-water wetland was altered depend on economic conditions. Nong Bong Khai wetland also confronts altering of agricultural land utilization around the lake which leads the fertilizers and chemicals into water body by elution.

The land use within the watershed has great impact on the water quality which may degrade due to the changes in the land use and land cover patterns within the watershed as human activities increase (Ngoye and Machiwa, 2004; Sliva and Williams, 2001). Change in the land cover and land management practices are the key influencing factor behind the alteration of the hydrological system, which lead to the change in runoff as well as the water quality (Yong and Chen, 2002; Junhong et al.,2010). Land use and land cover are very important elements in relation to water quality. Different types of land use and land cover affect the quality of water. Agricultural and household fertilizers have different chemicals within them, such as nitrogen and phosphorus which can be eluted into nearby water sources such as groundwater, streams and larger bodies of water. In turn, this could damage the nutrient content within that water supply, affecting the overall water quality itself (Carl et al., 2015).

2.2.2 Water level fluctuation on wetland

Water-level fluctuations in lake are dominant forces controlling the functioning of lacustrine ecosystems (Wilcox and Meeker, 1992; Poff et al., 1997) Water level fluctuation is a complex variable mentions not only range, but also the frequency and regularity of change. These different components of the level regime may affect the ecological processes and patterns of lakes and also the vegetation in different ways. For example, seasonal fluctuations are likely to have different impacts compared to those with a period of years or decades (Keddy and Reznicek, 1986). The distribution of plant species along lake margins are greatly determined by the hydrological gradient from permanently dry to permanently wet. This can be due to a direct effect on germination and establishment of plants (Nicol and Ganf, 2000) or indirectly via the influence of water regime on competitive interaction (Wilson and Keddy, 1985; Keddy and Constable, 1986).

Water-level fluctuation in wetland depends on changes of precipitation caused by climate change. Climate change can affect wetlands by direct and indirect effects of rising temperature, changes in rainfall intensity and frequency, changing hydrological patterns, extreme climatic events such as drought, flooding and the frequency of storms, which in turn can alter the biogeochemistry and function of the wetland to the degree that some important services might be turned into disservices. This means that a water purification service will no longer be provided and adversely they may start to decompose and release nutrients to the surface water causing problems such as eutrophication, acidification and brownification in the water bodies (Roulet and Moore, 2006; Stets and Cotner, 2008; Corman et al., 2018). Climate change also creates new pathways of introduction of invasive alien species (IUCN, 2021). Climate change, through rising average temperatures, increased variability of precipitation, and increased frequency and severity of storms, will affect the invasive species, especially its invasive potential, and the inversibility of the host ecosystem which led to completely replacement of the native species and be the new native. The utmost impacts of climate change on invasive species may arise from changes in the frequency and intensity of extreme climate events that disturb ecosystems, making them vulnerable to invasions, thus providing exceptional opportunities for dispersal and growth of invasive species (Masters and Norgrove, 2010).

In Thailand, wetlands are affected by climate change causing the fluctuation of water level in wetlands. Office of Natural Resources and Environmental Policy and Planning (2018) reported that Thailand confronted with drought situation almost every year which that results in less precipitation causing of low water level in the wetlands. Declining of water levels in many wetlands affects fauna and flora in the area. In addition, while the water level is decreasing, the terrestrial area around the water reservoir is increasing which that leads the wetland confronts with the invasion of *Mimosa pigra.*

2.2.3 Invasive alien species in wetland

Alien species is a species, subspecies or lower taxon, introduced to new environments, which includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce.

Invasive alien species refers to an alien species whose introduction and/or spread threaten biological diversity of the region/habitat (CBD, 2002).

In recent past, invasive alien species have been emerging as the second biggest threat to global biodiversity after habitat destruction. Wetlands are highly vulnerable to invasion of alien species. Invasive alien species are one of major factors causing species extinctions, damage to populations of wild and domesticated organisms, and significant alteration of ecosystems. The destruction resulting from invasive is through predation, introduction of disease, competition for food and other resources, hybridization, and habitat degradation. They are relevant to wetlands especially those in both tropical and temperate areas. Wetlands are especially vulnerable to invasives because of their position as ecotones or interfaces between terrestrial and aquatic environments that makes them susceptible to invasion from both spheres. Understanding, recognizing and managing infestations of invasives in wetlands is needed also, preparing for new arrivals.

Many wetland plants are defined to be "invasive plants" as species or strains that rapidly increase their spatial distribution by expanding into native plant communities (Richardson et al., 2000a). For example, *Eichhornia crassipes*, floating plant appearing in rivers, lakes and wetlands, can reproduce rapidly especially in global tropical zone They can form thick and extensive mats that can block both sunlight and air from reaching a water surface and so have impacts on aquatic biodiversity and fisheries. They can accumulate at barriers in flowing water and cause damage or blockage to, e.g., irrigation canals.

2.3 *Eichhornia crassipes*

The water hyacinth has scientific name is *Eichhornia crassipes* (C. Mart.) Solms in Pontederiaceae family is a free-floating annual aquatic plant. It is a highly invasive species that originates from the Amazon basin in South America and is believed to have been introduced into South Africa as an ornamental aquatic plant and spread widely in tropical and subtropical country around the world (Center, 1994; Kathryn et al., 2013). Nowadays, it is spreading into temperate country where the temperature is warmer by global climate change effects. *Eichhornia crassipes* is an invasive aquatic plant, it is cause major ecological and economic effect on freshwater ecosystem (Center, 1994). It commonly forms dense, interlocking mats due to its rapid reproductive rate and complex root structure (Mitchell, 1985). *Eichhornia crassipes* reproduces both sexually and asexually. Seed generally germinate within six months, with dry conditions promoting germination (Ueki and Oki, 1979). *Eichhornia crassipes* is found in dam, lake, swamp and riverine wetland throughout the main drainage system.

Eichhornia crassipes can live free-floating on the water surface, or may be anchored by bunches of long, feathery, hanging roots. Adult plants usually grow to 10 – 20 cm high, but may be as tall as 1 m when the plants are clustered together in dense mats on the water surface. The flowers, which are approximately 5 cm wide, are pale blue or violet and the upper 'petal' of each flower has a prominent dark blue patch with a yellow center. There are 8 – 10 flowers clustered together on each "flower spike" produced by the plant. *Eichhornia crassipes* can reproduce vegetatively by budding, which occurs when parts of the plant break off and develop into new plants. Each plant also produces thousands of seeds several times a year following flowering which can begin as early as October and continue through the summer months. When all the flowers on a plant have withered, the stalk gradually bends into the water and after about 18 days, seeds are released at the base of each dead flower. Seeds germinate on moist sediments or in warm, shallow water; flowering can occur 10 – 15 weeks thereafter. Under optimal conditions, *Eichhornia crassipes* has an exceptionally high growth rate – doubling its size in as little as a week. Seeds can remain viable in aquatic sediments for15

– 20 years, highlighting why this is such a problematic species to control (The State of Queensland, Department of Agriculture and Fisheries, 2020).

In Thailand, *Eichhornia crassipes* was imported from Indonesia in 1901. Nowadays, *Eichhornia crassipes* is an invasive alien species in Thailand cause damage to native plant species and ecosystem. It is tolerant to environment and can quickly propagate. When *Eichhornia crassipes* is abundant, it obstructs water flow. Moreover, the dense mats of *Eichhornia crassipes* obscures sunlight into the water and affects to submerged plant cannot photosynthesize. And also has an effect on the dissolved oxygen content in water resource decrease causing worse water quality.

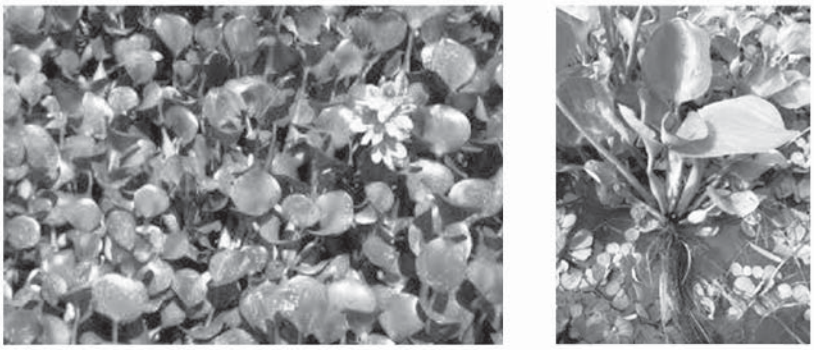


Figure 2.1 *Eichhornia crassipes.*

2.4 ***Mimosa pigra***

Mimosa pigra L., a prickly, perennial, woody shrub native to tropical America, is listed in the Global Invasive Species Database as one of the One Hundred of the World's Worst Invasive Alien Species (Heard, 2004). Outside its native area, especially Southeast Asia and Australia, an invasion may double in area each year (Lonsdale, 1993; Triet et al., 2004). *Mimosa pigra* can be as tall as 4 m. It has adventitious roots that allow growth in a variety of hydrological conditions, rapid growth and maturation, a high production rate of easily dispersed and long-lived seeds, and low nutrient requirements. Its seed viability more than 5 years and seed half-life varies from 9 to 99 weeks, depending on the soil type and depth of burial. It can survive in the dry season by steadily losing leaves, while in permanently moist sites growth and flowering can continue more or less all year round (Wanichanantakul and Chinawong, 1979). The main growth period is in the wet season. New shoots appear in the first rains and a dense canopy form within about a month. Under ideal conditions, it can begin flowering 6–8 months after germination. The main flowering period is the mid to late wet season, but flower production may continue as long as water is available (Lonsdale, 1988). Flower bud maturation usually takes 7–9 days from bud formation. Mature seed pods develop 25 or more days after the flower buds mature, with peak seed falls occurring between the late wet and early dry seasons (Lonsdale, 1988). *Mimosa pigra* has few or no natural enemies which makes it rapidly colonises suitable wetland habitat, forming a nearmonospecific shrubland. Its dense thickets affect both conservation areas and agricultural land (Samouth, 2004; Son et al., 2004) especially negatively impact to the diversity of plants and animals by competing with pasture species, hindering mustering of livestock, and restricting access to water by humans and livestock (Braithwaite et al., 1989; Lonsdale et al., 1989). Control of the weed is expensive and is hampered by the size, inaccessibility and often the remoteness of infestations, regrowth of the seedbed over many years requiring continual follow-up control, and the thorny nature of the stems.

Figure 2.2 *Mimosa pigra.*

2.5 Unmanned aerial vehicle (UAV) and wetland

Remote sensing has been used regularly to identify vegetation communities and monitor land cover changes. Olmsted and Armentano (1997) highlighted changes in the terrestrial-aquatic landscape transition is detected by monitoring wetland vegetation and its distribution. Water fluctuation creates rapid and frequent changes in the type, distribution, and density of plant coverage (Smith et al., 1998; Belluco et al., 2006). Remote sensing provides critical data to delineate, explain and predict changes in wetland ecosystems especially where a high spatial resolution is needed (Zweig et al., 2015). Survey and assessment of wetland can be practiced with various methods such as satellite imagery, manned airplanes or unmanned aircraft systems (UAS). Satellite imagery can offer high resolution products by a high cost but the long periods of revisiting time is its limitation (Nex and Remondino, 2014). Another practice is the manned airplane platform, its organization and performance are quite complex as well as its operational costs are considerable high (Zhang and Kovacs, 2012). Conversely, UAS can provide high spatial resolution with lower operational costs (Hunt et al., 2005) and is not constrained by orbital times or flight schedules (Zweig et al., 2015). Hence, UAS represent a suitable and affordable option in comparison to other platforms for monitoring applications. The advent of photogrammetry using UAV has proved a cost effective and efficient alternative to traditional remote sensing techniques (Shabazi et al., 2014). Some type of wetland, such as palustrine wetland, often includes dense vegetation which other forms of remote sensing, like LiDAR, nearly impossible Cost becomes a consideration when consistent monitoring must be completed on foot by a biologist. A full day of pedestrian surveys can be done in a few hours with a UAV (De Boisvilliers and Selve, 2019). Not only obtain vegetation data from UAVs surveys, but they also can acquire data of land cover, vegetation structure, habitat boundaries, elevation, tree type, and height data because of the extremely high-resolution imagery they produce. Moreover, the photogrammetry generated from UAVs can identify characteristics, such as texture and color, which can be used to identify plant communities. (Boon et al., 2016; Sarah, 2020). Husson et al. (2014) reported that UASs generating sub-decimetre resolution orthoimages offer great potential for lake and river vegetation identification and mapping at the species level.

2.6 Overall conceptual framework of the research

The purpose of this research is to study causes of increasing in *Eichhornia crassipes* in Nong Bong Khai wetland where being threatened by land use/land cover change around the wetland and the fluctuation of water level wrought by change of climate. This research was divided into 4 topics including (1) background of land use/land cover change by analyzes land use/land cover surrounds the lake watershed from satellite image provides by Landsat 7 and 8 (2009, 2012, 2016, and 2018). And also analyzes a water quality history for describe impacts of land use/land cover change. (2) Monitoring the distribution of non-submerged aquatic vegetation and invasive alien vegetation in the lake from orthophoto taken by unmanned aerial vehicle (UAV) for clarify current aquatic vegetation situation. (3) Study water level fluctuation caused by decreased precipitation and also water quality change in the lake. (4) Assessing change of non-submerged aquatic vegetation and invasive alien vegetation in the lake caused by water level fluctuation via orthophotos taken by unmanned aerial vehicle (UAV) for describe aquatic vegetation situation in the lake. The detail of overall conceptual framework research indicated in Figure 2.3.

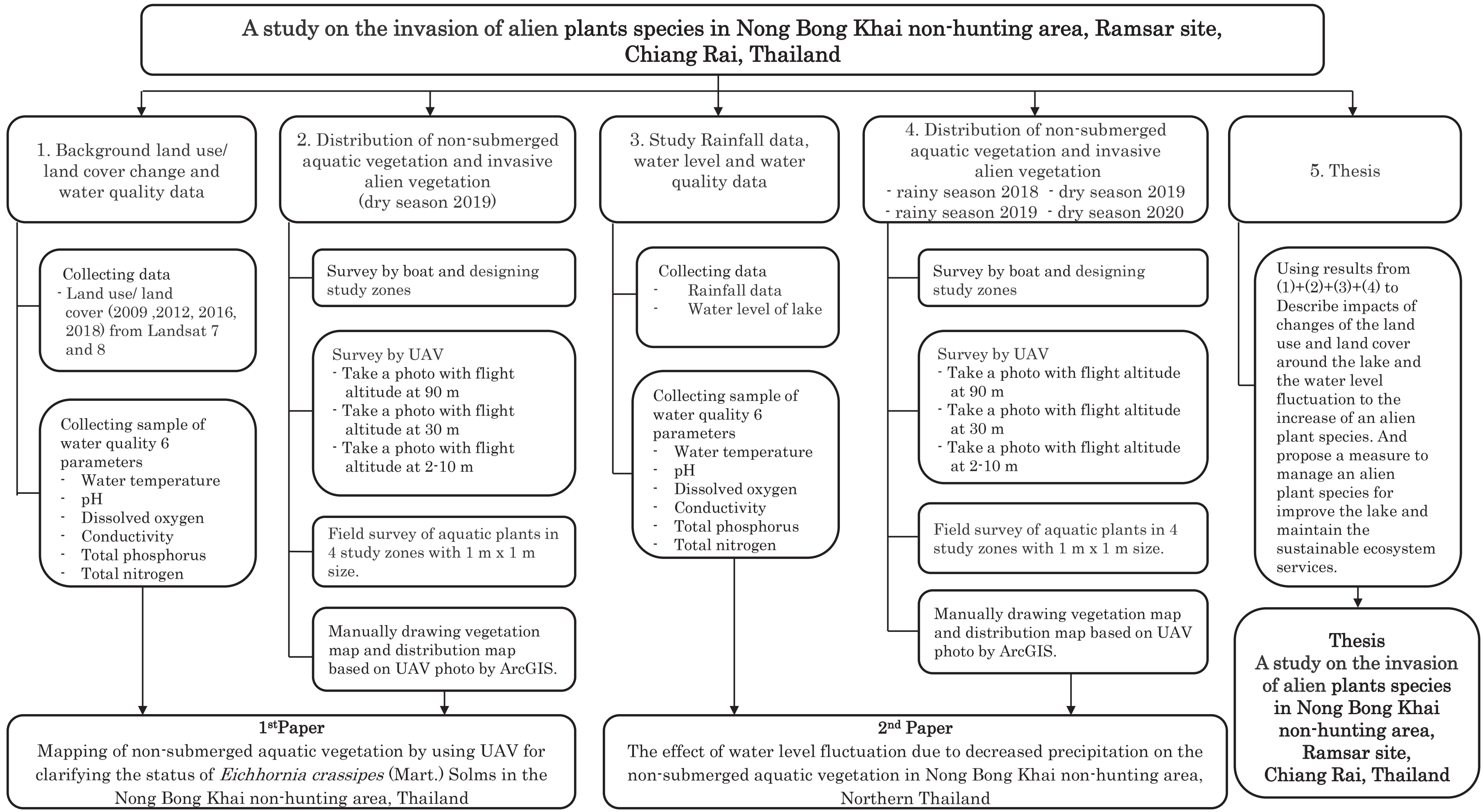


Figure 2.3 Overall conceptual framework of the research.

CHAPTER 3
Study Area – Nong Bong Khai non-hunting area

3.1 Establishment history

Nong Bong Khai lake is an artificial lake which its original area is a small swamp surrounded by low mountains and hills. Afterwards, Department of Rural Development built a dam to make a reservoir for agricultural purposes where covered an area around 434 ha. This scenic lake was an important habitat for fished and birds especially migratory birds which settled here in winter (November to February). Later, surrounding area of the lake was invaded and changed to be a residence. The animal’s habitats were destroyed. Many fishes and water birds were hunted. On 4 April 1985, Nong Bong Khai was officially announced to be the non-hunting area by Royal Forest Department. Then, it was registered as No. 1,101 of wetland of international index on 5 July 2001. The lake has a variety of aquatic plant, such as marginal plants, emerged plants, floating plants and submerged plants, which is a habitat, food resources and shelter of water birds and aquatic animals in the lake (Office of Natural Resources and Environmental Policy and Planning, 2006).

3.2 Physical condition

3.2.1 Geographic location

The Nong Bong Khai lake, in the Nong Bong Khai non-hunting area, is part of the Chiang Sean basin. It is in the Yonok and Pa Sak sub-districts in the Chiang Saen district, Chiang Rai province, in the northern region of Thailand between 20° 14' 33" N and 20° 15' 59" N and between 100° 0' 44" E and 100° 3' 7” E. It is approximately 5 km from the Mekong River (Figure 3.1).

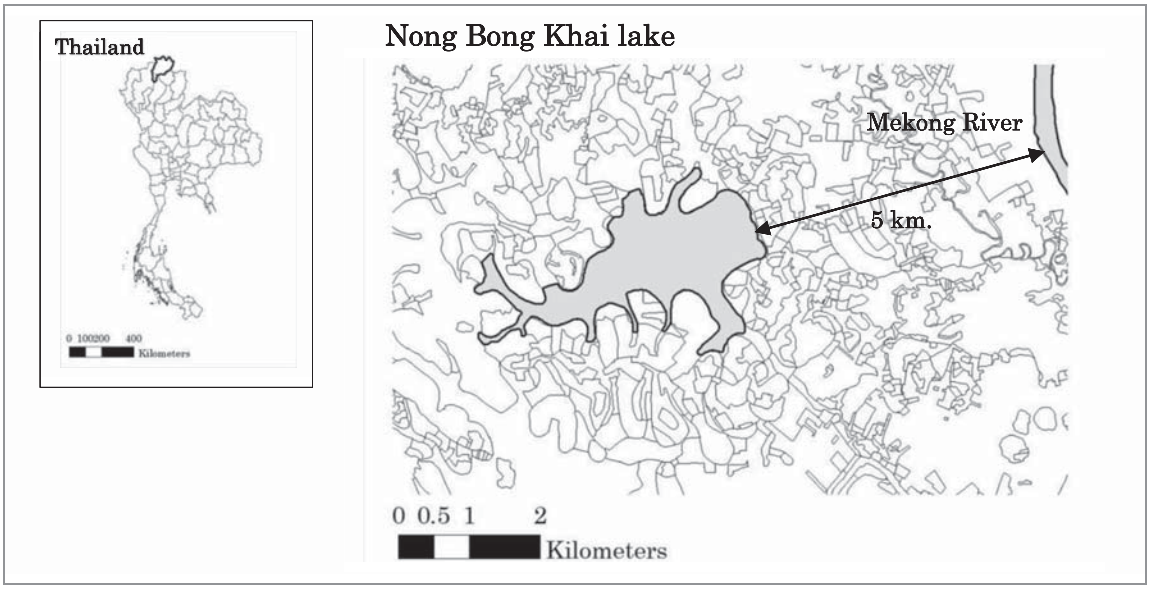


Figure 3.1 Location of Nong Bong Khai non-hunting area, Chiang Rai province, in the northern region of Thailand.

3.2.2 Geological characteristics

Approximately 80% of Nong Bong Khai wetland is flat with gentle slope not exceed 2 % and surrounded by hills with height between 360-500 meters except northeast side where is a flat plain. The lake has an average depth approximately 2 meters and the maximum water depth approximately 4.5 meters. The lake has a small island in about its center. Its surrounding area is degraded forest and private owned areas including residence and agricultural area.

3.2.3 Soil characteristics

Soil found in area around Nong Bong Khai wetland is Chiang Rai soil series which originates from the deposition of sediment in the river. Soil texture consists of clay loam and sandy loam. The pH value is 5.5-6.5. However, due to the area around the lake is an agricultural area, this can lead to soil erosion which can be a cause of shallow lake in the future.

3.3 Meteorological conditions

Nong Bong Khai wetland located in Chiang Rai province which is at the northern of Thailand. The climate of Chiang Rai depending on the influence of the two types of seasonal monsoons: the northeast monsoon which brings cold and dry air masses from China to cover Thailand in winter causing Chiang Rai to be cold and dry, and the southwest monsoon which bring the moist air masses from the Indian Ocean to cover Thailand during rainy season causing Chiang Rai to have general rain. The average annual temperature is 24.4 °C. In summer, the average of maximum temperature is 31.1 °C by the hottest period is in April (the highest temperature is 42.0 °C. And in winter, the average of minimum temperature is 19.31 °C by the coldest period is in January (the lowest temperature is 1.0 °C. The average rainfall in Chiang Saen district, which the Nong Bong Khai non-hunting area is located, is at 1,600-1,800 mm, with the highest rainfall in August and the lowest in January (Thai Meteorological Department, 2021).

3.4 Natural resource

3.4.1 Flora

Nong Bong Khai wetland can be dividing by plant characteristics into 4 types; marginal plant, emerged plant, floating plant and submerged plant. A total of 187 plant species were found. *Cephalanthus tetrandra* (Roxb.) Ridsdale & Bakh.f. and *Burmannia coelestis* D. Don were rare species found in this area. Fifteen exotic species were found, e.g., *Mimosa pigra* L. and *Eichhornia crassipes* (Mart.) Solms. (Office of Natural Resources and Environmental Policy and Planning, 2018).

Cephalanthus tetrandra **(Roxb.) Ridsdale & Bakh.f.**

Burmannia coelestis **D.Don**

Source: https://www.planthealthtalk.com/ and https://www.dnp.go.th/

Figure 3.2 Rare species in Nong Bong Khai non-hunting area.

3.4.2 Fauna

As forest area around Nong Bong Khai wetland is small and also used to be destroyed, small-size wild animals, e.g., birds and fishes, were only found in this area. However, the lake area is still plentiful and it is also a habitat of many fishes and water birds. There were 156 species of water birds found. Nong Bong Khai wetland is an important habitat for both native birds, e.g., *Dendrocygna javanica* (Horsfield, 1821), *Porphyrio porphyrio*, *Gallinula chloropus* (Linnaeus, 1758), and migratory birds, e.g., *Anas falcata*, *Aix galericulata*, *Podiceps cristatus* (Linnaeus, 1758). Moreover, the almost-extinct bird species, such as *Sarkidiornis melanotos*, *Sterna aurantia* and *Aythya baeri*, were found.

In the lake, 77 fish species from 19 families were found by 5 species of them were an almost-extinct species, such as *Pangasianodon gigas* (Chevey, 1931), *Clarias batrachus* (Linnaeus, 1758), *Clarias macrocephalus* Günther, 1864, *Betta splendens* and *Pangasianodon hypopyhalmus*.

Dendrocygna javanica **(Horsfield, 1821)** ***Anas falcata***

Source: https://www.thainationalparks.com/ and http://tolweb.org/

Figure 3.3 Fauna in Nong Bong Khai non-hunting area.

3.5 Utilization, recreation and tourism

The Nong Bong Khai non-hunting area is important of human's living around the lake. The lake is utilized for agriculture, fishery, rest area, and eco-tourism. This area is proper for students and tourists to learn about the nature especially migratory birds' observation in winter. Moreover, the Nong Bong Khai non-hunting area provides boat for birds' observation.

Figure 3.4 Famous attractive point for tourist in Nong Bong Khai non-hunting area.

CHAPTER 4

Mapping of non-submerged aquatic vegetation by using UAV for clarifying the status of *Eichhornia crassipes* (Mart.) Solms in the Nong Bong Khai non-hunting area, Thailand

4.1 Introduction

Nong Bong Khai lake is a wetland located in the Nong Bong Khai non-hunting area, Chiang Rai, Thailand. This area is a habitat for local and migratory water birds. In 2001, this area was classified as a Ramsar site of international importance (Office of Natural Resources and Environmental Policy and Planning, 2006). This lake contains a variety of aquatic plants including marginal plants, emerged plants, floating plants, and submerged plants. In 2017, the Thailand Institute of Scientific and Technological Research reported that the lake was invaded by *Eichhornia crassipes* (Mart.) Solms. If suitable management were neglected, they would have negatively affected the lake ecosystem. *Eichhornia crassipes*, a floating macrophyte indigenous to the Amazon basin, has been spread around the world, mostly as an ornamental plant, (José, 1996) and have been described as the world's worst water weed (Howard and Matindi, 2003). *Eichhornia crassipes* can double itself in five days (Wright and Purcell, 1995), which can be described as a weed in most countries in the world. Since it always densely crowns, it can obstruct and impact waterways, transportation, fisheries, and many other water uses (Center et al., 2002). Invasive plant species are exogenous species introduced into new environments (mostly by human activity) that rapidly propagate, changing the structure and function of the invaded ecosystems (Paul and James, 2003; Hong and Robert, 2006). One of the most basic tools for invasive plant management within aquatic ecosystems is vegetation mapping. Effective lake management requires detailed vegetation maps which describe the distribution of the plant species (Kaneko and Nohara, 2014). To generate a vegetation map, effective field survey data is necessary for initial input data. Occurrence and abundance data of vegetation are needed, especially at the species level, to enhance plant species detection (Husson et al., 2014; Andrea et al., 2019). To generate such data, ground truth survey is commonly used (Baattrup-Pedersen et al., 2001; Cruzan et al., 2016). However, ground truth survey is labor-intensive and limited to small spatial scales; in addition, it may not provide consistent results (Dudley, 2013).

Remote sensing has been applied to mitigate the limitations of ground truth survey (Husson et al., 2014). However, the inadequate spatial resolution of remote sensing techniques is a major limitation when identifying aquatic plants at the species level and may be a significant obstacle when mapping aquatic vegetation (Muller, 1997; Adam et al., 2010; Ashraf et al., 2010). Unmanned aerial vehicles (UAV) represent a new source that can provide useful data for ecological and natural resource management (Watts et al., 2010; Shahbazi et al., 2014; Marcaccio et al., 2016). UAV is able to produce a sufficient level of image resolution (from <10 cm to <2 cm per pixel) to identify individual plants (Getzin et al., 2012; Kaneko and Nohara, 2014) over large areas at low cost (Anderson and Gaston, 2013; Cruzan et al., 2016). Moreover, UAV can provide real-time vegetation information (Arnold et al., 2013; Rusnáka et al., 2018). In addition, they have the ability to access areas that are dangerous or difficult to reach (Hardin and Hardin, 2010).

The purpose of this research is to study causes of highly increasing in *Eichhornia crassipes* that affect the ecosystem. And applying UAV for non-submerged aquatic vegetation mapping in the Nong Bong Khai non-hunting area to study and analyze the distribution of *Eichhornia crassipes*. This research will be useful for management of *Eichhornia crassipes* in the Nong Bong Khai non-hunting area.

4.2 Materials and methods

4.2.1 Land use and land cover map

Land use and land cover maps for 2009, 2012, 2016, and 2018 were obtained from the Land Development Department, Thailand which those maps were generated by Landsat 7 and Landsat 8. The information was provided in provincial scale but only the area around Nong Bong Khai lake was focused by bases on its watershed.

4.2.2 Water quality data

Two sources of water quality data were collected. 1) Past data in 2008 (Kwanruen, 2008), 2011 and 2017 (Thailand Institute of Scientific and Technological Research, 2011,2017) was collected by review of literatures. 2) Current data in 2019 was collected during ground survey in study area.

4.2.3 Data collection

4.2.3.1 Study zone designation

In March 2019, a survey of the overall lake was implemented using two methods, an aerial survey and a ground truth survey. The data from these surveys were used to analyze the distribution of the non-submerged aquatic plants (marginal, emerged, and floating plants) to designate the study zones. Although marginal plants and emerged plants can be found at the same water level, they are totally different in habitat characteristics. Marginal plants usually grow around the edges of the lake where the water is shallow. They tolerate constantly moist soil but do not tolerate water over their crown or foliage. Emerged plants are rooted to the ground of the water with stiff stems but most of their vegetation exists above the water surface. They need constant exposure to sunlight. First, in the aerial survey, a DJI Mavic Pro UAV with a Mavic Pro 12.35M effective pixel RGB camera (FOV = 78.8°, focal length equivalent to 26 mm of a 35-mm format, F-stop = *f*/2.2) and a DJI GS Pro application (www.dji.com, Japan) were applied during an automatic UAV flight to obtain an aerial photo of the overall lake. Initial flight parameters were set such that the front and side overlap ratios were 80% and 60%, respectively, with a flight speed of 8.5 m/s and an altitude of 90 m to create a continuous multiple-shot photo with a 28-mm pixel size captured at 2-second time intervals. Agisoft Metashape software (Agisoft, Russia) was used to create an orthophoto of the entire lake. Then, surveying by boat and walk was conducted to observe the non-submerged aquatic plants as a ground survey. Also, interviews with officers in the Nong Bong Khai non-hunting area were conducted for background information. After the data from the two survey methods were analyzed, four study zones were chosen in different areas of the lake.

- Zone A was in the eastern part of the lake. Water depth was between 0.63 m and 1.75 m.

- Zone B was in the northern part of the lake. Water depth was between 0.80 m and 1.30 m.

- Zone C was in the western part of the lake. Water depth was between 0 m and 1.50 m.

- Zone D in the southern part of the lake. This zone was the deepest zone with a water depth between 2.70 m and 2.80 m.

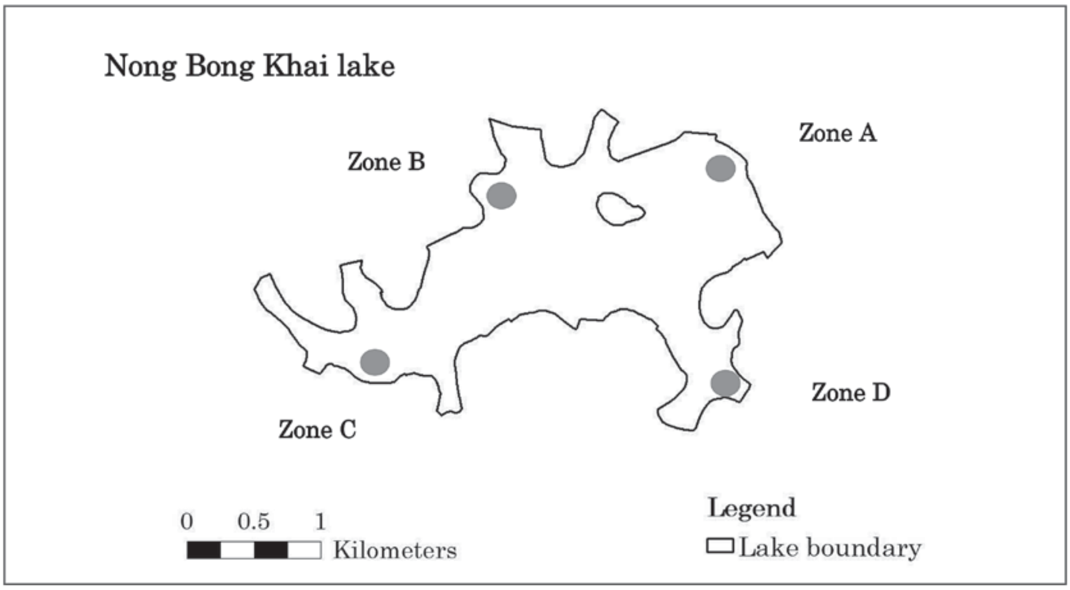


Figure 4.1 Study zones in Nong Bong Khai lake.

4.2.3.2 Data collection in the study zones

The process of collecting data in the four study zones was divided into four parts:

1) Taking aerial RGB photos at an altitude of 2–10 m: UAV flights were manually controlled, and single-shot photos were taken at very close range for a specific survey of the individual species. The pixel sizes were less than 3 mm.

2) Taking aerial RGB photos at an altitude of 30 m: An automatic flight program, the DJI GS Pro application, was used to create continuous multiple-shot photos with a 9-mm pixel size captured at equal time intervals (2 seconds) with a set 80%/60% front/side overlap. The flight speed was 2.8 m/s at an altitude of 30 m.

3) Random sampling plots: In each study zone, the dominant species were visually distinguished. Each dominant species was randomly selected by sampling several plots with a 1 m × 1 m quadrat. A total of 82 sampling plots could be separated by 25 plots in zone A, 19 plots in zone B, 19 plots in zone C, and 19 plots in zone D. Vegetation data for each species were recorded according to the Braun–Blanquet cover abundance scale (Mueller-Vombois and Ellenberg, 1974). A photo of each sample plot was taken using a GoPro 12M-pixel digital camera. The coordinates were recorded using a GPS-60CSx. The water depth was also measured by a level measurement staff and recorded at every sample plot (Figure 4.2).

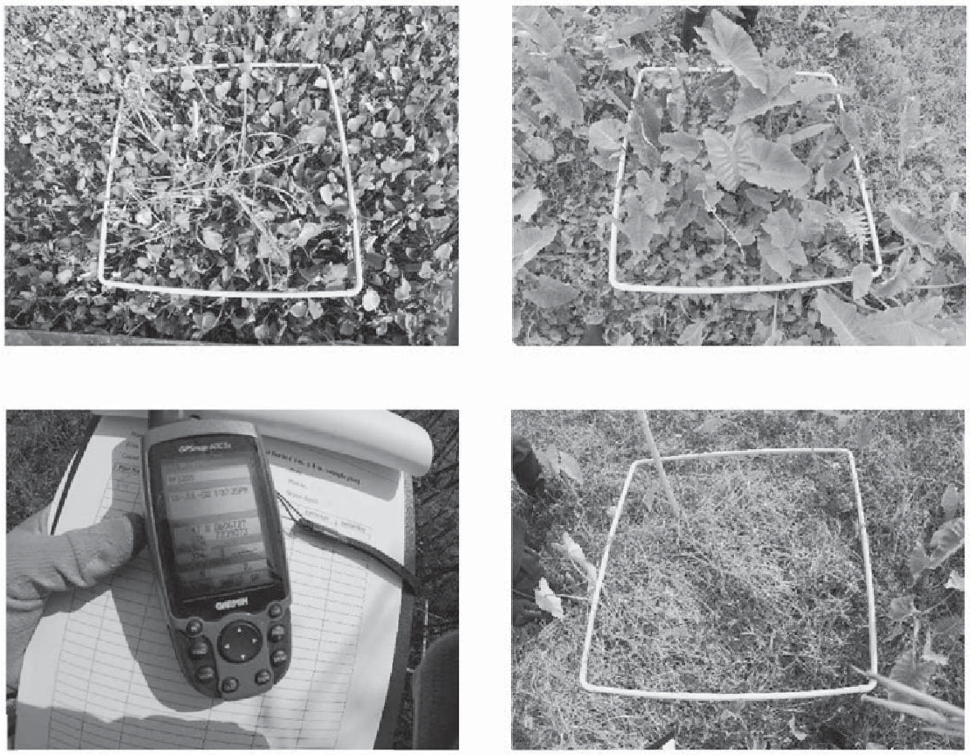


Figure 4.2 Random sampling plots, GPS-60CSx for coordinates recording and water depth measuring at sample plot.

4) Water quality sampling: twelve samplings from four study zones were collected. Total six parameters were measured by two methods. The field measure was conducted with a HORIBA U53G series to measure four parameters (Water temperature, pH, Dissolved Oxygen, and Conductivity). The laboratory

test was conducted to measure two parameters (Total Phosphorus and Total Nitrogen).

4.2.4 Data analysis

4.2.4.1 Plant species identification

According to data obtained from the sampling quadrats in the four study zones, the scientific name and family of each aquatic plant was identified by a taxonomist at the Herbarium Department of the National Parks, Wildlife and Plant Conservation, Bangkok, Thailand.

4.2.4.2 UAV data analysis

To combine the continuous multiple-shot photo taken by the UAV, Agisoft Metashape Metashape software (Agisoft, Russia) was used to create an orthophoto of each study zone via the following seven processes: align photos, build dense, build mesh, build texture, build tiled model, build DEM, and then create an orthophoto that is a high-resolution perpendicular photo with high-coordinate accuracy.

4.2.4.3 Water quality analysis

Compare the results of water quality test (6 parameters) from 12 sample plots in four study zones with Standard Quality of Surface Water Thailand (class 3) and Standard Methods for the Examination of Water and Wastewater. And the results were also compared with those of previous studies in 2008, 2011, and 2017.

4.2.5 Vegetation mapping

The process of vegetation mapping was manually completed using ArcMap software and referring to the UAV photos via direct visual interpretation with maximum patch size at 3 m x 3 m, based on two altitude levels (30 m and 90 m). At an altitude of 30 m, the maps are representative of the vegetation in the four study zones. Meanwhile the map interpreted from the data survey at an altitude of 90 m represents the vegetation over the entire lake.

Vegetation maps in the four study zones were directly interpreted from the 30-m orthophotos. The boundaries of the dominant plant species were drawn based on the color and texture differences that appeared in the orthophotos and were supported by the single-shot RGB photos taken at an altitude of 2–10 m. Moreover, ground truth survey data was co-analyzed for more accuracy. Meanwhile, the vegetation map over the entire lake was interpreted using the 90-m orthophoto. In this case, the boundaries were determined using the 30-m orthophotos references.

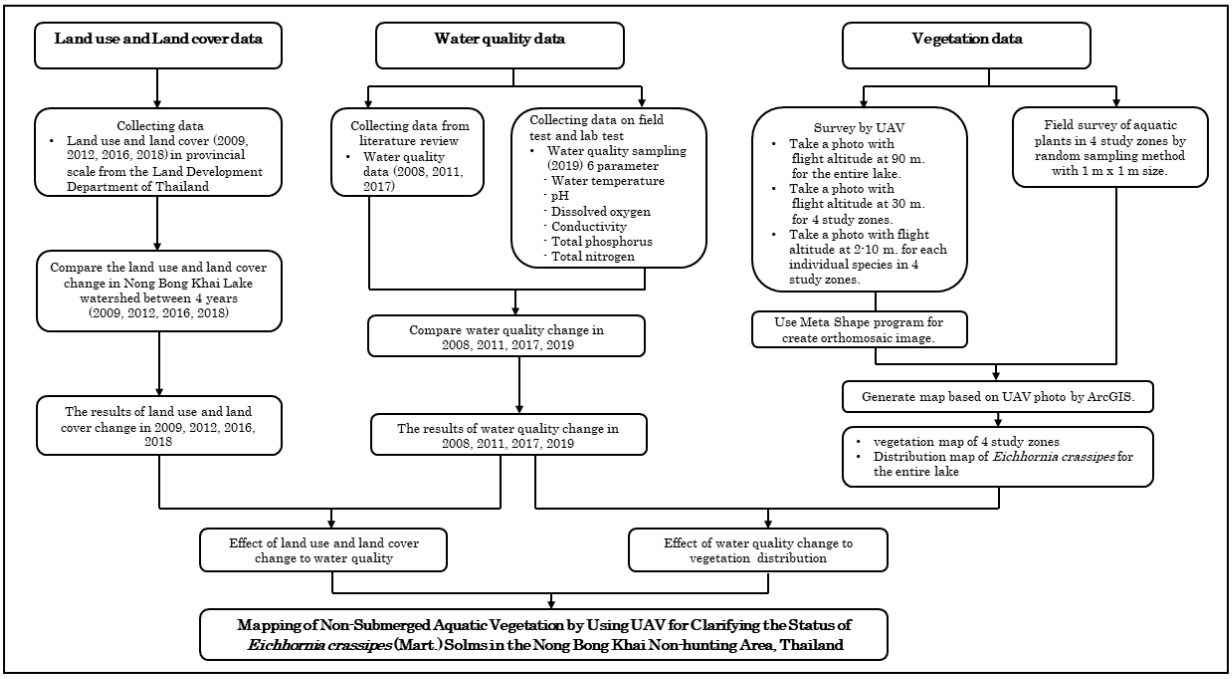


Figure 4.3 Flow chart of research methodology.

4.3 Results

4.3.1 Background interview

The officers of Nong Bong Khai non-hunting area reported that in 2001, *Eichhornia crassipes* was rarely found in this area but it obviously increased in 2011. They also reported that in 2011, surrounding areas of the lake were mostly turned from mixed deciduous forest to agricultural area.

4.3.2 Land use and land cover

Sixteen land use and land cover categories were identified in land use and land cover map of Nong Bong Khai lake watershed in 2009, 2012, 2016, and 2018 (Figure 4.4). Over four studied years, field crop, deciduous forest, and paddy field were the most area around the Nong Bong Khai lake. The average proportions of field crop, deciduous forest, and paddy field were 27.77%, 12.75%, and 7.28 %, respectively. Through 2009-2018, field crop area continuously increased. While deciduous forest area continuously decreased. And the paddy field area did not obviously change through 2009-2018. The materiality changes when compared 2009 and 2018 were the increases in field crop area and perennial crop area, and the decreases in the area of deciduous forest, rangeland, and orchard. Field crop area increased by 92.07 % (from 594.56 ha to 1,141.99 ha). Perennial crop area increased by 53.27% (from 78.78 ha to 120.74 ha). Conversely, deciduous forest area decreased by 53.23% (from 561.53 ha to 262.64 ha), rangeland area decreased by 47.86% (from 399.31 ha to 208.22 ha), and orchard area decreased by 38.90% (from 187.13 ha to 114.34 ha). The details of other land use and land cover categories are shown in Figure 4.5.

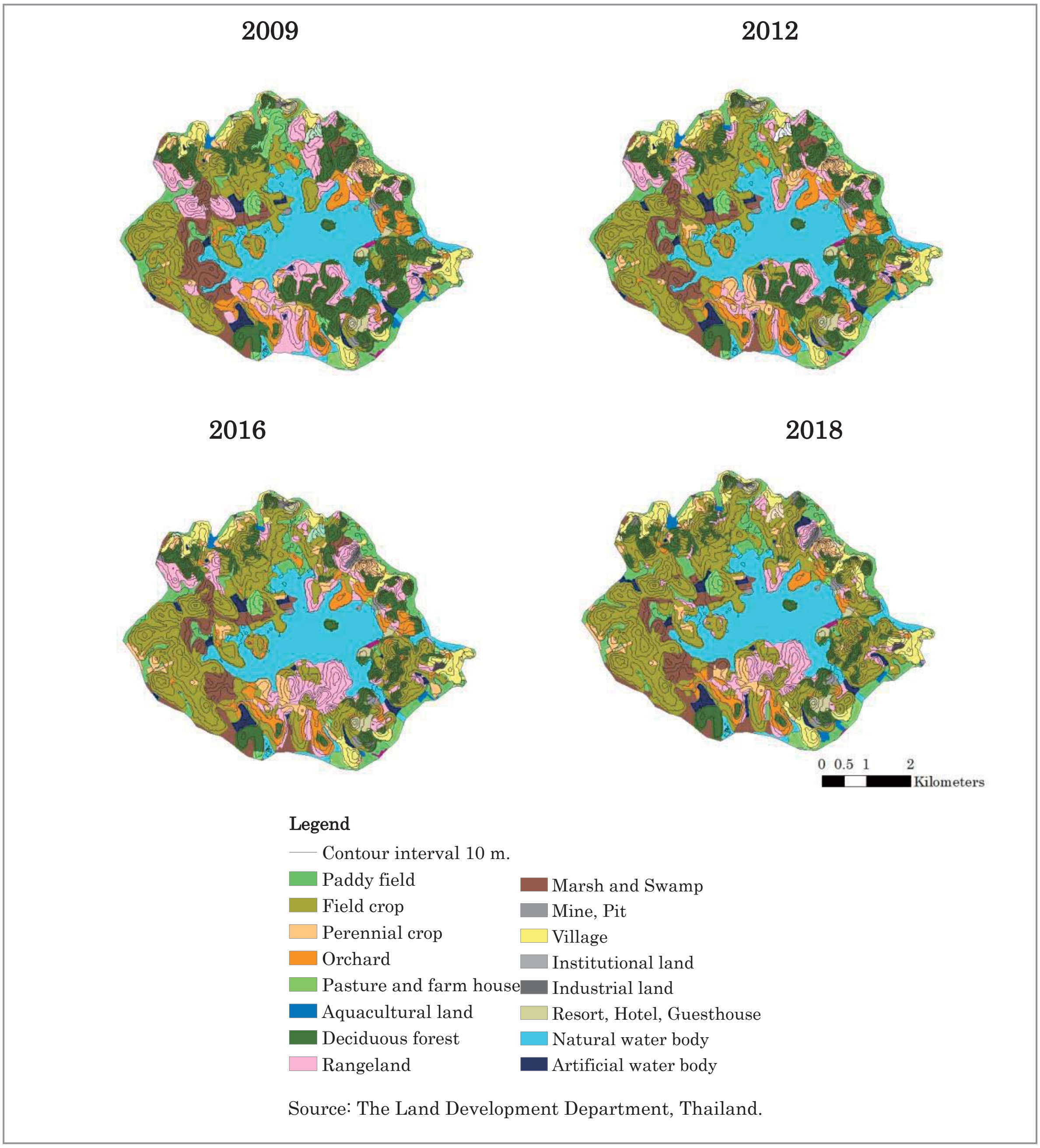


Figure 4.4 Land use and land cover change in Nong Bong Khai lake watershed during years 2009, 2012, 2016, and 2018.

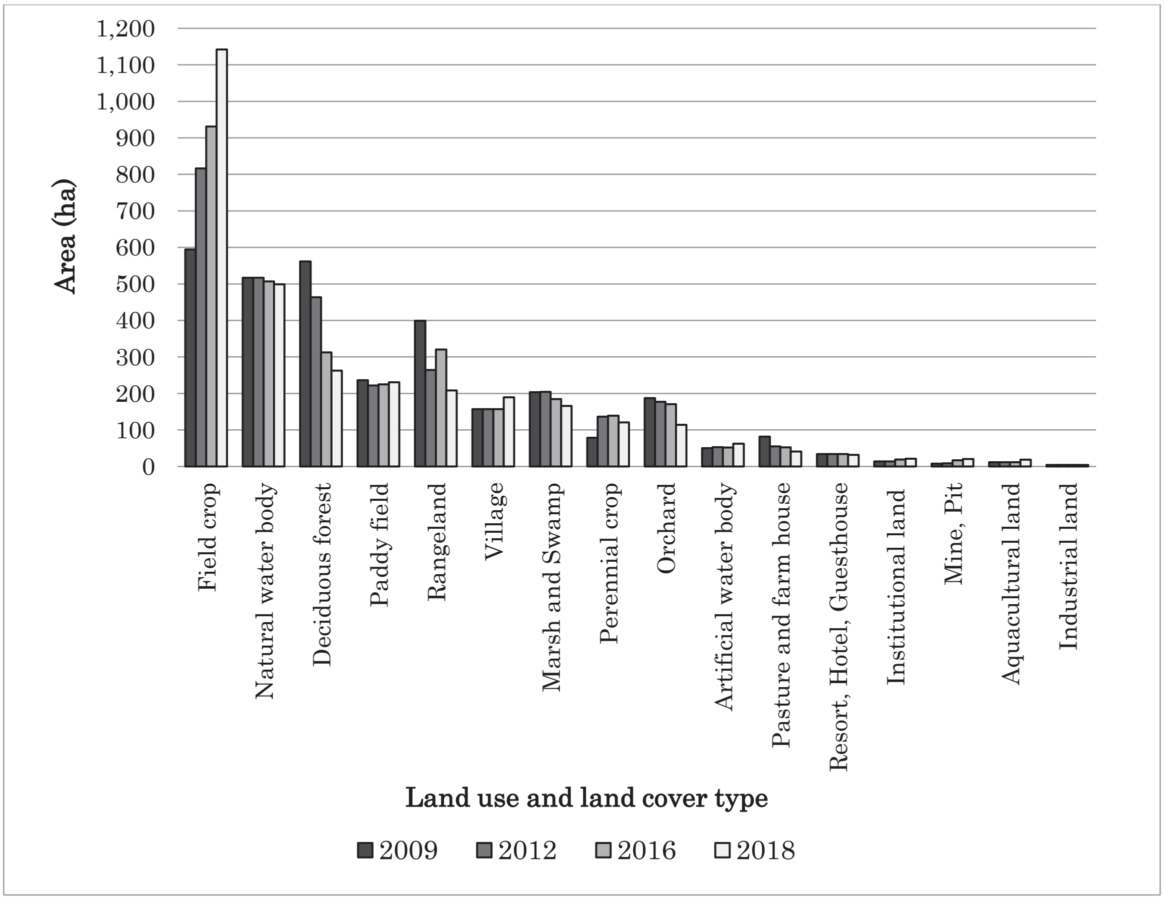


Figure.4.5 Land use and land cover change in Nong Bong Khai lake watershed in years 2009, 2012, 2016, and 2018.

4.3.3 Water quality

Results of water quality measurement of four study zones referring to Standard Quality of Surface Water Thailand (class3) found that the pH was between 6.50 and 7.03, which was within the standard values. DO value was between 3.07-3.53 mg/L, which was lower than the standard value (4 mg/L). Results of total nitrogen and total phosphorus were compared with the Standard Methods for the Examination of Water and Wastewater. Total nitrogen in zone B (4.98) and zone D (4.08) were higher than the standard (4 mg/L), and total phosphorus in zone A (1.12) also exceeded the standard (0.5 mg/L). Conductivity values in four study zones were quite low between 30.22 and 37.62 which the acceptable value of conductivity in freshwater is typically between 150-300 μS/cm (Table 4.1). Compared to the water quality measured by the study in years 2008 (Kwanruen,2008), 2011, and 2017 (Thailand Institute of Scientific and Technological Research, 2011,2017), pH value and conductivity value did not obviously change. However, the DO value in 2019 was lower than in the three previous studies. The TP and TN value could not be compared as the previous studies did not provide sufficient information (Table 4.2).

Table 4.1 Water quality in zone A, zone B, zone C and zone D.

Zone	No.	Parameter											
		Water Temp (°C)	Avg.	pH	Avg.	DO (mg/l)	Avg.	Conductivity (µs/cm)	Avg.	TP (mg/l)	Avg.	TN (mg/l)	Avg.
A	1	22.0		6.5		3.03		30.20		1.10		3.40	
	2	23.2	22.57	6.7	6.50	3.10	3.07	30.12	30.22	1.14	1.12	3.45	3.48
	3	22.5		6.3		3.07		30.35		1.12		3.58	
B	1	23.5		6.2		3.50		35.10		0.50		4.80	
	2	23.8	23.83	6.5	6.33	3.30	3.33	33.20	35.15	0.40	0.40	5.20	4.98
	3	24.2		6.3		3.20		37.15		0.30		4.93	
C	1	25.3		6.5		3.40		38.15		0.06		0.15	
	2	24.8	25.17	6.7	6.77	3.50	3.53	37.20	37.62	0.10	0.08	0.10	0.13
	3	25.4		7.1		3.70		37.50		0.08		0.13	
D	1	25.2		6.8		3.05		31.30		0.25		4.10	
	2	26.0	25.67	7.2	7.03	3.12	3.08	30.50	30.83	0.18	0.22	3.80	4.08
	3	25.8		7.1		3.08		30.70		0.22		4.35	

Table 4.2 Water quality comparison of the Nong Bong Khai lake in years 2008, 2011, 2017, and 2019.

Zone	Year	Water Temp (°C)	pH	DO (mg/l)	Conductivity (µs/cm)	TP (mg/l)	PO_4^{3-} (mg/l)	TN (mg/l)	NH_3-N (mg/l)	NO_3^- (mg/l)	NO_2^- (mg/l)
A	2008	-	-	-	-	-	-	-	-	-	-
	2011	-	-	-	-	-	-	-	-	-	-
	2017	33.50	5.00	5.80	21.60	-	0.100	-	0.090	0.100	-
	2019	22.57	6.50	3.0	30.22	1.12	-	3.48	-	-	-
B	2008	32.40	7.60	7.80	-	-	0.008	-	0.023	-	0.002
	2011	22.30	5.60	6.38	14.99	-	-	-	-	-	-
	2017	34.00	5.00	3.90	73.50	-	0.100	-	0.180	0.140	-
	2019	23.83	6.33	3.33	35.15	0.40	-	4.98	-	-	-
C	2008	32.80	7.80	7.80	-	-	0.007	-	0.030	-	0.002
	2011	-	-	-	-	-	-	-	-	-	-
	2017	-	-	-	-	-	-	-	-	-	-
	2019	25.17	6.77	3.53	37.62	0.08	-	0.13	-	-	-
D	2008	32.30	6.30	4.90	-	-	0.030	-	0.048	-	0.007
	2011	22.10	6.08	4.53	13.66	-	-	-	-	-	-
	2017	-	-	-	-	-	-	-	-	-	-
	2019	25.6	7.03	3.08	30.83	0.22	-	4.08	-	-	-

4.3.4 Species identification

A total of 54 plant species in 29 families of aquatic plants were identified from four study zones. Regarding the general life forms, there were 19 (35.19%) herbs, 12 (22.22%) grasses, 7 (12.96%) aquatics, 5 (9.26%) climbers, 4 (7.41%) shrubs, 2 (3.70%) epiphytes, 2 (3.70%) terrestrial ferns, 1 (1.85%) tree, 1 (1.85%)

undershrub, and 1 (1.85%) bamboo species. In addition, these species had different habitats: marginal (24), terrestrial (23), floating (5), and emerged (2) (Appendix 4). A ground survey considering the covering area of each plant species showed dominant species of each sample plot in each study zone (Appendix 5). The average water depth in plots dominated by each major plant species was calculated and shown in Appendix 6. Moreover, from the ground truth survey, an interesting species was *Thrixspermum amplexicaule* (Blume) Rchb.f, which was found in zone C and zone D; this species is normally found in wetlands in southern Thailand (Suwit, 2006).

4.3.5 Vegetation maps

The vegetation maps generated by the 30-m orthophotos (Figure4.6) provided a high-resolution picture that was clear, in terms of color, shape, and texture. The map showed the covering area of dominant plant species in zones A-D (Figure 4.7). For the details and covering area of each dominant species found in the four study zones, see Table 4.3. The map based on the 90-m orthophoto (Figure 4.8) focused on the entire lake. In the center of the 90-m orthophoto (Figure 4.9), the UAV did not take a photo in that area because it was proved by ground survey that there was no distribution of aquatic plant. In addition, as the lake is very large, taking a photo for all the entire lake requires too much time consumption. This may take a several days to finish which that can reduce the accuracy of the distributed area as a result from moving of *Eichhornia crassipes* influenced by wind. The 90-m orthophoto had an insufficient resolution to identify the plant species. The map was able to describe the distribution of *Eichhornia crassipes*. It was clearly identified in the 90-m orthophoto with a covering area of approximately 592,888 m^2 for the total area of the lake. Moreover, the vegetation maps interpreted from the 30-m orthophoto also showed the distribution of *Eichhornia crassipes* in four study zones.

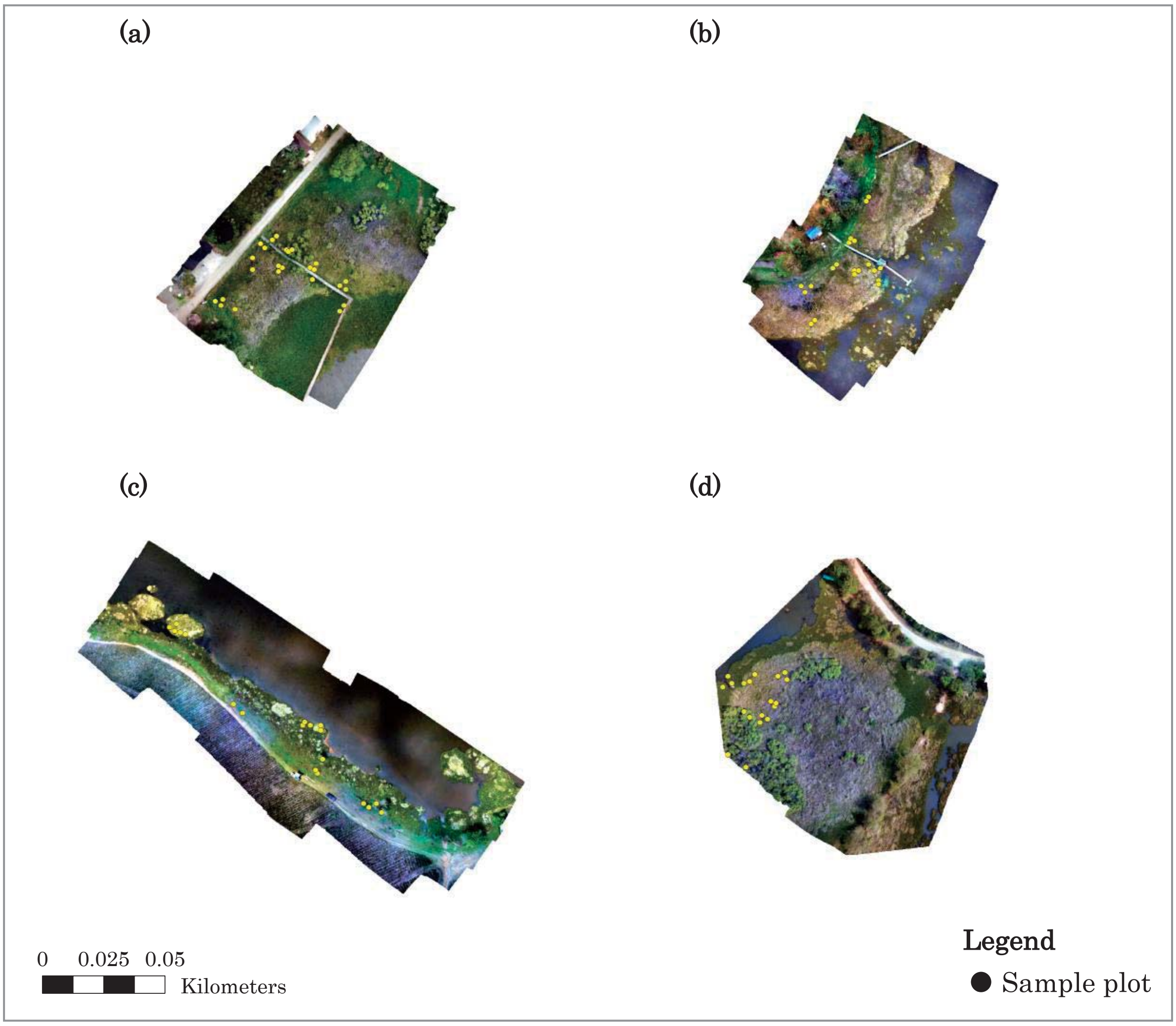


Figure 4.6 Orthophoto of zone A (a); zone B (b); zone C (c); and zone D (d).

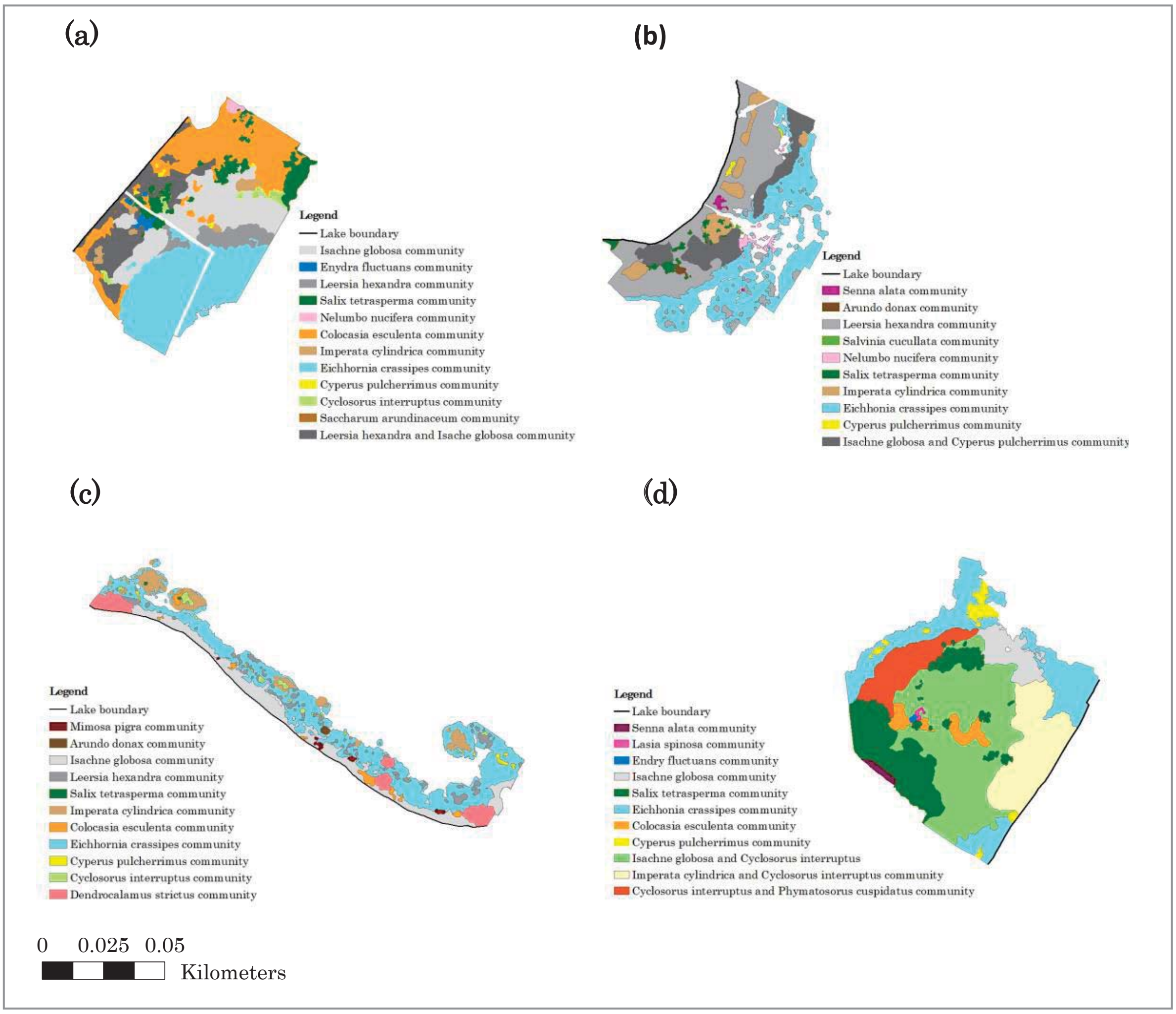


Figure 4.7 Manual mapping by direct visual interpretation of zones A (a); B (b); C (c); and D (d).

Table 4.3 Covering area of each plant community in zone A, zone B, zone C and zone D.

Community name	Study area								Total	Percentage of total of species to total plant area (%)
	A		B		C		D			
	m²	%	m²	%	m²	%	m²	%		
Eichhornia crassipes (Mart.) Solms	2,315	29.26	2,209	36.20	2,904	49.85	2,084	19.60	9,512	31.21
Colocasia esculenta (L.) Schott	1,921	24.28	-	-	112	1.92	293	2.76	2,326	7.63
Isachne globosa (Thunb.) Kuntze	1,528	19.31	-	-	1,264	21.70	543	5.11	3,335	10.94
Leersia hexandra Sw *and Isachne globose (*Thunb.) Kuntze	1,030	13.02	-	-	-	-	-	-	1,030	3.38
Leersia hexandra Sw	426	5.38	2,276	37.30	388	6.66	-	-	3,090	10.14
Salix tetrasperma Roxb	301	3.80	141	2.31	8	0.14	1,754	16.49	2,204	7.23
Imperata cylindrica (L.) Raeusch	140	1.77	445	7.29	497	8.53	-	-	1,082	3.55
Cyclosorus interruptus (Willd.) H. Itô	123	1.55	-	-	84	1.44	-	-	207	0.68
Enhydra fluctuans Lour	60	0.76	-	-	-	-	11	0.10	71	0.23
Nelumbo nucifera Gaertn	41	0.52	76	1.25	-	-	-	-	117	0.38
Cyperus pulcherrimus Willd. ex Kunth	25	0.32	24	0.39	51	0.88	225	2.12	325	1.07
Saccharum arundinaceum Retz	2	0.03	-	-	-	-	-	-	2	0.01
Isachne globosa (Thunb.) Kuntze *and Cyperus pulcherrimus* Willd. ex Kunth	-	-	876	14.36	-	-	-	-	876	2.87
Senna alata (L.) Roxb	-	-	29	0.48	-	-	-	-	29	0.10
Arundo donax L	-	-	21	0.34	20	0.34	-	-	41	0.13
Salvinia cucullata Roxb. ex Bory	-	-	5	0.08	-	-	-	-	5	0.02
Dendrocalamus strictus (Roxb.) Nees	-	-	-	-	450	7.73	-	-	450	1.48
Mimosa pigra L.	-	-	-	-	47	0.81	-	-	47	0.15
Lasia spinosa (L.) Thwaites	-	-	-	-	-	-	17	0.16	17	0.06
Imperata cylindrica (L.) Raeusch *and Cyclosorus interruptus (*Willd.) H. Itô	-	-	-	-	-	-	1,553	14.60	1,553	5.10
*Isachne globosa (*Thunb.) Kuntze *and Cyclosorus interruptus (*Willd.) H. Itô	-	-	-	-	-	-	3,340	31.41	3,340	10.96
*Cyclosorus interruptus (*Willd.) H. Itô *and Phymatosorus cuspidatus* (D. Don) Pic.Serm.	-	-	-	-	-	-	814	7.65	814	2.67
Total	**7,912**	**100.00**	**6,102**	**100.00**	**5,825**	**100.00**	**10,634**	**100.00**	**30,473**	**100.00**

Remark: Index: m² = Covering area, % = Percentage to total plant species

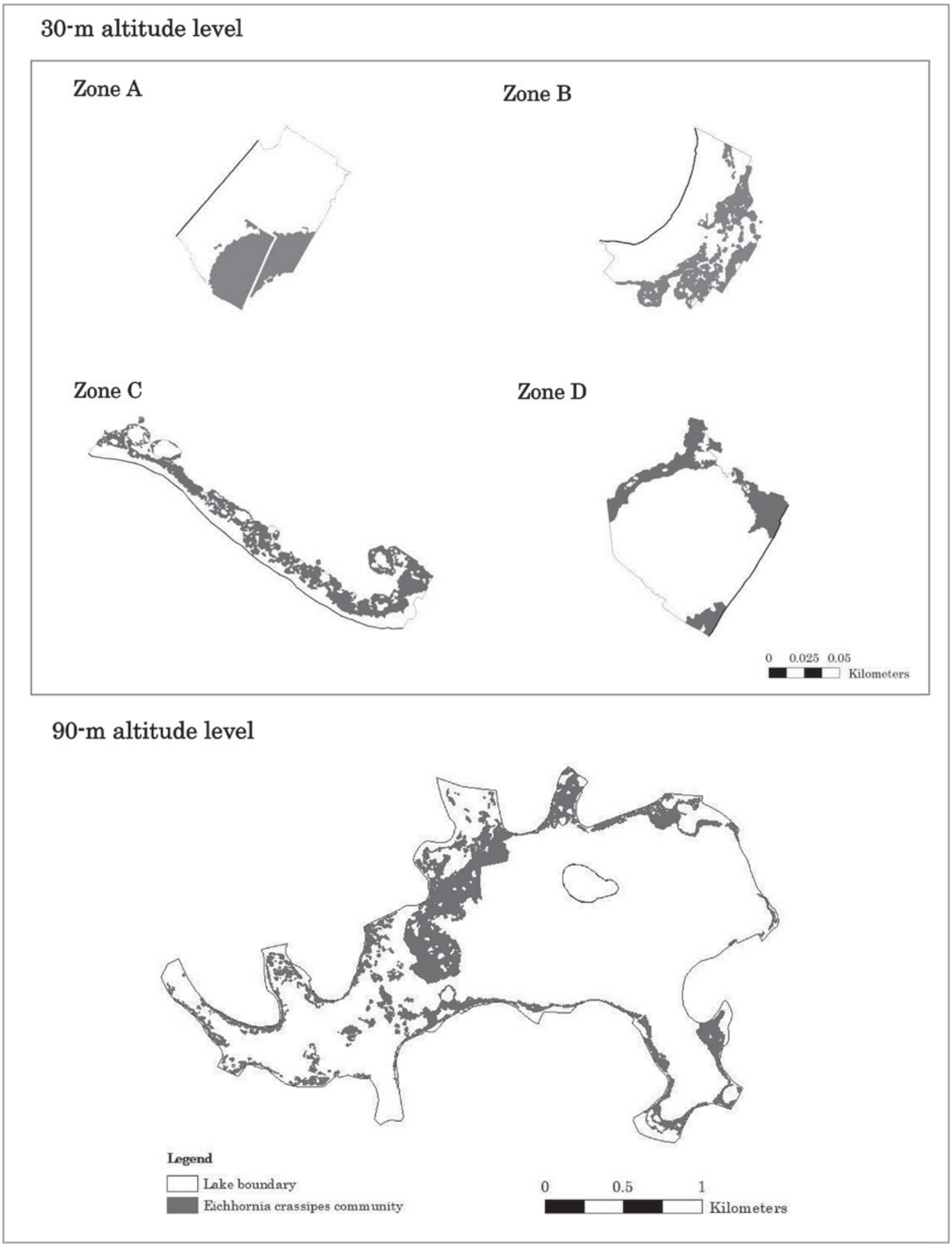


Figure 4.8 Distribution map of *Eichhornia crassipes* community by direct visual interpretation.

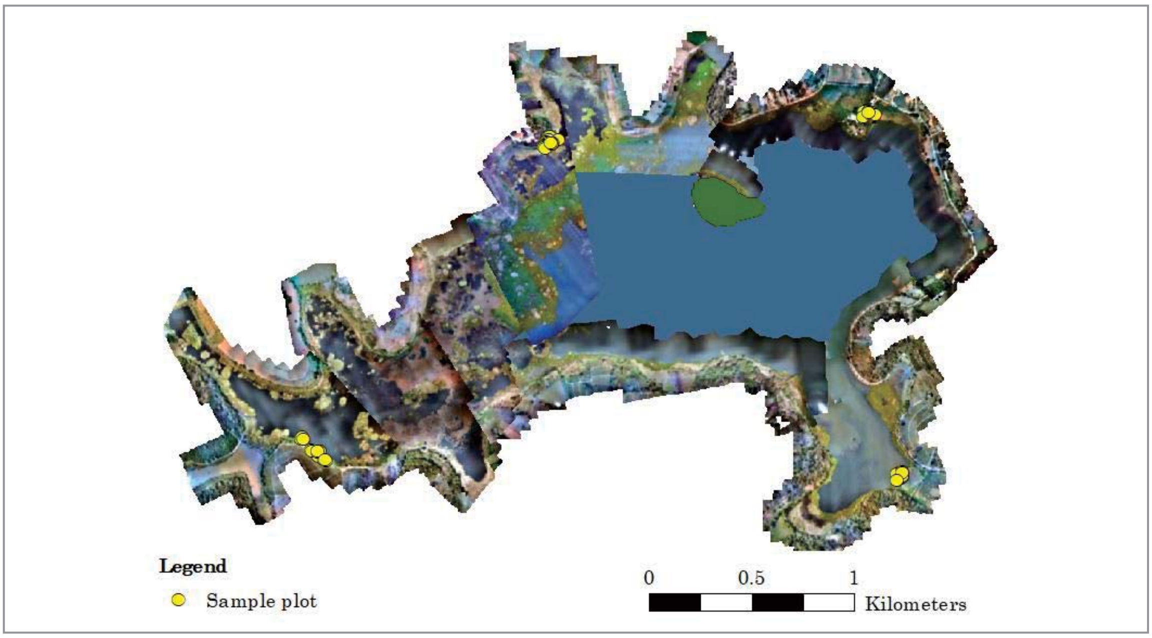


Figure 4.9 Orthophoto of the entire lake.

CHAPTER 5

The effect of water level fluctuation due to decreased precipitation on the non-submerged aquatic vegetation in Nong Bong Khai non-hunting area, Northern Thailand

5.1 Introduction

Hydrology is the most influential variable of wetland ecosystems. It can determine plant species composition, distribution, productivity, and nutrient uptake capacity (Fennessy et al., 2004). Along lake borders, the distribution of plant species is influenced by the hydrological gradient from permanently dry areas on land to permanently wet areas in the water (Nicol and Ganf, 2000). Water level fluctuation is one of the major factors affecting vegetation biomass, diversity, composition, and structure by influencing variables that impact plant growth, such as light, oxygen, air temperature, and nutrient availability (Nõges and Nõges, 1999; Geest et al., 2005; Yang et al., 2014).

Seasonal fluctuations are commonly used as the primary factor for understanding wetland biotic processes (Hofmann et al., 2008; Jabłońska et al., 2011). Water level fluctuation is a complex variable, and its range, frequency, and regularity of change should be considered as they may affect the vegetation in different ways and present major disturbances that influence the wetland ecosystem (Keddy and Reznicek, 1986; Raulings et al., 2010; McGowan et al., 2011; Nielsen et al., 2013). Water-depth ranges have affinities and influence to physiological adaptations of individual plant species and communities of species, and also their life forms (Sculthorpe, 1967; Spence, 1982; Kozlowski, 1984; Wooten, 1986; Hejny and Hroudova, 1987; Keddy, 2000).

Shallow-rooted aquatic plants in wetland areas, in particular, are extremely vulnerable to water level fluctuation in the dry season (Li et al., 2013; El-Vilaly et al., 2018). These plants cannot tolerate extreme drought and may be lost from the ecosystem, dramatically changing wetland vegetation composition (Liu et al., 2012). The hydrological interactions between the water body and the surrounding areas may be altered by more frequent water level fluctuation, increasing the area affected (Wright et al., 2017; Garssen et al., 2015; Striker et al., 2017).

Many wetlands in Thailand suffer from drought caused by low precipitation, which results in water level fluctuation, altering vegetation (Office of Natural Resources and Environmental Policy and Planning, 2013). In 2017, the Thailand Institute of Scientific and Technological Research reported that the Nong Bong Khai wetland is also affected by low precipitation, impacting native and alien plant species. The most notable effect of these drier conditions is increased *Eichhornia crassipes*. This crisis increases the risk of extinction of rare and native species and overall species variation in wetland ecosystems.

Aquatic wetland plant populations may be successfully evaluated using unmanned aerial vehicles (UAVs), which can provide data for vegetation mapping surveys (Wongsupathai et al., 2021). The physiological and ecological characteristics of plant communities, such as texture and color, can be represented in high-resolution orthophotos obtained by low-altitude UAV photogrammetry (Li et al., 2010). Furthermore, UAVs are excellent in discriminating and mapping various vegetation classes and species (Klemas, 2015).

The purpose of this research is to study the effects of water level fluctuation caused by decreased precipitation on the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* in the Nong Bong Khai lake in the Nong Bong Khai non-hunting area, Chiang Rai, Thailand. Non-submerged aquatic vegetation distribution maps based on images from UAV were used. This research will inform further conservation measures and management strategies in this natural area.

5.2 Materials and methods

5.2.1 Rainfall data

Monthly Chiang Rai province rainfall data from 2018 to 2020 were obtained from the Northern Meteorological Center, Thailand (2020). The weather can be clearly delineated into two season types (dry season and rainy season), in which the dry season occurs in summer and winter. Thus, there are three separate seasons.

5.2.2 Water level

The monthly water levels of Nong Bong Khai lake during the study period (September 2018 to December 2020) were obtained from measurements collected by Nong Bong Khai non-hunting area personnel using a level measurement staff at the lake pier.

5.3 Data collection

5.3.1 Study zone designation

The study spanned four periods: rainy season (September 2018), dry season (March 2019), rainy season (September 2019), and dry season (March 2020). The distribution data of the non-submerged aquatic plants (marginal, emerged, and floating plants) were needed to designate the study zones. An aerial survey and a ground truth survey were implemented to obtain vegetation distribution data over the entire lake. An aerial survey of the entire lake was carried out by the automatic flight of a DJI Mavic Pro UAV with a built-in Mavic Pro 12.35 M effective pixel RGB camera (FOV = 78.8°, focal length equivalent to 26 mm of a 35-mm format, F-stop = f/2.2) and a DJI GS Pro application (www.dji.com, Japan). To obtain a continuous multi-shot aerial photo with a 28-mm pixel size captured at 2-s intervals, the initial flight parameters were set at 80% and 60% for the front and side overlap ratios, respectively, with a flight speed of 8.5 m/s and an altitude of 90 m (the maximum flight height permitted by Thailand law). An orthophoto of the entire lake was created using Agisoft Metashape software version 1.5 (Agisoft, Russia). A ground survey was conducted by boat and on foot to observe the non-submerged aquatic plants. Background information for Nong Bong Khai non-hunting area was obtained via officer interviews. Four study zones in different areas of the lake were designated by analysis of the information obtained from the two survey methods: zone A was in the eastern part of the lake (approximate area, 9,804 m2), zone B was in the northern part of the lake (≈11,017 m2), zone C was in the western part of the lake (≈7,503 m2), and zone D was in the southern part of the lake (≈12,407 m2).

5.3.2 Data collection in the study zones

Four procedures were used to collect data:

1) Aerial RGB photos were taken at an altitude of 2–10 m in the four study zones. The UAV was manually controlled to capture a single-shot photo of the individual species at very close range with less than 3-mm pixel size.

2) Aerial RGB photos were taken at an altitude of 30 m in four study zones in March 2019, September 2019, and March 2020. The UAV was controlled by an automatic flight program, the DJI GS Pro application, to record a continuous multi-shot photo with a 9-mm pixel size captured at equal 2-s time intervals with an 80%/60% front/side overlap. The flight speed was 2.8 m/s. Over the entire lake, aerial RGB photos at an altitude of 90 m were taken in September 2018, March 2019, September 2019, and March 2020.

3) Random vegetation sampling plots were selected, of which 82 were sampled in March 2019, 95 in September 2019, and 165 in March 2020, randomized in the four study zones with a 1 × 1 m quadrat. In each zone, the dominant species was visually distinguished. For each dominant species, several sampling plots were randomized. The Braun–Blanquet cover-abundance scale was applied to record vegetation data (Mueller and Ellenberg, 1974). A photograph of each sample plot was captured by a GoPro 12-MP digital camera. The coordinates were recorded by a GPS-60CSx. The water depth was also recorded at every sample plot.

4) For water quality sampling, six parameters were measured for 12 samples from four study zones (three samples in each zone) by two methods. A HORIBA U53G series was used in the field test to measure four parameters (water temperature, pH, dissolved oxygen [DO], and conductivity). Two parameters (total phosphorus and total nitrogen) were measured in the laboratory.

5.4 Data analysis

5.4.1 Plant species identification

According to the data obtained from the sampling quadrats in the four study zones, the scientific name and family of each aquatic plant were identified by a taxonomist at the Herbarium Department of the National Parks, Wildlife and Plant Conservation, Bangkok, Thailand.

5.4.2 UAV data analysis

The analysis involved two procedures, generating orthophotos and generating vegetation maps. An orthophoto of each study zone was generated by Agisoft Metashape Professional software version 1.5 (Agisoft, Russia), which combined the UAV multi-shot photos by the following seven processes: photo alignment, build the dense, mesh creation, texture building, tile model building, DEM building, and creation of an orthophoto that is a high-resolution perpendicular photo with a high level of coordinate accuracy.

Vegetation maps were manually processed by ArcMap software (version 10.5). A UAV orthophoto was directly visually interpreted with a maximum patch size of 3 × 3 m at two altitude levels (30 m and 90 m). At 30 m altitude with a resolution of 7.64 mm/pixel, the UAV orthophoto was used to construct a vegetation map that could describe the coverage and type of all plant communities in the area. Although the 90-m orthophoto with a resolution of 27.02 mm/pixel did not provide sufficient resolution to aid in constructing a vegetation map, it could be referred to for a vegetation distribution map to provide the coverage of some distinct color and texture species in the area. The maps constructed from the 30-m orthophoto are representative of the vegetation in the four study zones. Moreover, the map interpreted from the 90-m orthophoto represented the distribution of *Eichhornia crassipes* over the entire lake.

After direct interpretation of the 30-m orthophotos to create vegetation maps of the four study zones, the boundaries of the dominant plant species in the 30-m vegetation map were designated with reference to the color and texture differences in the orthophotos and supported by the single-shot RGB photos captured at an altitude of 2–10 m. Furthermore, the ground truth survey data were co-analyzed for more accuracy.

The distribution map of the entire lake was interpreted using the 90-m orthophoto. The boundaries of the 90-m map were determined using the 90-m orthophoto as the color and texture of *Eichhornia crassipes* could be distinguished.

5.4.3 Water quality analysis

The results of water quality analyses of samples collected in each zone were averaged and compared with the Standard Quality of Surface Water, Thailand (Class 3), and the Standard Methods for the Examination of Water and Wastewater. All the parameters were compared in the samples collected in September 2018, March 2019, September 2019, and March 2020 and analyzed with vegetation distribution.

5.5. Results

5.5.1 Species identification

A total of 90 plant species in 38 aquatic plant families were identified within the 4 study zones. The highest number of species (71) was found in March 2020. The next highest number (55) was found in September 2019. A total of 54 species was found in March 2019. Poaceae was the most prevalent family found in the three surveys. Regarding general life forms, there were 35 species of herbs, 20 grasses, nine climbers, eight aquatics, six shrubs, four undershrubs, three trees, two terrestrial ferns, two epiphytes, and one bamboo. These species had different habitats: terrestrial (47), marginal (34), floating (5), and emerged (4) (Appendix 7). In addition, *Sparganium erectum*, a plant species native to the United Kingdom (Newman, 2005), was identified three times in the survey results.

5.5.2 Vegetation maps

The vegetation maps generated by the 30-m orthophotos showed the coverage area of the dominant plant species in zones A, B, C, and D in March 2019, September 2019, and March 2020 (Figs.5.2-5.4). The details and coverage areas of each dominant species found in the four study zones are summarized in Appendix 8. The distribution map based on the 90-m orthophoto concentrated on the entire lake. The map showed the distribution of *Eichhornia crassipes* in September 2018, March 2019, September 2019, and March 2020 (Fig.5.5). The coverage area of *Eichhornia crassipes* was approximately 359,832 m^2 in September 2018, 592,888 m^2 in March 2019, 892,420 m^2 in September 2019, and 678,365 m^2 in March 2020.

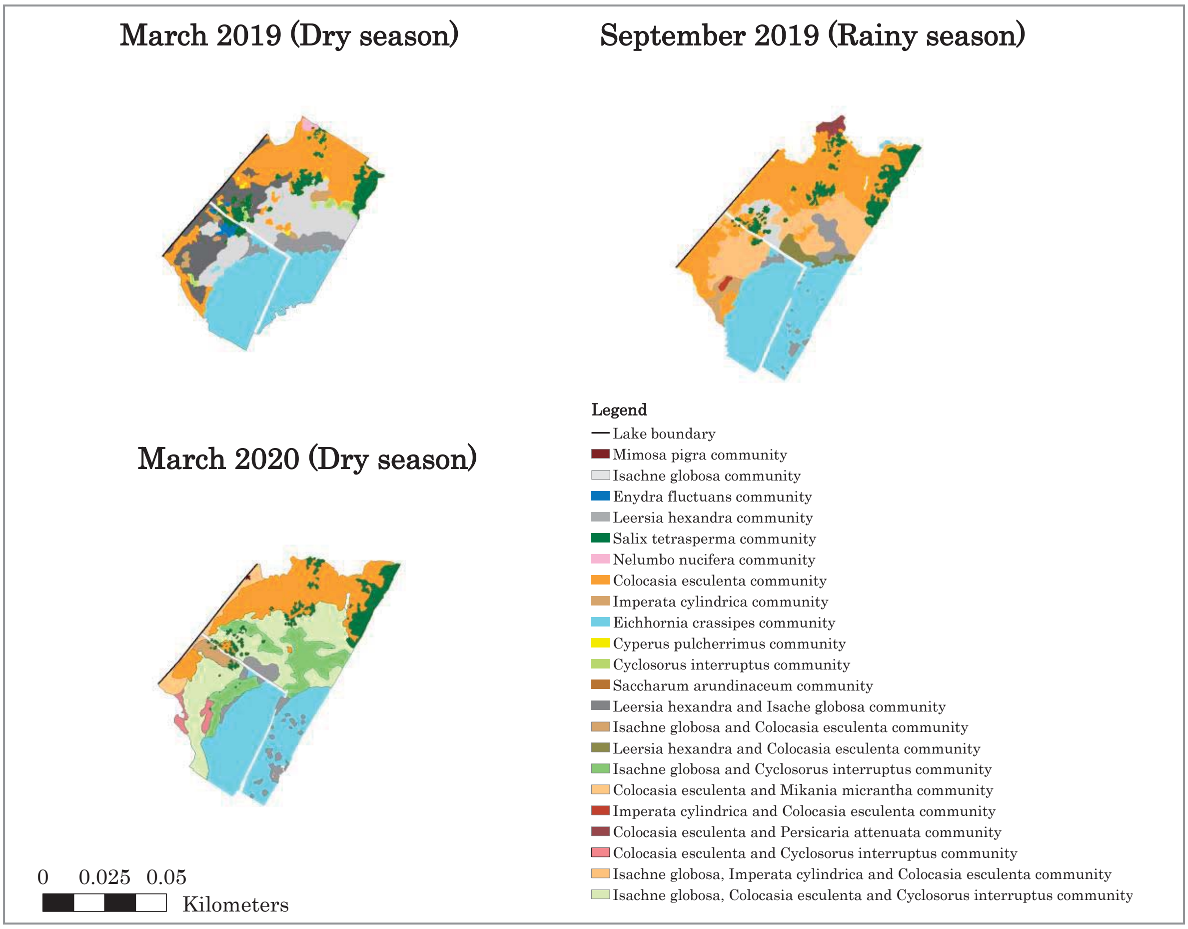


Fig. 5.1 Manual mapping by direct visual interpretation of Zone A in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

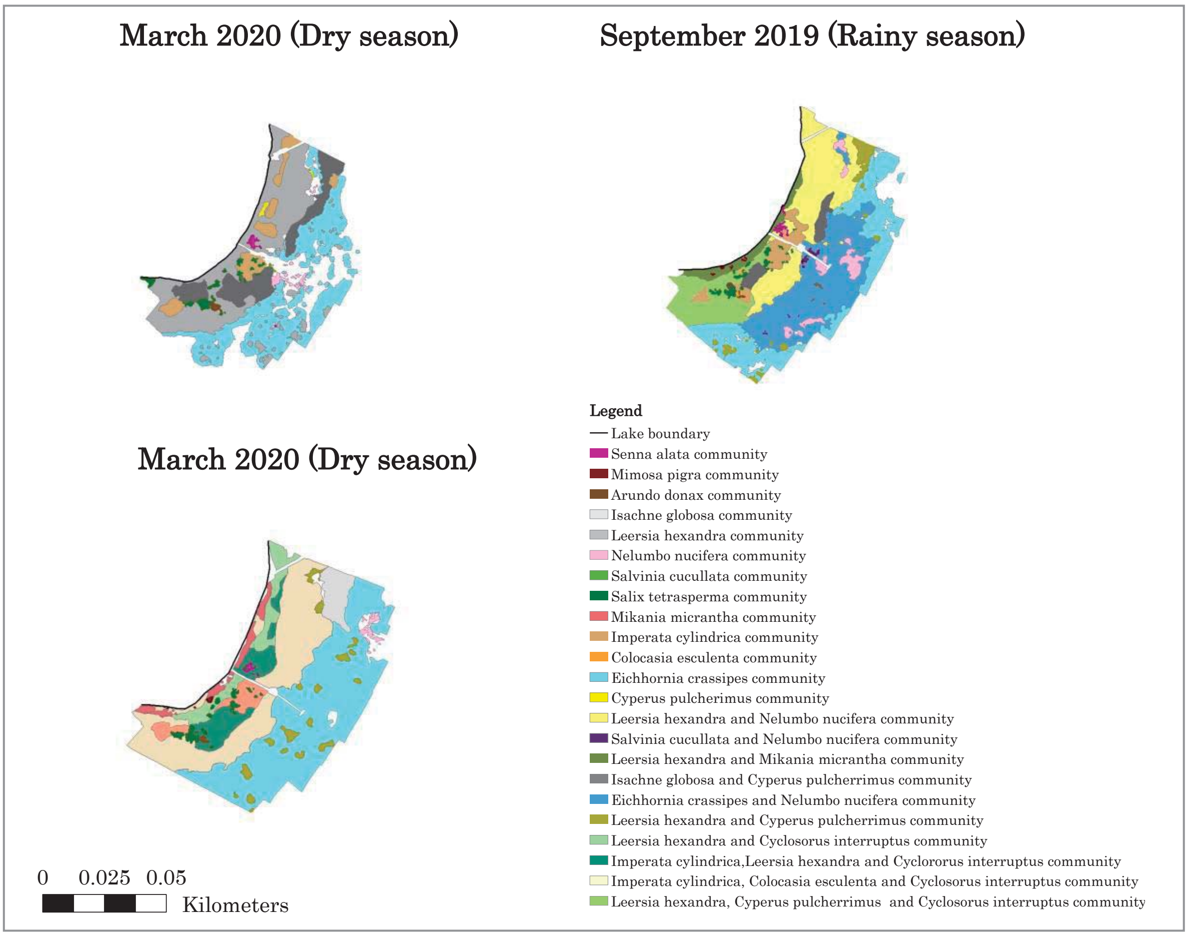


Fig. 5.2 Manual mapping by direct visual interpretation of Zone B in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

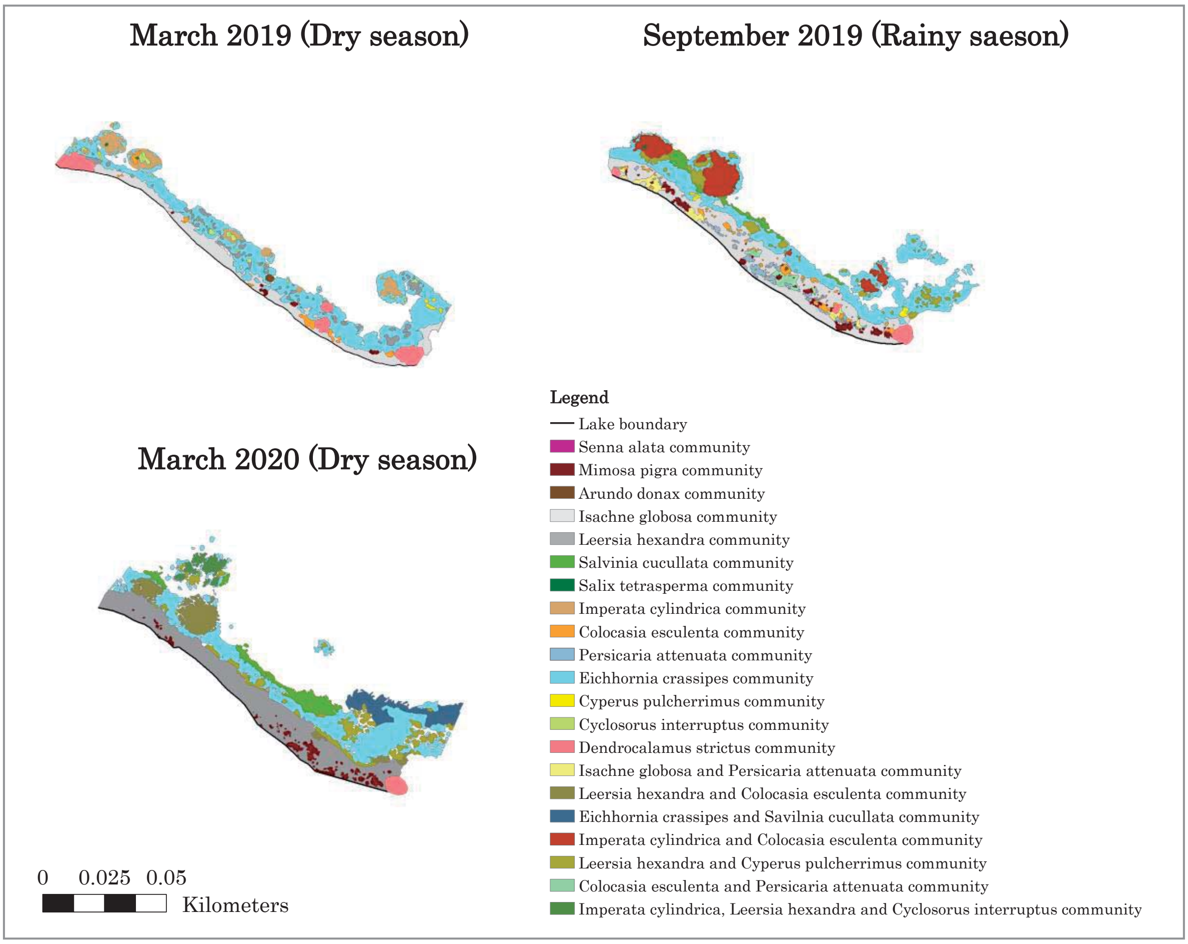


Fig. 5.3 Manual mapping by direct visual interpretation of Zone C in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

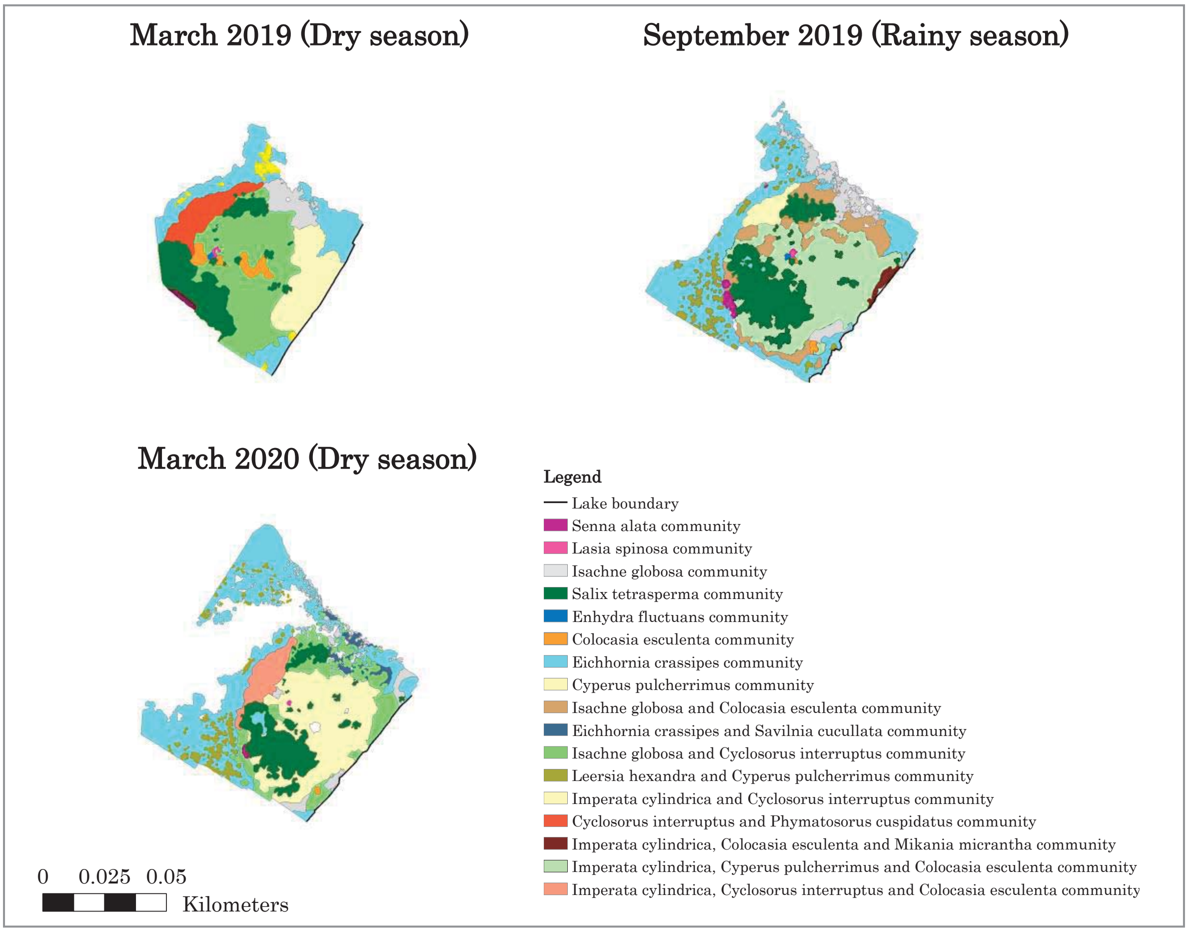


Fig. 5.4 Manual mapping by direct visual interpretation of Zone D in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

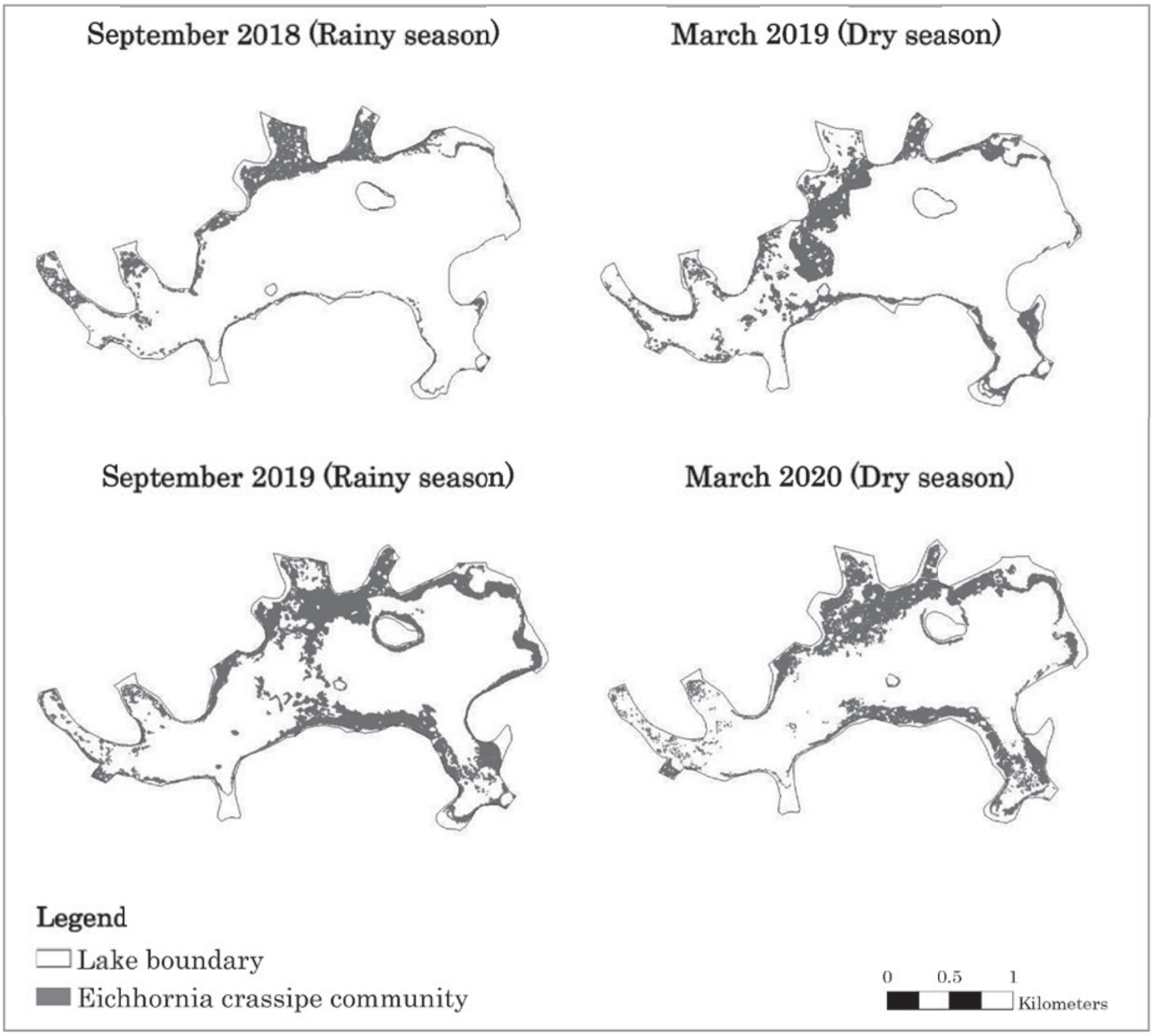


Fig. 5.5 Distribution map of the *Eichhornia crassipes* community by direct visual interpretation in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

5.5.3 Relationship between non-submerged vegetation and rainfall

Comparing coverage area of vegetation and actual rainfall data in three survey periods (March 2019, September 2019, and March 2020) (Fig.5.6) shows that the highest vegetation coverage areas in zones A and D (11,202 m^2 and 13,184 m^2) occurred in September 2019 with 70.7 mm actual rainfall. The greatest coverage in zones B and C (12,955 m^2 and 8,490 m^2) occurred in March 2020 with 0.8 mm actual rainfall.

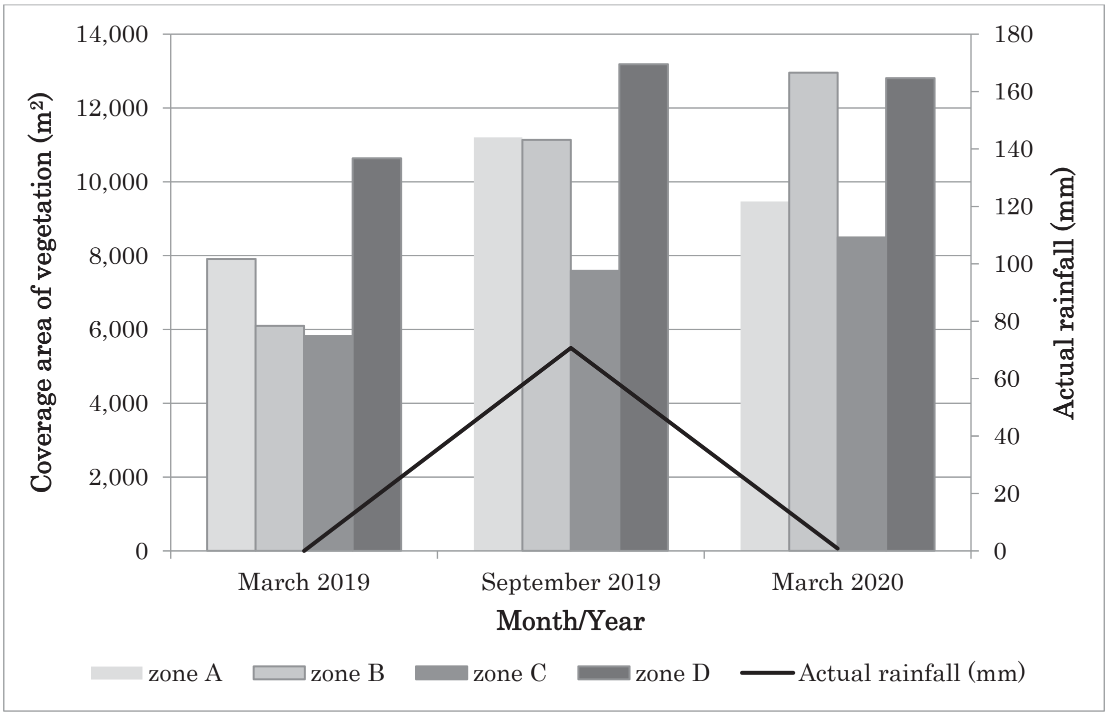


Fig. 5.6 Coverage area of vegetation and actual rainfall in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

The lowest vegetation coverage area of all study zones occurred in March 2019 with zero actual rainfall. Considering the actual rainfall data over the entire lake in the four survey periods (September 2018, March 2019, September 2019, and March 2020), the highest *Eichhornia crassipes* coverage area occurred in September 2019 (892,420 m^2). The lowest coverage area occurred in September 2018 (359,832 m^2) (Fig.5.7).

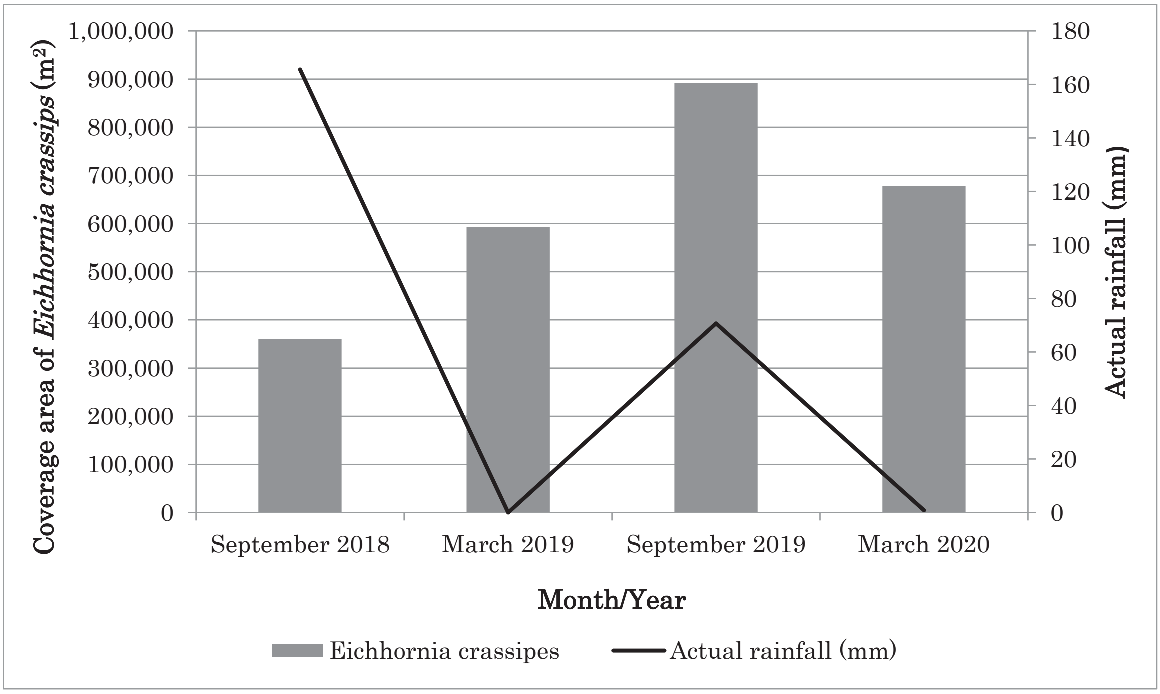


Fig. 5.7 Coverage area of *Eichhornia crassipes* and actual rainfall in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

5.5.4 Relationship between non-submerged vegetation and water level

A comparison of the coverage area classified by vegetation habitat and water depth in all study zones (Fig.5.8) shows vegetation changed as the water depth declined in the four study zones. In zone A, marginal plants and floating plants increased from March 2019 to September 2019 by 2,280 m^2 and 1,012 m^2, respectively, while in March 2020, they decreased by 1,174 m^2 and 877 m^2, respectively. In zone B, the floating plant area increased from March 2019 to September 2019 by 3,415 m^2, then decreased by 132 m^2 in March 2020. One example, *Nelumbo nucifera*, increased from March 2019 to September 2019 by 275 m^2, then by March 2020, had decreased by 267 m^2. Marginal plants decreased from March 2019 to September 2019 by 1,256 m^2 then increased by 4,489 m^2 in March 2020. In zone C, marginal plants and floating plants increased from March 2019 to March 2020 by 2,253 m^2 and 736 m^2, respectively. For example, the area covered by *Mimosa priga* increased continuously from March 2019 to March 2020 by 293 m^2. In zone D, marginal plants increased from March 2019 to September 2019 by 1,524 m^2, and then decreased by March 2020 by 817 m^2. Floating plants increased from March 2019 to March 2020 by 2,263 m². As the water level declined between September 2018 (1 m) and March 2020 (0.2 m), the coverage area of *Eichhornia crassipes* increased by 532,588 m² between September 2018 and September 2019, and then decreased by 214,055 m² in March 2020 (Fig.5.9).

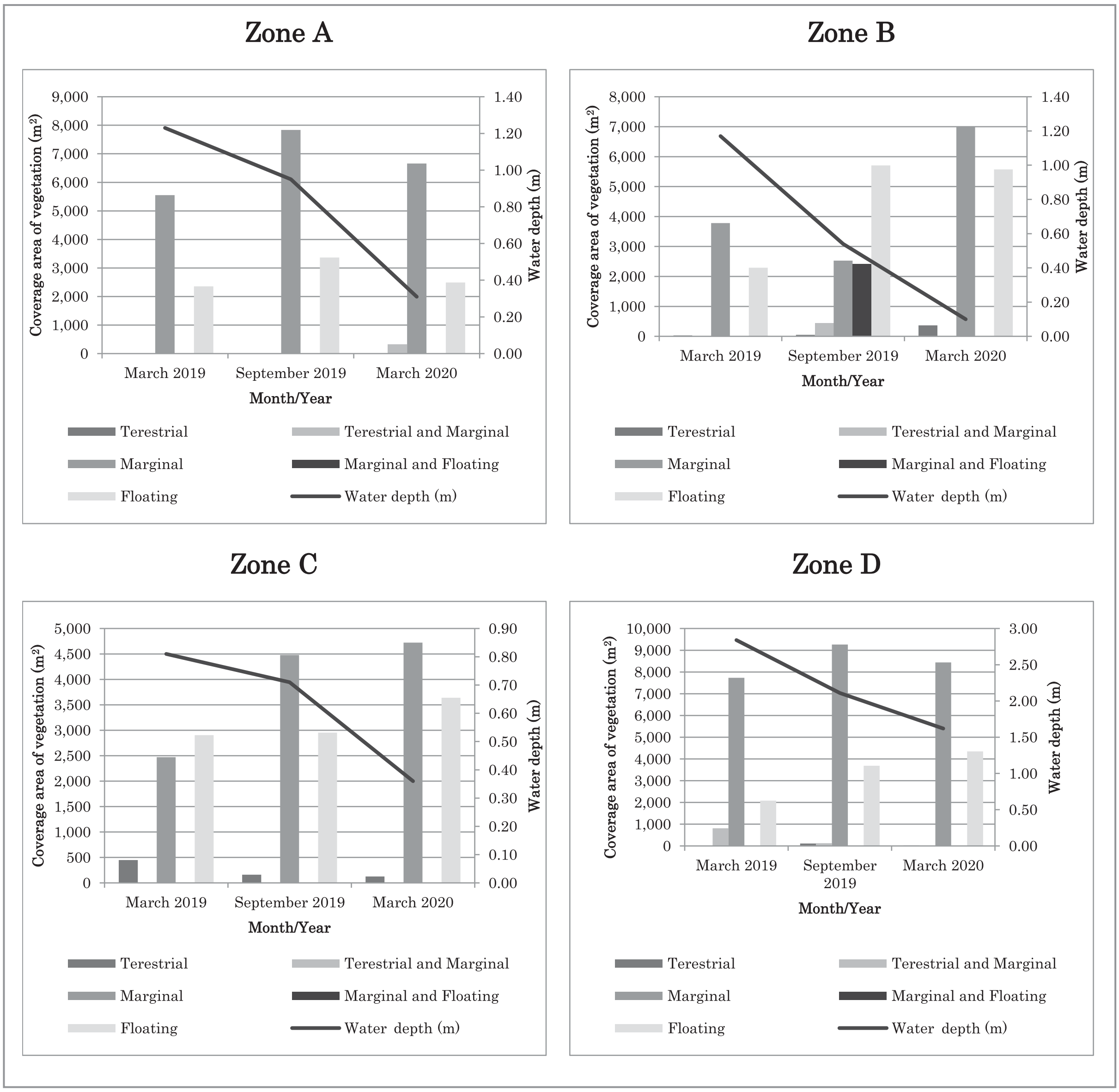


Fig. 5.8 Coverage area of vegetation and water depth in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

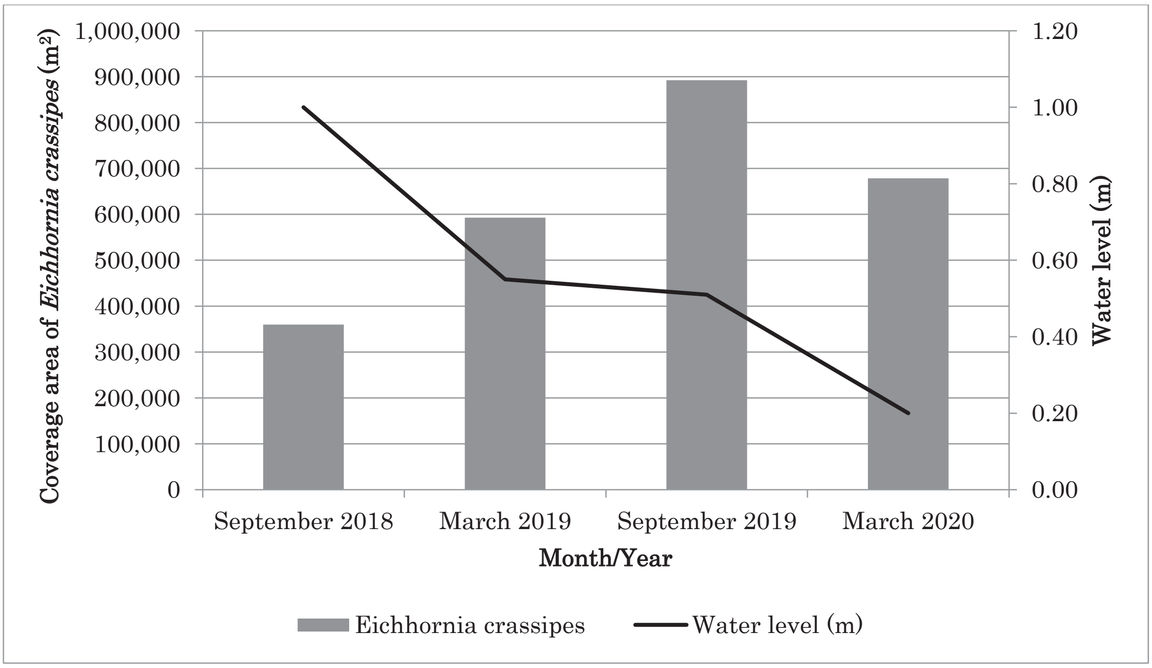


Fig. 5.9 Coverage area of *Eichhornia crassipes* and water level in September 2018 (rainy season), March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

5.5.5 Relationship between non-submerged vegetation and water quality

Results of the water quality measurements in the four study zones (Table 5.1) were compared to the accepted values of the Standard Quality of Surface Water, Thailand (Class 3). The pH was between 6.07 and 8.10, within the accepted values (pH 5–9). The DO values in March 2019, September 2019, and March 2020 were lower than the standard value (4 mg/L). The results of the total phosphorus and total nitrogen were compared to the accepted values of the Standard Methods for the Examination of Water and Wastewater. Total phosphorus measured in samples collected in March 2019 (1.12 mg/L) and March 2020 (1.14 mg/L) in zone A and March 2020 (0.80 mg/L) in zone B were higher than the standard (0.5 mg/L). Moreover, total nitrogen measured in samples collected from zone B in March 2019 (4.98 mg/L) and March 2020 (5.32 mg/L), as well as those in zone D in March 2019 (4.08 mg/L) and March 2020 (4.53 mg/L), also exceeded the standard (4 mg/L). The conductivity values in the four study zones were between 30.22 μS/cm and 82.39 μS/cm, and they rapidly increased from September 2019 to March 2020 in all zones.

The coverage area of floating plants in the four study zones continuously increased after March 2019. Furthermore, the coverage area of *Eichhornia crassipes* over the entire lake increased after September 2018. These results are consistent with the decline of observed DO values after September 2018 and increased TP, TN, and conductivity, especially in March 2020.

Table 5.1 Water quality comparison of the Nong Bong Khai lake in September 2018, March 2019, September 2019, and March 2020.

Zone	Month	Year	Water Temp (°C)	pH	DO (mg/l)	Conductivity (μs/cm)	TP (mg/l)	TN (mg/l)
A	September	2018	29.22	7.63	8.60	31.20	-	-
	March	2019	22.57	6.50	3.07	30.22	1.12	3.48
	September	2019	29.20	6.62	3.08	30.86	0.00	0.56
	March	2020	23.05	6.79	3.24	82.39	1.14	3.86
B	September	2018	29.10	6.63	4.21	37.10	-	-
	March	2019	23.83	6.33	3.33	35.15	0.40	4.98
	September	2019	26.90	6.24	3.40	39.46	0.04	0.59
	March	2020	25.30	6.07	3.25	60.35	0.80	5.32
C	September	2018	30.50	8.10	9.72	37.50	-	-
	March	2019	25.17	6.77	3.53	37.62	0.08	0.13
	September	2019	29.82	6.95	3.36	38.06	0.00	0.13
	March	2020	26.68	6.39	3.54	50.80	0.04	1.79
D	September	2018	29.78	6.71	7.12	31.12	-	-
	March	2019	25.67	7.03	3.08	30.83	0.22	4.08
	September	2019	30.58	6.94	3.09	31.17	0.05	0.29
	March	2020	26.82	7.98	3.48	45.75	0.28	4.53

CHAPTER 6
Discussion and Conclusion

6.1 Discussion

6.1.1 UAV and efficiency for vegetation mapping

The UAV photos in different altitude levels were able to be used for various purposes. Images at an altitude of 90 m (the maximum flight height limited by Thailand's regulation) were used for mapping the entire lake. However, they were unsuitable in identifying individual plant species. When they were used for mapping via direct visual interpretation in the ArcMap program, plant identification was difficult, especially at the species level. However, species that had a distinct shape or color, e.g., *Eichhornia crassipes*, could be identified and used to generate a distribution map at this orthophoto level. Differentiating the specific characteristics of individual species is possible with a high level of spatial resolution (Husson et al., 2017). Mapping from visual interpretation could identify a wide variety of species in a similar way to Valta-Hulkkonen et al. (2003b), who found that mapping from visual interpretation gave more specific information of species than automated classification.

Accordingly, 30-m orthophotos with higher resolution were required for greater accuracy. When mapping with the 30-m orthophotos, the boundaries of each plant species could be discriminated. Since the photos had clear colors, textures, and shapes, the species, including trees and herbs (e.g., *Salix tetrasperma* Roxb and *Colocasia esculenta* (L.) Schott), could be distinguished. Nevertheless, identifying micro-species (e.g., *Eleocharis dulcis* (Burm.f.) Trin. ex Hensch) and similar-color species (e.g., grasses) required single-shot photos at altitudes of 2–10 m and ground truth survey data. Result is similar to that of Andrea (2019), who found that photos at 25 m were adequate for mapping the plant communities and that photos at 5 m could better identify plant species from the botanical and taxonomical points of view.

To survey vegetation over moderately large areas, low-altitude UAV surveys are a suitable, highly efficient, and relatively accurate method (Cruzan et al., 2016). However, UAV orthoimages combine many single-shot photos with different flights at different times of the day under various weather conditions, the reflection of clouds, and sunlight which those might affect the image quality, especially the color (Husson et al., 2016). Mapping via direct visual interpretation only provides information concerning the species that had most coverage because the UAV photos only showed a picture from the top view. Therefore, micro-species, less coverage species, or under-crowned species were likely omitted or under-represented. Referring to the study of Husson (2014), the omission of a single species does not occur only with low-covered species but also with different species that have a similar color and/or texture. However, these limitations can be mitigated by a 2-10 m single shot photo. Therefore, plant communities can be effectively discriminated using UAV methods. Taxonomists can also use UAV images to discriminate the shapes and habitats of plants (Kaneko and Nohara, 2014). However, field surveys should always be necessary to obtain greater accuracy (Andrea, 2019).

6.1.2 Land use and land cover

Land use and land cover around Nong Bong Khai lake watershed between year 2009, 2012, 2016, and 2018, During theses 4 years, the area of field crop continuously increased from 2009 to 2018 by 92.07% while, the area of deciduous forest and rangeland continuously decreased by 53.23% and 47.86% respectively. This change showed that the area of deciduous forest and rangeland was replaced by filed crop. In details of field crop from 2009 to 2018 (Figure 6.1), the cultivated areas that obviously increased were pineapple and cassava which increased by 344.48% and 100.25% respectively.

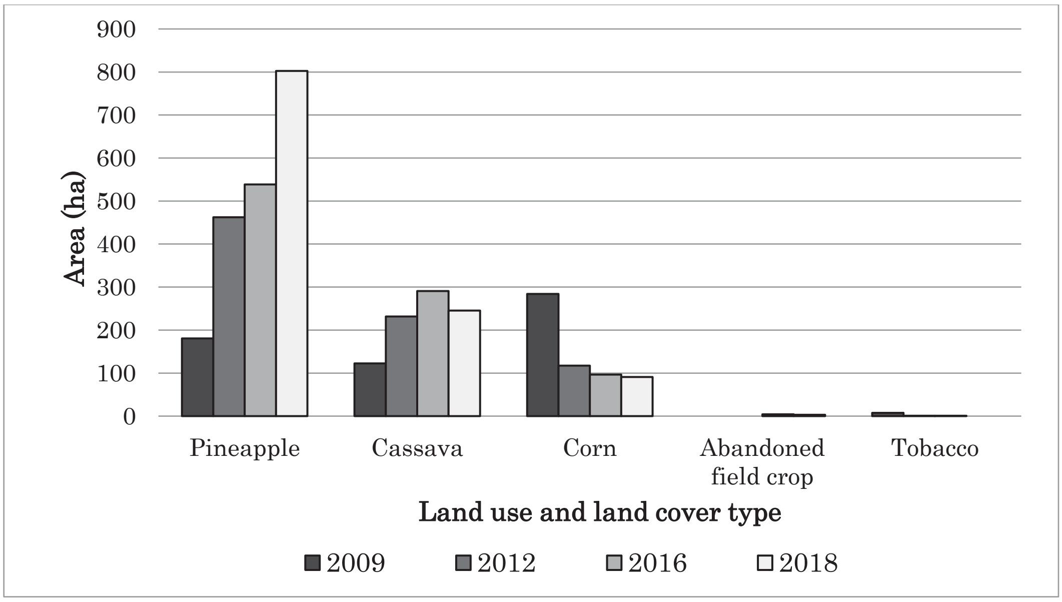


Figure 6.1 Land use and land cover change in Nong Bong Khai lake watershed (sub-category under field crop) in years 2009, 2012, 2016, and 2018.

Figure 6.2 shows the amount of fertilizer used in the agricultural area around the lake especially in pineapple field, cassava field, and paddy field (The Department of Agriculture, Thailand, 2020). The data of fertilizer utilization in the area of Nong Bong Khai watershed in 2009, 2012, 2016 and 2018 is calculated bases on the information from the Department of Agriculture, Thailand about the appropriate amount of fertilizer utilizing for cultivation of pineapple, cassava, and paddy in one harvest cycle. The usage of fertilizer in the area of pineapple field and cassava field were increasing by the highest usage per year were 813.43 and 100.19 tons per year respectively. Although the fertilizer was also used in the paddy field area, the impact of soil erosion to water bodies was less than the other two areas because paddy field was cultivated on a flat plain area around the outer of lake as refer to land use and land cover map. On the other hand, pineapple field and cassava field were cultivated on a sloping area of the hill around the lake where fertilizer could be eluted into the lake (Reinhardt, 1991; Ciesiolka et al., 1995). After rain, soil erosion led to higher levels of fertilizer in the lake. Contamination of fertilizer was a cause of high nutrient in the lake especially, phosphorous and nitrogen. Although fertilizer with high potassium (K) was used in the agricultural area, there were no known deleterious effects of potassium in fresh or saline waters except to increase the salt content and electric (United States Environmental Protection Agency, 2021). Agricultural activities increase amount of fertilizers in the field crop and some of those enters into the nearest water bodies. Water quality is degraded by direct and indirect impact of agricultural activities (Yu et al., 2013) which is the consequences of land use change.

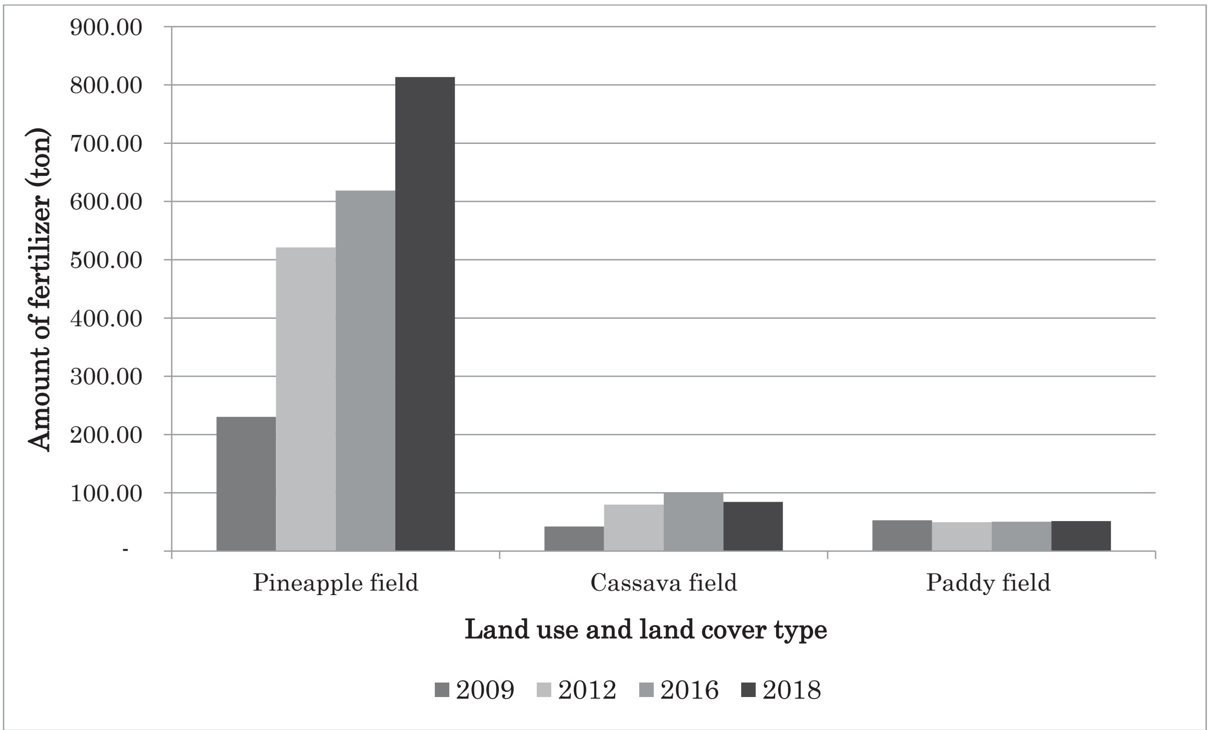


Figure 6.2 The amount of fertilizer utilization in paddy field, cassava field and pineapple field in years 2009, 2012, 2016, and 2018.

The vegetation maps of 2019 based on the 30-m data indicated differences in the aquatic plant distributions in the four study zones. The distribution of aquatic plant was different based by their habitat and water depth (Kumar and Pandit, 2008). However, referring to the ground truth survey, some of terrestrial plants might appear at deep water area because they grew on a floating island that was a buoyant mat consisting of plant detritus (Graig et al., 2001; Jaikumar et al., 2011; Feldmann, 2012; Tamire and Mengistou, 2012; Naichia et al., 2015). Moreover, the vegetation maps of four study zones showed that *Eichhornia crassipes* was presented in all of the study zones. The proportion of dominant plant species showed that the covering area of *Eichhornia crassipes* was mostly greater than other native species. From the map, *Eichhornia crassipes* was presented as a floating mat at the outside edge of four study zones. They moved according to wind and wave and were able to threaten the ecological stability. With their heavy weight, they encircled and pressed native plants which could destroy aquatic biodiversity.

For the distribution of *Eichhornia crassipes* based on the 90-m data indicated that *Eichhornia crassipes* were primarily distributed in the northern and western areas of the lake due to the influence of the southeast monsoon which regularly blew through Thailand during March and April (The Meteorological Department, Thailand, 2014). Also, the distribution of aquatic plants is obviously affected by wind and waves (Chambers, 1987; Vermaat and De Bruyne, 1993; Pankhurst, 2005; Dar et al., 2014). In Yongyut's (2006) study, *Eichhornia crassipes* were not prominently found but they might increase as a result of land use and water quality changes which that similar with interview of officers of Nong Bong Khai non-hunting area. They reported that a few *Eichhornia crassipes* were found between the years of 2001 and 2010. But in 2011, they found that the amount of *Eichhornia crassipes* was increasing. This might be a result from changing of surrounding areas of the lake where were mostly turned from mixed deciduous forest to agricultural area. The distribution map in 2019 showed a large coverage area of *Eichhornia crassipes* by almost 600,000 m^2 (13.82% of total lake area) which conformed to Yongyut's study and officers' interview.

Refer to water quality data, the values of phosphorous and nitrogen that detected in 2008 (Kwanruen, 2008), 2011, and 2017 (Thailand Institute of Scientific and Technological Research, 2011, 2017) were sitting in the standard but in 2019, those values were higher than the standard which that showed excessive nutrients in the water. Phosphorous and nitrogen are essential for growth of aquatic plants. However, excessive composition of nutrients can over-encourage aquatic plant growth (Paul and James, 2003; Prita et al., 2017). Some studies have shown that the rapid growth of *Eichhornia crassipes* is correlated with the nutrient level of water bodies, especially with phosphorus and nitrogen (Xie and Yu, 2003; Bowness et al., 2013). Moreover, the large amount of *Eichhornia crassipes* is a result of water quality degradation which can be proved by water quality data of the year 2008, 2011, 2017, and 2019. In 2019, DO value was lower than the standard which that meant the water became pollute. The large mat of *Eichhornia crassipes* was a cause of polluted water by blocking the water from the sunlight. *Eichhornia crassipes* density affected growth of aquatic animals by suppressing growth of phytoplankton and degrading water quality. With decay, nutrient concentration in the water increased, which affected the high growth rates of algae, which, in turn, reduced oxygen levels (Villamagna and Murphy, 2010; Gichuki et al., 2012; Patel, 2012). The study showed that land use and land cover change effect to water quality change and increasing in invasive alien species.

6.1.3 Water level fluctuation

The report from the Northern Meteorological Center showed that the level of rainfall (2020) (Fig. 6.3) was continuously lower than normal from the beginning of 2019 to the middle of 2020 (normal values of the actual rainfall are referred to as the average rainfall over the 30-year period 1981–2010). The Thai Meteorological Department (2021) reported that the occurrence of El Niño in the first half of 2019 caused the low actual rainfall. Although the El Niño phenomena did not occur in the second half of 2019, the actual rainfall was still low due to the Positive Indian Ocean Dipole. In addition, the precipitation decreases directly resulted in the decline of water level because the lake's water originates only from precipitation.

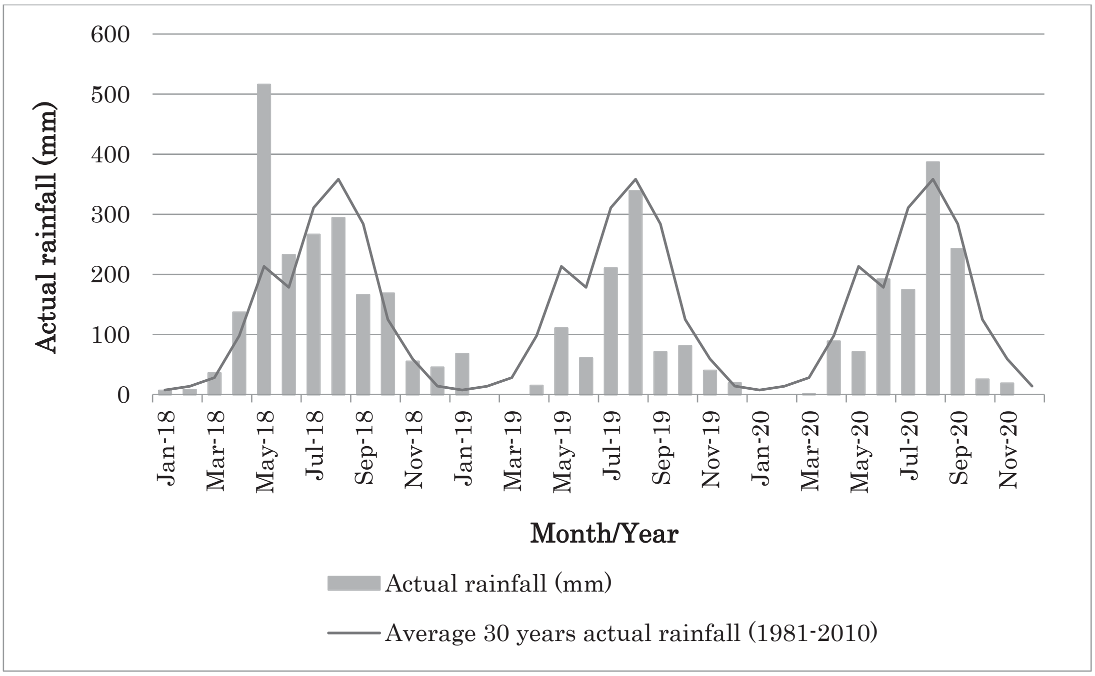


Fig. 6.3 Actual rainfall and normal value in Chiang Rai, Thailand, from January 2018 to December 2020.

The vegetation coverage area in the four study zones and the rainfall data in three of the surveys (March 2019, September 2019, and March 2020) indicate that the vegetation in zones A and D was highest during the highest rainfall of 70.7 mm in September 2019. In zones B and C, the vegetation coverage area was highest in March 2020 when rainfall was scant (0.8 mm). When there was zero rainfall in March 2019, the vegetation coverage area in all study zones was lowest. These data show that the amount of rainfall affects vegetation coverage. Coverage of a plant found in wet, humid environments (rainfall > 2000 mm/year), *Colocasia esculenta*, clearly increased in zones A and D during the high amount of rainfall (Hunter et al., 2000). Various meteorological factors such as the size, frequency, and timing of precipitation pulses, may affect plant eco-physiological responses (Ogle and Reynolds, 2004), but plant responses may differ depending upon the species (Hayden et al., 2010; Ensslin and Fischer, 2015; Gao et al., 2015). The precipitation patterns are widely known as governing functional and species diversity (Dodd et al., 1998; Schwinning et al., 2003). On a daily basis, the intensity of precipitation profoundly affects plant photosynthesis, transpiration, or stomatal conductance (Zhao and Liu, 2010; Yang et al., 2014). So, the impact of precipitation changes on the different life-history stages of plants is important to ecological research (Bai et al., 2008; Franks and Weis, 2008; Gornish et al., 2015).

The water level in the study area during the entire study period (September 2018–December 2020) (Fig. 6.4) shows that the amount of actual rainfall was a major determinant of the water level in the lake. Comparing the vegetation coverage area and the water depth in all study zones shows the relationship between the decrease in water depth and decline in the native plant species. This is evident in the vegetation map of zone B for *Nelumbo nucifera*. In September 2019, it covered 351 m^2 at 0.51 m water depth and declined to 84 m^2 at 0.20 m in March 2020. Normally, this species survives in habitats with water depths between 0.30 m and 1.50 m (Nohara and Tsuchiya, 1990; Sou and Fujishige, 1995). The vegetation map shows that terrestrial plants and marginal plants increased during the low water depth in March 2020 (the lowest in three survey periods), especially *Mimosa pigra,* a marginal plant. The vegetation maps reveal that this species coverage increased enormously by 316 m^2 since the 2019 dry season. Yongyut (2006) found few *Mimosa pigra* in the study area in 2006 because the water in the lake was maintained at a high level, and the plant could not invade into the lake area. High water levels have a strong negative effect on *Mimosa pigra* (Asyraf and Micheal, 2011). One of the main causes of increased coverage by *Mimosa pigra* is a decrease in water level. The low water level in March 2020 also resulted in an increase in other terrestrial plant species, especially grasses (*Isachne globosa* and *Leersia hexandra*). The results from 2020 dry season vegetation survey show the appearance of alien species, such as *Bidens pilosa*, *Chromolaena odorata*, and *Mimosa pudica*. These results are consistent with Barros and Albernaz (2014), who observed that a reduction in precipitation could result in low water levels in rivers and extended drought in the Amazon floodplain (Marengo and Nobre, 2001). Under these conditions, the flooded areas might be reduced or replaced with drylands (Burkett and Kusler, 2000). An inadequate flooding period might result in the decline of many species that require an adequate flooding period to complete their life cycle. Moreover, a short flooding period might offer a window of opportunity for invasive species (Poff, 2002; Döll and Zhang, 2010).

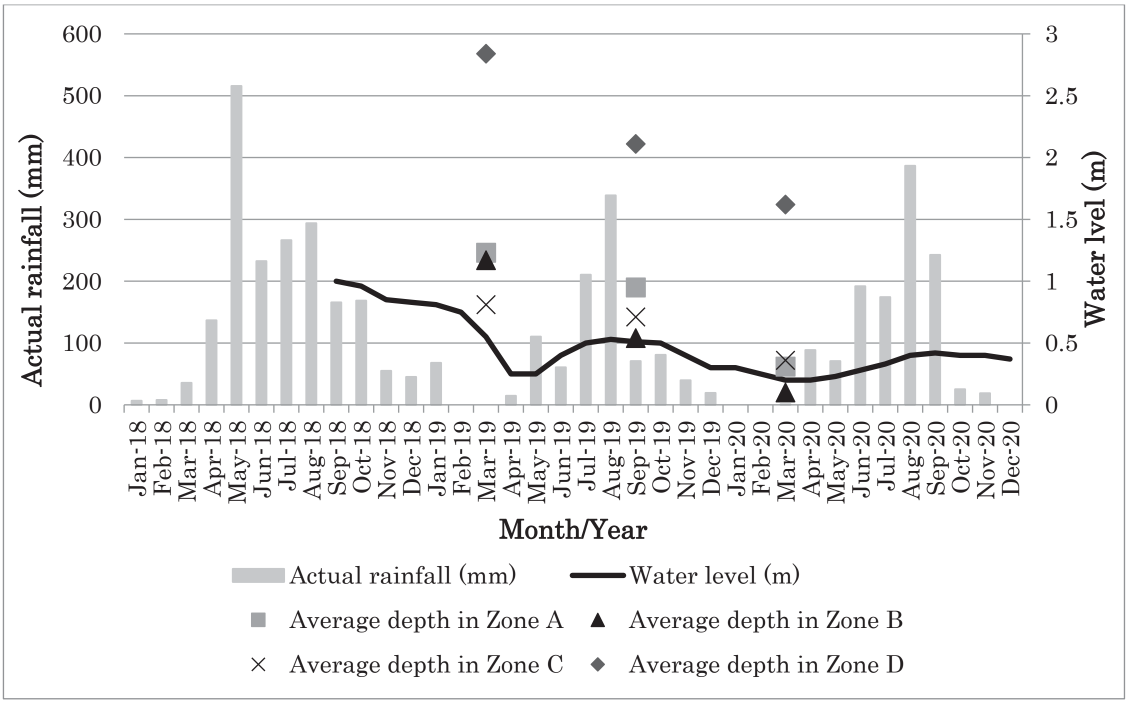


Fig. 6.4 Actual rainfall, water level (measured at office's pier), and average depth (measured at sampling plots) in Nong Bong Khai lake from September 2018 to December 2020.

The water level of the lake and the coverage area of *Eichhornia crassipes* between September 2018, March 2019, September 2019, and March 2020 were compared. This comparison showed that the coverage area of *Eichhornia crassipes* continuously increased while the water level decreased. Excluding March 2020, the overall coverage area of *Eichhornia crassipes* decreased by 214,055 m^2 while the lake's water level continuously decreased. This abnormal event occurred due to an unusually heavy 30-minute hailstorm in December 2019 (The Meteorological Department, 2021). The officer of Nong Bong Khai non-hunting area reported that many plants in the lake were destroyed by the impact (and likely cold) of the heavy hail. An increase of *Eichhornia crassipes* during decreasing water levels shows how well this species adapts to the unfavorable environment. *Eichhornia crassipes* is an aquatic plant that can survive for several months with no water and in moist sediments (Center et al., 2002). In shallow water, *Eichhornia crassipes* can grow roots into sediment or mud (Hasan et al., 1989; Adrian, 2006). Furthermore, the species can be propagated by its seeds and stolon (Pieterse, 1978). *Eichhornia crassipes* is commonly spread by vegetative propagation, but it can also be propagated by seeds that can remain viable for 20 years (Matthews et al., 1977; Pieterse, 1978).

The results of water quality analyses in September 2018, March 2019, September 2019, and March 2020 showed below acceptable DO values during March 2019 to March 2020, an indicator of potential water pollution. In March 2020, during the lowest water level of all survey periods, the highest concentrations of nutrients (phosphorous and nitrogen) were detected (Sale et al., 1985; Gopal, 1987; Santamaría, 2002; Xie and Yu, 2003; Xie et al., 2004). The increase in phosphorous and nitrogen also increased conductivity in March 2020 (Wiser and Blom, 2016).

Water quality test results are consistent with the increase in the floating plants, especially *Eichhornia crassipes*, the coverage of which increased beginning in September 2018. Kwanruen (2008) found that areas with dense floating islands and *Eichhornia crassipes* in Nong Bong Khai lake had low DO, resulting in unsuitable living conditions for aquatic animals. The large *Eichhornia crassipes* mats cover the water, blocking the sunlight and obstructing oxygen exchange. Dense *Eichhornia crassipes* mats degrade water quality, potentially altering species composition and decreasing biodiversity (Masifwa, 2001; Center et al., 2002; Brendock, 2003; Meerhoff et al., 2003). Moreover, the average temperatures (22.57°C to 30.58°C) and pH values (6.07 to 7.98) were suitable for the growth of *Eichhornia crassipes*. This species grows very well in warm water that is rich in macronutrients, especially waters that are still or slow-moving (Howard and Harley, 1998; Center et al., 2002).

6.1.4 General discussion

In overall, Nong Bong Khai wetland suffered from a negative impact of local and global environmental changes. These impacts are the cause of degrading the wetland's ecosystem by creates the opportunity of invasion for the alien plant species especially *Eichhornia crassipes* and *Mimosa pigra*.

A local environmental change is a change of land use and land cover around this wetland. Mostly, deciduous forest and rangeland were changed into agricultural areas where a high amount of fertilizer was used. The fertilizer can be leached and runoff into the lake which that result in over-nutrification. The high concentration of nutrients in the water favorably encourage to the growth of *Eichhornia crassipes*.

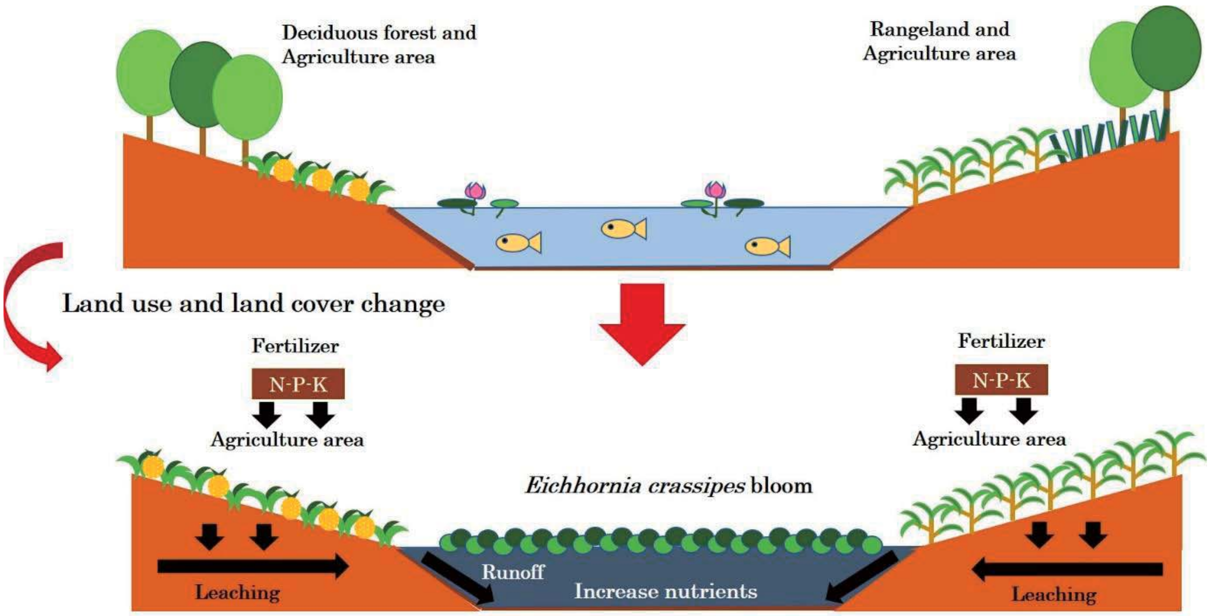


Fig. 6.5 Land use and land cover change in Nong Bong Khai lake.

And a global environmental change is a change of climate that causes of the low precipitation. Since rainfall is the only source of the water filling into the lake, the water level will fluctuate during the low precipitation. The prolonged low water level in the lake destroys the growth opportunity of some native plant species and also provides more opportunities for alien plant species to invade, especially *Eichhornia crassipes* and *Mimosa pigra*.

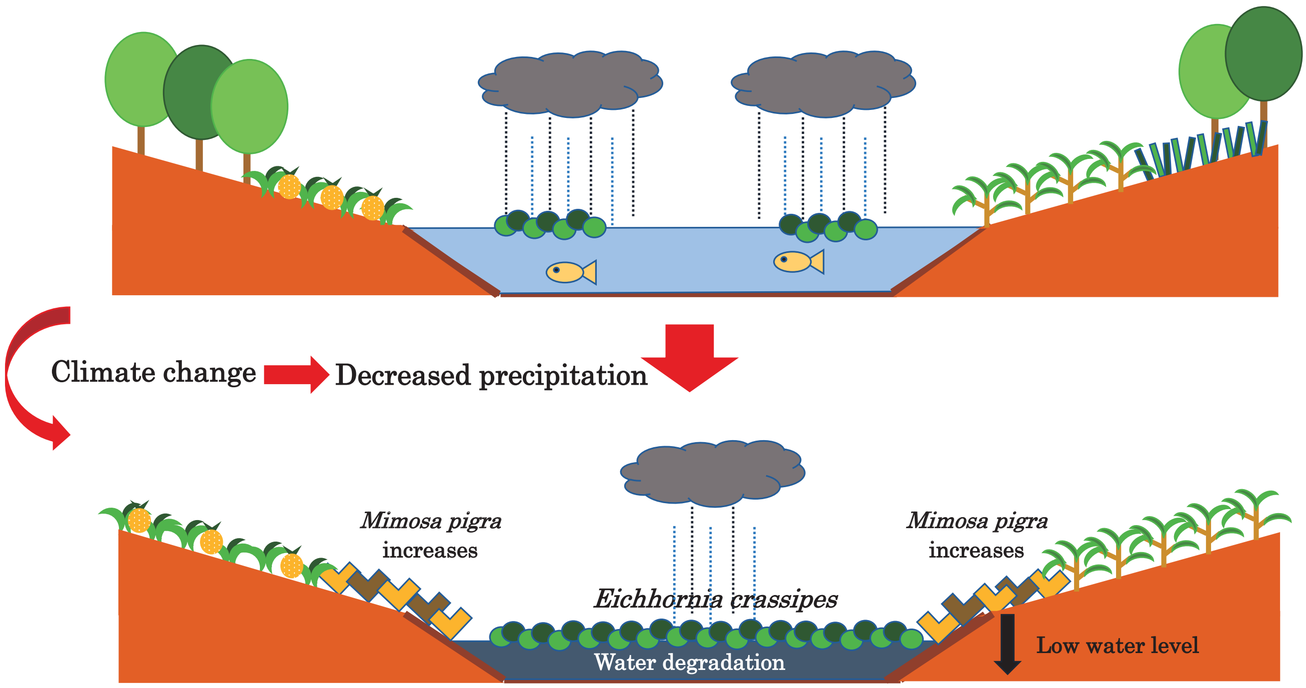
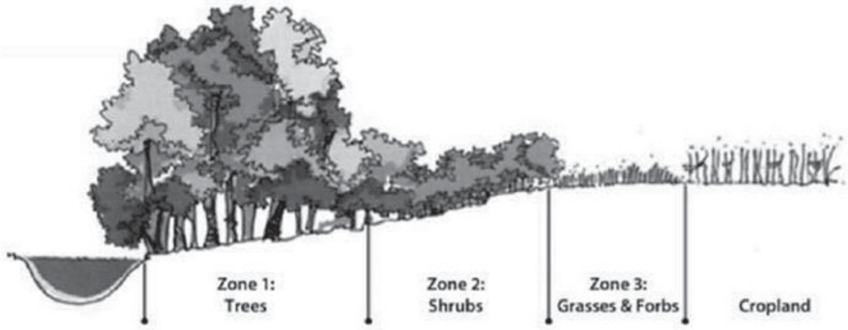


Fig. 6.6 Global climate change in Nong Bong Khai lake.

6.1.5 Practical proposal for improving of the lake ecosystem based on the study.

(1) Countermeasures for soil erosion and nutrification.

Land use and land cover change results in increase of nutrients concentration in the lake which is a cause of rapid growth of *Eichhornia crassipes*. Due to the area around Nong Bong Khai lake is mostly hill with slope that causing erosion of topsoil into the lake. Applying a buffering area around the lake can mitigate soil erosion, which leads insecticide and fertilizer from agricultural areas into the lake. A vegetation buffer (e.g., trees, shrubs, and groundcovers) can absorb soluble nutrients, sediments, other pollutants, and also slow runoff by the root systems and leaf layer. Specifically, root systems and other chemical and biological components in the soil can transform and reduce harmful nutrients and other pollutants (The Berkshire Regional Planning Commission, 2003; University of New Hampshire Cooperative Extension, 2007). As the area around Nong Bong Khai lake is mostly privately owned, building a vegetation buffer all around the lake is very difficult. Hence, the concerned government department should allocate the budget to support the landowners to building a vegetation buffer. Conversely, if they avoid building a vegetation buffer, the measure for penalty should be stated as a regulation. The buffer should be at least 15 m from the edge of water body. However, the larger buffer is better reducing the pollutants. In fact, a 30 m buffer is known to remove 60% or more of the pollutants (Deanna and Mike, 2017; Jordan and Sharon, 2019).



Source: Jordan and Sharon, 2019

Fig. 6.7 Example of vegetation buffer zone.

(2) Countermeasures for water fluctuation

Water fluctuation caused by decreased rainfall affects low water level in the lake. This resulted in the increase of many alien plant species, especially *Eichhornia crassipes* and *Mimosa pigra*. To handling with large quantities of *Eichhornia crassipes*, machinery, such as hydraulic mowing boat, should be applied for removing *Eichhornia crassipes* out of the lake. However, mechanization for removal *Eichhornia crassipes* can affect the bird habitat on floating mat which is an important service from this Ramsar site. Therefore, to avoid the effects of *Eichhornia crassipes* removal, this should not be done during the laying an egg and migration seasons of bird. For control and removal of the *Mimosa pigra* should be entirely dig, hand pulling or bulldozing for reduce the spread and propagation of *Mimosa pigra* to prevent further spread (CRC, 2003). Moreover, it is necessary to maintain at least 1 m of the water level to prevent their invasion. During the low water level, the water usage for agriculture should be restricted. Besides, the other water sources should be provided as an alternative source for agriculturists. As the inflow water of the lake only comes from rainfall, maintaining the water at 1 m during low rainfall period is difficult. A sustainable solution should be implemented to eliminate the impact from the low water level.

The concerned government department should launch a project to construct a pipeline for water transmission from Mekong River to Nong Bong Khai lake.

Fig. 6.8 Example of removal machines.

6.2 Conclusion

This study of the invasion of alien vegetation in Nong Bong Khai non-hunting area, Ramsar site, Chiang Rai, Thailand showed that the impact of changes in land use and land cover around Nong Bong Khai lake, especially with increasing field crops, where fertilizer was used in large amount. This human activity induced increased nutrient concentration in the water which affected the rapid growth of *Eichhornia crassipes*. UAV photos are effective to identify plant species. Referring to the map in March 2019 interpreted from the 90-m orthophoto, *Eichhornia crassipes* covered 13.82% of the total lake area. Also, maps interpreted from the 30-m orthophoto showed the increasing in distribution and proportion of *Eichhornia crassipes* and other native plant species in small areas. Applying a vegetation buffer around the lake with trees, shrubs and ground cover plants should be done alongside for mitigate erosion of topsoil that contains nutrients from fertilizers in agriculture area into the lake. Another than changes of land use and land cover, changes of climate also affected the increase in *Eichhornia crassipes* and other alien plant species. It caused low rainfall in 2018-2020 which resulting in water level fluctuation. A water level fluctuation affects the distribution of the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* in Nong Bong Khai wetland. Especially during decreased precipitation period in 2019 and 2020, although it seems to be a short period, it is a cause of very low water level. A vegetation map from the 30-m orthophoto shows an increasing in alien plant species, especially *Mimosa pigra* which highly increases during low water level period. A distribution map of *Eichhornia crassipes* interpreted from 90-m orthophoto shows an increasing in *Eichhornia crassipes* among a decline of water level which that because they can adapt well and survive in spite of low water level. Moreover, the results of water quality test indicate that the water in the lake is getting degraded. Using a hydraulic mowing boat to remove *Eichhornia crassipes* from the lake as well as digging or bulldozing all *Mimosa pigra* around the lake will help to limit the spread of the *Eichhornia crassipes* and *Mimosa pigra*.

6.3 Recommendations

To monitoring and assessment the change of invasive alien plants, long-term data should be gathered for analyze the factor effecting increases in alien species, especially *Eichhornia crassipes* and *Mimosa pigra*, for further planning of effective management (Table 6.1).

Table 6.1 Recommended plan for further study.

Data collection	Collection frequency
Survey aquatic vegetation overall the lake.	Twice a year (dry season, rainy season)
Collect and analyze land use and land cover around Nong Bong Khai lake watershed	Every 2 years
Collect and analyze water quality in lake	Twice a year (dry season, rainy season)
Measure and record water level	Continuously monitoring (by data logger)
Collect rainfall data of Nong Bong Khai lake.	Continuously monitoring (by data logger)

References

Adam, E., Mutanga, O. and Rugege, D. (2010) Multispectral and hyperspectral remote sensing for Identification and mapping of wetland vegetation: A review. Wetlands Ecology and Management 18:281-296.

Adrian, E. W. (2006) Water Hyacinth, Van Nostrandís Scientific Encyclopedia. Copyright © 2006 John Wiley & Sons, Inc.

Anand, J., Gosain, A.K. and Khosa, R. (2018) Prediction of land use changes based on Land Change Modeler and attribution of changes in the water balance of Ganga basin to land use change using the SWAT model Sci. Total Environ., 644 (2018), pp. 503-519.

Anderson, K. and Gaston, J.K. (2013) Lightweight unmanned aerial vehicles will revolutionize Spatial Ecology. Frontiers in Ecology and the Environment 11:138-146. https://doi.org/10.1890/120150.

Andrea, B., Vittoria, G., Carmelo Di, F. and Nicola, S. (2019) Using unmanned aerial vehicles for vegetation mapping and identification of botanical species in wetlands. Landscape and Ecological Engineering 15(2), 231-240.

Arnold, T., Biasio, M.D., Fritz, A. and Leitner, R. (2013) UAV-Based Measurement of Vegetation Indices for Environmental Monitoring. Seventh International Conference on Sensing Technology, Wellington, 708-711.

Ashraf, S., Brabyn, L., Hicks, B.J. and Collier, K. (2010) Satellite remote sensing for mapping vegetation in New Zealand freshwater environments: A review. New Zealand Geographer 66:33-43.

Asyraf, M. and Micheal, J.C. (2011) Current status of *Mimosa pigra* L. infestation in peninsula Malaysia. Tropical Life Sciences Research 22(1) :41-55.

Baattrup-Pedersen, A., Andersson, B., Krattunen, K., Riis, T. and Toivonen, H. (2001) Macrophytes. In: Skriver, J (ed.) Biological monitoring in Nordic rivers and lakes, 53-60. TeamNord, Copenhagen, DK. https://doi.org/10.1007/s11355-018-00368-1.

Bai, Y., Wu, J., Xing, Q., Pan, Q., Huang, J., Yang, D., Han, X. (2008) Primary production and rain use efficiency across a precipitation gradient on the mongolia plateau. Ecology 89:2140-2153.

Bartley, D.M, Bhujel, R.C, Funge-Smith, S., Olin, P.G., Phillips, M.J. (comps/eds) (2005) International mechanisms for the control and responsible use of alien species in aquatic ecosystems. FAO, Rome.

Barros, D.F. and Albernaz, A.L.M. (2014) Possible impacts of climate change on wetlands and its biota in the Brazilian Amazon, Braz. J. Biol., 74(4):810-820.

Belluco, E., Camuffo, M., Ferrari, S., Modenese, L., Silvestri, S., Marani, A., and Marani, M. (2006) Mapping saltmarsh vegetation by multispectral and hyperspectral remote sensing. Remote Sensing of Environment, 105:54-67.

Boon, M.A., Greenfield, R., Tesfamichael, S. (2016) Wetland assessment using unmanned aerial vehicle (UAV) photogrammetry. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch. 41:781-788.

Bowness, A., Hill, M.P. and Byrne, M.J. (2013) The role of nutrients in the responses of water hyacinth, *Eichhornia crassipes* (Pontederiaceae) to herbivory by a grasshopper *Cornops aquaticum* Bruner (Orthoptera: Acrididae). Biological Control 67(3):555-562.

Braithwaite, R. W., Lonsdale, W. A., and Estbergs, J. A. (1989) Alien vegetation and native biota in tropical Australia: the spread and impact of *Mimosa pigra*. Biological Conservation 48:189-210.

Brander, L., Florax, R. and Vermaat, J. (2006) The empirics of wetland valuation: a comprehensive summary and a meta-analysis of the literature. Environ Resour Econ. 33:223-250.

Brendock, L. (2003) The impact of water hyacinth (*Eichhornia crassipes*) in a eutrophic subtropical impoundment (Lake Chivero, Zimbabwe) II. Species diversity. Arch Hydrobiol 158(3):389-340.

Burkett, V. and Kusler, J. (2000) Climate Change: Potential Impacts and Interactions in Wetlands of the United States, Journal of the American Water Resources Association, 36:313-320.

Carl, A., Bannuscher, A., and von Klitzing, R. (2015) Partical stabilized aqueous foams at different length scales: Synergy between silica particles and alkyl-amines. Langmuir, 31(5), 1615-1622.

CBD (2002) Decision VI/23 (Annex, footnote): Alien species that threaten ecosystems, habitats and species. Document UNEP/CBD/COP/6/23. Convention on Biological Diversity Secretariat, Montreal, Canada. https://www.cbd.int/decision/cop/?id=7197, (Accessed: 14 August 2021).

Center, T. D. (1994) Biological Control of Weeds: Water Hyacinth and Water Lettuce. In: D. Rosen, F. D. Bennet, and J. L. Capinera (Eds.). Pest Management in the Subtropics, Biological Control-A Florida Perspective. Intercept Ltd., Andover, UK, p. 737.

Center, T.D., HILL, M.P, Cordo, H. and Julien, M.H. (2002) Water hyacinth. Biological Control of Invasive Plants in the Eastern United States. USDA Forest Service Publication FHTET- 2002-04:41-64.

Centre for Biodiversity Policy and Law (2003) Invasive alien species threat to inland wetlands of India, National Biodiversity Authority.

Chambers, P.A. (1987) Nearshore occurrence of submersed aquatic macrophytes in relation to Wave action. Journal of Fisheries and Aquatic Sciences 44(9):1666-1669.

Ciesiolka, C.A.A., Coughlan, K.J., Rose, C.W. and Smith, G.D. (1995) Erosion and hydrology of steep lands under commercial pineapple production. Soil Technology 8:243-258.

Corman, J.R., Bertolet, B.L., Casson, N.J., Sebestyen, S.D., Kolka, R.K. and Stanley, E.H. (2018) Nitrogen and phosphorus loads to temperate seepage lakes associated with allochthonous dissolved organic carbon loads. Geophys. Res. Lett. 45: 5481-5490.

Cruzan, M.B., Weinstein, B.G., Grasty, M.R., Kohrn, B.F., Hendrickson, E.C., Arredondo, T.M. and Thompson, P.G. (2016) Small unmanned aerial vehicles (micro-UAV s, drones) in plant ecology. Applications in Plant Sciences 4(9):1600041. https://doi:10.3732/apps.1600041.

Dar, N.A., Pandit, A.K. and Ganai, B.A. (2014) Factors affecting the distribution patterns of aquatic macrophytes. Limnological Review 14(2): 75-81.

Deanna, O. and Mike, B. (2017) Agricultural Riparian Buffers SoilFacts, North Carolina State University, North Carolina Riparian Buffer Publications.

De Boisvilliers, M., and Selve, M. (2019) UAS Lidar for Ecological Restoration of Wetlands. GIM International: Mapping the World.

De Fries, R.S., Foley and J.A., Asner, G.P. (2004) Land-use choices: Balancing human needs and ecosystem functions Frontiers in Ecology and the Environment, 2:249-257.

Dodd, M.B., Lauenroth, W.K., Welker, J.M. (1998) Differential water resource use by herbaceous and woody plant life forms in a shortgrass steppe community. Oecologia 117, 504-512.

Döll, P. and Zhang, J. (2010) Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations, Hydrology and Earth System Sciences, 14(5): 783-799.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J. and Sullivan, C.A. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges Biol. Rev. Camb. Philos. Soc., 81, pp. 163-182.

Dudley, B., Dunbar, M., Penning, E., Kolada, A., Hellsten, S., Oggioni, A., Bertrin, V., Ecke, F.,and Sondergaard, M. (2013) Measurement of uncertainty in macrophyte metrics used to assess European lake water quality. Hydrobiologia 704:179-191.

El-Vilaly, M.A.S., Didan, K., Marsh, S.E., Leeuwen, W.J. D, Crimmins, M.A., Munoz, A.B. (2018) Vegetation productivity responses to drought on tribal lands in the four corners region of the Southwest USA. Front Earth Sci, 12(1): 37-51.

Ensslin, A., Fischer, M. (2015) Variation in life-history traits and their plasticities to elevational transplantation among seed families suggests potential for adaptative evolution of 15 tropical plant species to climate change. American Journal of Botany 102:1371-1379.

Feldmann, T. (2012) The structuring role of lake conditions for aquatic macrophytes (Ph.D. Thesis) Estonian University of Life Sciences, Tartu, pp.182.

Fennessy, M.S., Siobhan, M., Mack, J.J., Rokosch, A., Martin, K. and Mick, M. (2004) Integrated Wetland Assessment Program Part 5, Biogeochemical and Hydrological Investigations of Natural and Mitigation Wetlands, Columbus, Ohio, USA.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., et al. (2005) Global consequences of land use Science, 309 (5734):570-574.

Franks, S.J., Weis, A.E. (2008) A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. Journal of Evolutionary Biology 21:1321-1334.

Gagne, S.A. and Fahrig, L. (2007) Effect of landscape context on anuran communities in breeding ponds in the National Capital Region, 22, Landscape Ecology, Canada, pp. 205-215.

Galbraith, H., Amerasinghe, P. and Huber-Lee, A. (2005) The effects of agricultural irrigation on wetland ecosystems in developing countries: A literature review*,* Comprehensive Assessment Secretariat, Colombo.

Gao, R.R., Yang, X.J., Liu, G.F., Huang, Z.Y. and Walck, J.L. (2015) Effects of rainfall pattern on the growth and fecundity of a dominant dune annual in a semi-arid ecosystem. Plant and Soil 389: 335-347.

Garssen, A.G., Baattrup-Pedersen, A., Voesenek, L.A.C.J., Verhoeven, J.T.A., Soons, M.B. (2015) Riparian plant community responses to increased flooding: a meta-analysis. Glob Change Biol. 21: 2881-2890.

Geest, G.V., Wolters, H., Roozen, F., Coops, H., Roijackers, R., Buijse, A. and Scheffer, M. (2005) Water-level fluctuations affect macrophyte richness in floodplain lakes, Hydrobiologia 539:239-248.

Getzin, S., Wiegand, K. and Schöning, I. (2012) Assessing biodiversity in forests using very high-Resolution images and unmanned aerial vehicles. Methods in Ecology and Evolution 3(2):397-404. https://doi.org/10.1111/j.2041-210X.2011.00158.x.

Gichuki, J., Omondi R., Boera, P., Tom, O.T, SaidMatano, A., Jembe, T. and Ofulla, A. (2012) Water Hyacinth *Eichhornia crassipes* (Mart.) Solms-Laubach Dynamics and Succession in the Nyanza Gulf of Lake Victoria

(East Africa). Implications for Water Quality and Biodiversity Conservation. The Scientific World Journal.

Gopal, B. (1987) Water hyacinth. aquatic plant studies I. Elsevier, Amsterdam, the Netherlands.

Gornish, E.S., Aanderud, Z.T., Sheley, R.L., Rinella, M.J., Svejcar, T., Englund, S.D., James, J.J. (2015) Altered snowfall and soil disturbance influence the early life stage transitions and recruitment of a native and invasive grass in a cold desert. Oecologia 177:595-606.

Graig, T.M., Randall, K.S. and Charles, E.C. (2001) Physical and Vegetative Characteristics of Floating Island. J. Aquat. Plant Manage 39: 107-111.

Hammer, Donald, A. (1996) Creating Freshwater Wetlands, Second Edition, CRC Press: Boca Raton, FL.

Hardin, P.J. and Hardin, T.J. (2010) Small scale remotely piloted vehicles in environmental research. Geography Compass 4(9):1297-1311.

Hasan Z., Toshniwal, C. L. and Khan, H. L. (1989) Water hyacinth and its role in waste water treatment. J. Indian Wat. Wks Assoc. 9(3):142-145.

Hayden, B., Greene, D.F., Quesada, M. (2010) A field experiment to determine the effect of dry-season precipitation on annual ring formation and leaf phenology in a seasonally dry tropical forest. Journal of Tropical Ecology 26: 237-242.

Heard, T. A. (2004) The taxonomy of *Mimosa pigra*. In Research and Management of *Mimosa pigra*, ed. M. Julien, G. Flanagan, T. Heard, et al. Canberra, Australia: CSIRO Entomology, p.10.

Hejny, S. and Hourodova, Z. (1987) Plant adaptations to shallow water habitats 157-66. In J. Pokorny, O. Lhotsky, and P. Denny (eds.) Waterplants and Wetland Processes. Archive fur Hydrobiologie, Beiheft 27. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany.

Hofmann, H., Lorke, A. and Peeters, F. (2008) Temporal scales of water-level fluctuations in lakes and their ecological implications. Hydrobiologia, 613(1): 85-96.

Hong, Q. and Robert, E.R. (2006) The role of exotic species in Homogenizing the North American Flora. Ecology Letter 9: 1293-1298.

Howard, G.W. and Harley, K.L.S. (1998) How do floating aquatic weeds affect wetland conservation and development? How can these effects be minimised?, Wetlands Ecology and Management 5:215-225.

Howard, G.W. and Matindi, S.W. (2003) Alien Invasive Species in Africa's Wetlands: Some Threats and Solutions, IUCN Eastern Africa Regional Office, Nairobi, Kenya.

Hulme, P.E. (2005) Adapting to climate change: is there scope for ecological management in the face of a global threat?, J Appl Ecol 42:784-794.

Hunter D.G., Iosefa, T., Charles, J.D. and Fonti, P. (2000). Beyond taro leaf blight: a participatory approach for plant breeding and selection for taro improvement in Samoa. Proceedings of the International Symposium on Participatory Plant Breeding and Participatory Plant Genetic Resource Enhancement,1-5.

Hunt, G., Roy, K. and Jablonski, D. (2005) Species-level heritability reaffirmed: a comment on "On the heritability of geographic rangesizes." American Naturalist 166:129-135.

Husson, E., Hagner, O. and Ecke, F. (2014) Unmanned aircraft systems help to map aquatic vegetation. Applied Vegetation Science 17(3):567-577.

Husson, E., Ecke, F. and Reese, H. (2016) Comparison of manual mapping and automated object-based image analysis of non-submerged aquatic vegetation from very-high-resolution UAS images. Remote Sens 8(9):724. https://doi.org/ 10.3390/rs8090724.

Husson, E., Reese, H. and Ecke, F. (2017) Combining spectral data and a DSM from UAS-images for Improved classification of non-submerged aquatic vegetation. Remote Sens 9(3):247.

IPCC (1992) Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Cambridge University Press, Cambridge.

IPCC (2001) Clinate Change 2000: The science of climate change. Contribution of working group, I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IUCN (International Union for Conservation of Nature) (2021) Invasive alien species and climate change, https://www.iucn.org/ (Accessed: 26 August

2021).

Jabłońska, E., Pawlikowski, P., Jarzombkowski, F., Chormański, J., Okruszko, T., Kłosowski, S. (2011) Importance of water level dynamics for vegetation patterns in a natural percolation mire (Rospuda fen, NE Poland). Hydrobiologia, 674(1):105-117.

Jaikumar, M., Chellaiyan, D., Kanagu, L., Kumar, P.S. and Stella, C. (2011) Distribution and succession of aquatic macrophytes in Chilka Lake, Journal of Ecology and the Natural Environment 3(16):499-508.

Jefferson, R.G. and Grice, P.V. (1998) Conservation of lowland wet grassland in England. In: European Wet Grasslands: Biodiversity, Management and Restoration (eds CB Joyce and PM Wade), Wiley & Sons, Chichester.

Jordan, D. and Sharon, L.D., (2019) Riparian buffers in agricultural areas, international poplar commission.

José, A.B. (1996) The relative importance of water quality,sediment composition and floating vegetation in explaining macrobenthic community structure of floodplain lakes (Parana River, Argentina). Hydrobiologia 333: 95-109.

José L. and Pérez L. (2008) Impact of Climate Change on Wetland Ecosystems (2008). Expo zara goza.

Junhong, B., Ouyang, H., Rong, X. et al. (2010) Spatial variability of soil carbon, nitrogen, and phosphorus content and storage in an alpine wetland in the Qinghai-Tibet Plateau, China, Australian Journal of Soil Research, 48 (8):730-736.

Kaneko, K. and Nohara, S. (2014) Review of effective vegetation mapping using the UAV unmanned aerial vehicle method. Journal of Geographic Information System 6(6):733-742. https://doi.org/10.4236/jgis.2014.66060.

Kathryn, T., Nicola, D. M., Errol, D. et al. (2013) Water Hyacinth Control: Insight into Best Practice, Removal Methods, Training & Equipment, EThekwini Municipality, Durban, South Africa.

Keddy, P.A. and Constable, P. (1986) Germination of ten shoreline plants in relation to seed size, soil particle size andwater level: an experimental study. J. Ecol. 74:133-141.

Keddy, P.A. and Reznicek, A.A. (1986) Great lakes vegetation dynamics: the role of fluctuating water levels and buried seeds, Great Lakes Res.12:26-36.

Keddy, P.A. (2000) Wetland Ecology: Principles and Conservation. Cambridge University Press, Cambridge, UK.

Keddy, P.A. (2010) Wetland Ecology: Principles and Conservation (second ed.), Cambridge University Press, Cambridge.

Kingsford, R.T. and Thomas, R. (2002) Use of satellite image analysis to track wetland loss on the Murrumbidgee River floodplain in arid Australia, 1975-1998 Water Science & Technology 45(11):45-53.

Klemas, V.V. (2015) Coastal and environmental remote sensing from unmanned aerial vehicles: An overview. Journal of Coastal Research 315:1260-1267.

Kozlowski, T.T. (ed.) (1984) Flooding and Plant Growth. Academic Press, Orlando, FL, USA.

Kristensen, S.P. (1999) Agricultural land use and landscape changes in Rostrup, Denmark: processes of intensification and extensification. Landscape and Urban Planning, 46:117-123.

Kwanruen, Y. (2008) Study on aquatic ecology to generate guideline for fisheries conservation in Wetland of Nong Bong Khai Non-Hunting Area,Chiang Rai Province, Thailand (in Thai).

Kumar, R. and Pandit, A.K. (2008) Effect of water level fluctuations on distribution of emergent vegetation in Hokerser wetland, Kashmir. Proceedings of the National Academy of Sciences, India, Section B: Biological Sciences 78:227-233.

Lechner. A., Fletcher. A., Johansen, K., and Erskine, P., (2012) Characterising Upland Swamps Using Object-Based Classification Methods and Hyper-Spatial Resolution Imagery Derived from An Unmanned Aerial Vehicle. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Melbourne, Australia Vol. 1-4, pp. 101-106.

Li, F., Qin, X., Xie, Y., Chen, X., Hu, J., Liu, Y., Hou, Z. (2013) Physiological mechanisms for plant distribution pattern: responses to flooding and drought in three wetland plants from Dongting Lake, China. Limnology, 14(1): 7176.

Li, N., Zhou, D., Duan, Z., Wang, S. and Cui, Y. (2010) Application of unmanned airship image system and processing techniques for identifying of fresh water wetlands at a community scale. In: Proceedings IEEE 18th Geoinformatics International Conference. Beijing: IEEE.

Lonsdale, W. M. (1988) Litterfall in an Australian population of *Mimosa pigra*, an invasive tropical shrub. Journal of Tropical Ecology, 4, 381–392.

Lonsdale, W. M., Miller, I. L. and Forno, I. W. (1989). The biology of Australian weeds. 20. *Mimosa pigra* L. Plant Protection Quarterly, 4, 119–131.

Lonsdale, W. M. and Miller, I. L. (1993) Fire as a Management Tool for a Tropical Woody Weed: *Mimosa pigra* in Northern Australia. Journal of Environmental Management 39:77-88.

Manfreda, S., Mccabe, M., Miller, P., Lucas, R., Pajuelo, V.M., Mallinis, G., Ben Dor, E., Helman, D., Estes, L., Ciraolo, G., et al. (2018) On the Use of Unmanned Aerial Systems for Environmental Monitoring. Remote Sens.10, 641.

Marcaccio, J.V., Markle, C.E. and Chow-Fraser, P. (2016) Use of fixed-wing and multi-rotor Unmanned aerial vehicles to map dynamic changes in a freshwater march. Journal of Unmanned Vehicle Systems 4(3):193-202. https://doi.org/10.1139/juvs-2015-0016.

Marengo, J.A. and Nobre, C.A. (2001) The hydro climatological framework in Amazonia. In RICHEY, J., MCCLAINE, M. and VICTORIA, R. (Eds.), Biogeochemistry of Amazonia. Oxford: Oxford University Press.17-42.

Masifwa, W.F., Twongo, T. and Denny, P. (2001) The impact of water hyacinth, *Eichhornia crassipes* (Mart.) Solms on the abundance and diversity of aquatic macroinvertebrates along the shores of northern Lake Victoria, Uganda. Hydrobiologia 452:79-88.

Masters, G. and Norgrove, L. (2010) Climate change and invasive alien species. CABI Workung Paper1, 30 pp.

Matthews, L.J., Manson, B.E. and Coffey, B.T. (1977) Longevity of water hyacinth (*Eichhornia crassipes* (Mart.) Solms.) seed in New Zealand Proceedings 6th Asian, Pacific Weed Science Society Conference 1968, 1: 263-7.

McGowan, S., Leavitt, P.R., Hall R.I., et al. (2011) Interdecadal declines in flood frequency increase primary production in lakes of a northern river delta, Global Change Biol. 17:1212-1224.

Meerhoff, M., Mazzeo, N, Moss, B and Rodriguez-Gallego, L. (2003) The structuring role of free floating versus submerged plants in a subtropical shallow lake. Aquatic Ecology 37: 377- 391.

Millennium Ecosystem Assessment (MA) (2005) Ecosystems and human well-being: Wetlands and water synthesis World Resources Institute, Washington, DC.

Mitchell, D.S. (1985) Surface-floating aquatic macrophytes. In: The Ecology and Management of African Wetland Vegetation (Eds P. Denny), pp. 109– 124. Dr. W. Junk Publishers, Dordrecht.

Mitsch, W.J. and Gosselink, J.G. (2007) Wetlands. 4th ed. Hoboken (NJ): Wiley

Mueller-Vombois, D. and Ellenberg, H. (1974) Aim and Methods of vegetation Ecology. Wiley, New York.

Muller, E. (1997) Mapping riparian vegetation along rivers: Old concepts and new methods. Aquatic Botany 58(3-4):411-437.

Naichia, Y., Pulin, Y. and Yuan-Hsiou, C. (2015) Artificial Floating Islands for Environmental Improvement. Renewable and Sustainable Energy Reviews 47: 616-622.

National Statistical Office (2019) http://web.nso.go.th/. (Accessed: 6 August 2021) (in Thai).

Newman, J. (2005) CEH Information Sheet 20: *sparganium erectum*, UK Centre for Ecology & Hydrology.

Nex, F.C. and Remondino, F. (2014) UAV for 3D mapping applications: a review. Applied geomatics, 6(1), 1-1-2015.

Ngoye, E. and Machiwa, J.F. (2004) The Influence of Land Use Patterns in the Ruvu River Watershed on Water Quality in the River System. Physics and Chemistry of the Earth 29(15&18): 1161- 1166.

Nicol, J. and Ganf, G.G. (2000) Water regimes, seedling recruitment and establishment in three wetland plant species, Mar. Freshwater Res. 51:305-309.

Nielsen, D.L., Podnar, K., Watts, R., et al. (2013) Empirical evidence linking increased hydrologic stability with decreased biotic diversity within wetlands, Hydrobiologia 708:81-96.

Nõges, T. and Nõges, P. (1999) The effect of extreme water level decrease on hydrochemistry and phytoplankton in a shallow eutrophic lake, Hydrobiologia 408:277-283.

Nohara, S. and Tsuchiya, T. (1990) Effects of water level fluctuation on the growth of *Nelumbo nucifera* Gaerm. in Lake Kasumigaura, Japan. Ecological Research 5:237-252.

Office of Natural Resources and Environmental Policy and Planning. (2006) Biodiversity in Nong Bong Khai Non-hunting Area Chiang Rai province. Ministry of Natural Resources and Environment, Bangkok, Thailand (in Thai).

Office of Natural Resources and Environmental Policy and Planning (2013). http://chm-thai.onep.go.th/. (Accessed: 8 August 2021) (in Thai).

Office of Natural Resources and Environmental Policy and Planning (2018). http://chm-thai.onep.go.th/. (Accessed: 8 August 2021) (in Thai).

Ogle, K. and Reynolds, J.F. (2004) Plant responses to precipitation in desert ecosystems: integrating functional types, pulses, thresholds, and delays. Oecologia 141, 282-294.

Olmsted, I.C. and Armentano, T.V. (1997) Vegetation of Shark Slough, Everglades National Park. South Florida Research Center Report 97-001. Homestead, FLNational Park Service, 41 p.

Pankhurst, H. (2005) Patterns in the Distribution of Aquatic Macrophytes in Georgian Bay, Ontario, Final Report for Senior Honours Project Submitted to: Department of Biology McMaster University 1280 Main Street West Hamilton, ON L8S 4K1.

Patel, S. (2012) Threats, management and envisaged utilizations of aquatic weed *Eichhornia crassipes*. Environ Sci Biotechnol 11:249-259.

Paul, V.M. and James, A.L. (2003) Effects of increased phosphorus loading on dissolved oxygen in a subtropical wetland, the Florida Everglades. Wetlands Ecology and Management 11: 199-216.

Pieterse, A.H. (1978) The water hyacinth (*Eichhornia crassipes*) a review. Abstracts Tropical Agriculture 4(2): 9-42.

Pimentel, D., Lach, L., Zuniga, R. and Morrison, D. (2000) Environ-mental and economic costs associated with non-indigenous species in the United States. BioScience 50(1): 53-6.

Poff, N. L. and J. D. Allan, et al. (1997) The natural flow regime: a paradigm for river conservation and restoration. BioScience 47(11): 769–784.

Poff, N.L. (2002) Ecological response to and management of increased flooding caused by climate change, The Royal Society of London. Series A, 360(1796):1497-1510.

Popp, J., Lankner, Z., Harangi-Rakos, M. and Fari, M. (2014) The effect of bioenergy expansion: Food, energy, and environment, Renewable and Sustainable Energy Reviews, 32:559-578.

Poulos, H.M., Chernoff, B., Fuller, P.L., Butman, D. (2012) Aquatic Invasions 7: 59-72.

Prita, A.P., Yudi, S., Rahmi, N.K. and Hefni, E. (2017) The effect of land use change on water quality: A case study in Ciliwung Watershed. The IOP Conference Series: Earth and Environmental Science 54.

Ramsar Convention Secretariat (2013) The Ramsar Convention Manual A Guide to the Convention on Wetlands (Ramsar, Iran, 1971) 6th edition.

Ramsar (2014) https://www.ramsar.org/. (Accessed: 15 September 2021).

Ratanasermpong, S. (2000) Monitoring mangrove forest in relation with shrimp farm. In GISTDA. Proceeding of the 9th Regional Seminar on Earth Observation for Tropical Ecosystem management, 20-24 November 2000. Thailand: Khao Yai. 127-133.

Raulings, E.J., Morris, K., Roache, M.C., et al. (2010) The importance of water regimes operating at small spatial scales for the diversity and structure of wetland vegetation, Freshwater Biol 55:701-715.

Reinhardt, H. (1991) Long-term effect of cassava cultivation on soil productivity. Field Crops Research 26: 1-18.

Richardson, D.M., Pyšek, P., Rejmánek, M., Barbour, M.G., Panetta, D.F. and West, C.J. (2000a.) Naturalization and invasion of alien plants-concepts and definitions. Diversity and Distributions, 6:93-107.

Roulet, N. and Moore, T.R. (2006) Browning the waters. Nature 444: 283-284.

Rusnáka, M., Sládeka, J., Kidová, A. and Lehotský, M. (2018) Template for high-resolution river landscape mapping using UAV technology. Measurement 115:139-151.

Sale, P.J.M., Orr, P.T., Shell, G.S. and Erskine, D.J.C. (1985) Photosynthesis and growth rates in *Salvinia molesta* and *Eichhornia crassipes.* Journal of Applied Ecology 22:125-137.

Samouth, C (2004). *Mimosa pigra* infestation and the current threat to wetlands and flood plains in Cambodia. In Research and Management of *Mimosa pigra* (eds. M. Julien, Flanagan, G. Heard, T., Hennecke, B., Paynter, Q. and Wilson, C.), pp. 29-32. CSIRO Entomology, Canberra, Australia.

Santamaría, L. (2002) Why are most aquatic plants widely distributed? Dispersal, clonal growth and small-scale heterogeneity in a stressful environment. Acta Oecologica 23(3):137-154.

Sarah, H. (2020) Wetland Mapping and Restoration Decision Making using Remote Sensing and Spatial Analysis: A Case Study at the Kawainui Marsh, A Thesis Proposal Presented to the Faculty of the USC Dornsife College of Letters, Arts and Sciences University of Southern California.

Schwinning, S., Starr, B.I., Ehleringer, J.R., (2003) Dominant cold desert plants do not partition warm season precipitation by event size. Oecologia 136, 252-260.

Sculthorpe, C.D. (1967) The Biology of Aquatic Vascular Plants (reprinted in 1985). Edward Arnold, London, UK.

Shahbazi, M., Théau, J. and Ménard, P. (2014) Recent applications of unmanned aerial imagery in natural resource management. GIScience & Remote Sems 51(4):339-365. http://doi.org/10.1080/15481603.2014.926650.

Sliva, L. and Williams, D.D. (2001) Buffer zone versus whole catchment approaches to studying land use impact on river water quality. Water Research 35, 3462–3472.

Smith, G.M., Spencer, T., Murray, A.L., and French, J.R. (1998) Assessing seasonal vegetation change in coastal wetlands with airborne remote sensing:An outline Methodology. Mangroves and Salt Marshes, 2:15-28.

Son, N. H., Lam, P. V., Cam, N. V., et al. (2004) Preliminary studies on control of *Mimosa pigra* in Vietnam. In Research and Management of *Mimosa pigra*, ed. M. Julien, G. Flanagan, T. Heard, et al. Canberra, Australia: CSIRO Entomology, pp. 110–116.

Sou, S.Y. and Fujishige, N. (1995) Cultivation comparison of lotus (*Nelumbo nucifera*) between China and Japan. Journal of Zhejiang Agricultural Sciences 4:187–189.

Spence, D.H. N. (1982) The zonation of plants in freshwater lakes, Advances in Ecological Research 12:37-125.

Stets, E.G. and Cotner, J.B. (2008) The influence of dissolved organic carbon on bacterial phosphorus uptake and bacteria-phytoplankton dynamics in two Minnesota lakes. Limnol. Oceanogr. 53:137-147.

Stonestrom, D.A., Scanlon, B.R. and Zhang, L. (2009) Introduction to special section on impacts of land use change on water resources Water Resour. Res., 45:2-4.

Striker, G.G., Casas, C., Kuang, X., Grimoldi, A.A. (2017) No escape? Costs and benefits of leaf de-submergence in the pasture grass Chloris gayana under different flooding regimes. Funct Plant Biol. 44: 899-906.

Suwit, T. (2006) The Orchids in Narathiwat Province. Department of National Parks, Wildlife and Plant Conservation, Bangkok, Thailand (in Thai).

Tamire, G. and Mengistou, S. (2012) Macrophyte species composition, distribution and diversity in Relation to some physiochemical factors in the littoral zone of Lake Ziway, Ethiopia. African Journal of Ecology 51(1):66-77.44).

Thailand Institute of Scientific and Technological Research (2011) Project of survey the status of freshwater swamp in Thailand's wetland. Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand (in Thai).

Thailand Institute of Scientific and Technological Research (2017) Efficiency enhancement of Thailand's wetland management project. Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand (in Thai).

The Berkshire Regional Planning Commission (2003) The Massachusetts Buffer Manual Using Vegetated Buffers to Protect our Lakes and Rivers, Massachusetts Executive Office of Environmental Affairs, 8-13.

The CRC for Australian Weed Management and the Commonwealth Department of the Environment and Heritage (CRC) (2003) Mimosa (*Mimosa pigra*) – Weed Management Guide.

The Department of Agriculture, Thailand (2020). https://www.doa.go.th/th/ (Accessed: 15-April-2021).

The Department of National Parks, Wildlife and Plant Conservation, Thailand (2019). http://www.dnp.go.th/ (Accessed: 11-Febuary-2020).

The Environmental Management and Engineering 2011(EME) (2011) conference in Calgary, AB, Canada has ended.

The Meteorological Department, Thailand (2014). http://www.tmd.go.th/ (Accessed: 13-Febuary-2020) (in Thai).

The Meteorological Department, Thailand (2021).http://www.tmd.go.th/ (Accessed: 10-December-2020) (in Thai).

The Northern Meteorological Center, Thailand (2020). http://www.cmmet.tmd.go.th/ (Accessed: 10-December-2020) (in Thai).

The State of Queensland, Department of Agriculture and Fisheries (2020). https://www.daf.qld.gov.au/ (Accessed: 10-December-2021).

Triet, T., Kiet, L.C., Thi, N.T.L., and Dan, P.Q. (2004) The invasion of *Mimosa pigra* of wetlands of the Mekong Delta, Vietnam. In Research and Management of *Mimosa pigra* (eds. M. Julien, Flanagan, G. Heard, T., Hennecke, B., Paynter, Q. and Wilson, C.), pp. 45-51. CSIRO Entomology, Canberra, Australia.

Ueki, K. and Oki, Y. (1979) Seed production and germination of *Eichhornia crassipes* in Japan. In: Proceedings of the Seventh Asian Pacific Weed Science Society Conference. pp. 257–260.

University of New Hampshire Cooperative Extension (2007) Landscaping at the water's Edge, An Ecological Approach. U.S. Department of Agriculture, National Integrated Water Quality Program, 25-27.

United States Environmental Protection Agency (2021) Agricultural Management Practices for Water Quality Protection. http://www.epa.gov/watertrain (Accessed: 19-April-2021).

U.S. Fish and Wildlife Service (2019) National Wetland Inventory. https://www.fws.gov/wetlands/ (Accessed: 10-December-2020).

Valta-Hulkkonen, K., Partanen, S. and Kanninen, A. (2003b) Remote sensing as a tool in the aquatic macrophyte mapping of a eutrophic lake: a comparison between visual interpretation and spectral sorting. Proceedings 9th Scandinavian Research Conference on Geographical Information Science. 79-90.

Van Asselen, S., Verburg, P.H., Vermaat, J.E. and Janse, J.H. (2013) Drivers of wetland conversion: A global meta-analysis. PLoS ONE 8: e81292.

Van Doorn, A.M., Bakker, M.M. (2007): The destination of arable land in a marginal agricultural landscape in South Portugal: an exploration of land use change determinants. Landscape Ecology, 22, 1073–1087.

Vermaat, J.E. and De Bruyne, R.J. (1993) Factors limiting the distribution of submerged water plants in the lowland River Vecht (The Netherlands). Freshwater Biology 30(1):147-157.

Villamagna, A. and Murphy, B. (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*). Freshwater Biology 55: 282-298.

Wanichantakul, P. and Chinawong, S. (1979) Some aspects on the biology on M. *pigra* in Northern Thailand. Proc. 7th Asian Pac. Weed Sci. Soc. Conf., Sydney, Australia.

Watts, A.C., Perry, J.H., Smith, S.E., Burgess, M.A., Wilkinson, B.E., Szantori, Z., Ifju, P.G. and Percival, H.F. (2010) Small unmanned aircraft systems for low-altitude aerial surveys. The Journal of Wildlife Management 74(7):1614-1619. https://doi.org/10.2193/2009-425.

Wilson, S.D. and Keddy, P.A., (1985) Plant zonation on a shoreline gradient: physiological response curves of component species. J. Ecol. 73, 851-860.

Whitehead, K., Hugenholtz, C.H., Myshak, S., Brown, O., LeClair, A., Tamminga, A., Barchyn, T.E., Moorman, B. and Eaton, B. (2014) Remote sensing of the environment with small unmanned aircraft systems (UASs), part 1: A review of progress and challenges. J. Unmanned Veh. Syst. 2, 86-102.

Wilcox, D. A., and Meeker, J. E. (1992) Implications for faunal habitat related to altered macrophyte structure in regulated lakes in Northern Minnesota. Wetlands 12(3): 192-203.

Wiser, L. and Blom, T.J. (2016) The Effect of Nitrogen and Phosphorus Ratios and Electrical Conductivity on Plant Growth. American Journal of Plant Sciences, 7, 1590-1599.

Wongsupathai, C., Takagi, K and Hioki, Y. (2021) Mapping of Non-Submerged Aquatic Vegetation by Using UAV for Clarifying the Status of *Eichhornia crassipes* (Mart.) Solms in the Nong Bong Khai Non-hunting Area, Thailand. Journal of the Japanese Society of Revegetation Technology 47 (2): 273-291.

Wooten, J.W. (1986) Variations in leaf characteristics of six species of Sagittaria (Alismataceae) caused by various water levels. Aquatic Botany 23:321-27.

Wright, A.D. and Purcell, M.F. (1995) *Eichhornia crassipes* (Mart.) Solms-Laubach. The Biology of Australian Weeds. RG and FJ Richardson, Melbourne.

Wright, A.J., de Kroon, H., Visser, E.J.W., Buchmann, T., Ebeling, A., Eisenhauer, N., et al. (2017) Plants are less negatively affected by flooding when growing in species-rich plant communities. New Phytol. 213: 645-656. https://doi.org/10.1111/nph.14185 PMID: 27717024.

Xie, Y.H. and Yu, D. (2003) The significance of lateral root in phosphorus (P) acquisition of water hyacinth (*Eichhornia crassipes*). Aquatic Botany 75:311-321.

Xie, Y.H., Yu, D. and Ren, B. (2004) Effects of nitrogen and phosphorus availability on the decomposition of aquatic plants. Aquatic Botany

80(1):29-37.

Yang, J., Li, E., Cai, X., Wang, Z. and Wang, X. (2014) Research progress in response of plants in wetlands to water level change, Wetl. Sci. 12:807-813.

Yong, S.T.Y. and Chen, W. (2002) Modeling the relationship between land use and surface water quality, Journal of Environmental Management, 66 (4): 377-393.

Yongyut, T. (2006) Community-based Wetland Management in Northern Thailand. International Journal of Environmental, Cultural, Economic and Social Sustainability 2(1): 49-62.

Yu, D., Shi, P., Liu, Y. and Xun, B. (2013) Detecting land use and water quality relationships from the view point of ecological restoration in an urban area. Ecological Engineering 53: 205-21.

Zedler, J.B. and Kercher, S. (2005) Wetland Resources: status, trends, ecosystem services, and restorability Rev. Lit. Arts Am, pp. 39-47.

Zhang, C. and Kovacs, J.M. (2012) The application of small unmanned aerial systems for precision agriculture: a review, Precision Agric,13:693-712.

Zhao, W.Z., Liu, B. (2010) The response of sap flow in shrubs to rainfall pulses in the desert region of China. Agric. For. Meteorol. 150 (9):1297-1306.

Zweig, C.L., Burgess, M.A., Pecival, H.F., and Kitchens, W.M., (2015) Use of Unmanned Aircraft Systems to Delineate FineScale Wetland Vegetation Communities. Wetlands, 35:303- 309.

List of Publications

CHAPTER 4

Author : Chitapa Wongsupathai, Kohei Takagi, Yoshiyuki Hioki

Title : Mapping of non-submerged aquatic vegetation by using UAV for clarifying the status of *Eichhornia crassipes* (Mart.) Solms in the Nong Bong Khai non-hunting area, Thailand

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CHAPTER 5

Author : Chitapa Wongsupathai, Kohei Takagi, Yoshiyuki Hioki

Title : The effect of water level fluctuation due to decreased precipitation on the non-submerged aquatic vegetation in Nong Bong Khai non-hunting area, Northern Thailand

Journal : The Japanese Society of Revegetation Technology

Appendix List

Appendix 1 Plant species list in the Nong Bong Khai lake.

Family	Species	Life from
Acanthaceae	*P. latifolium* (Vahl) B.Hansen	S
	Peristrophe lanceolaria (Roxb.) Nees	H
	Pseuderanthemum graciliflorum (Nees) Ridl.	S
	Ruellia tuberosa L.	ExH
	Thunbergia fragrans Roxb. var. *fragrans*	C
Aizoaceae	*Trianthema portulacastrum* L.	H
Alangiaceae	*Alangium indochinense* W.J.de Wilde & Duyfjes	ST/T
Amaranthaceae	*A. sessilis* (L.) DC.	H
	A. viridis L.	H
	Achyranthes aspera L.	US
	Alternanthera philoxeroides (Mart.) Griseb.	AqH
	Amaranthus spinosus L.	H
	Celosia argentea L.	H
	Cyathula prostrata (L.) Blume	US
	Gomphrena celosioides Mart.	H
Anacardiaceae	*Spondias pinnata* (L.f.) Kurz	T
Anciatrocladaceae	*Ancistrocladus tectorius* (Lour.) Merr.	ScanS
Annonaceae	*Atabotrys harmandii* Finet & Gagnep.	WC
	Cananga latifolia (Hook.f. & Thomson) Finet & Gagnep.	T
	Desmos chinensis Lour.	ScanS
	Hubera cerasoides (Roxb.) Chaowasku	T
	Melodorum fruticosum Lour.	T
	U. rufa (Dunal) C.Meade var. *rufa*	WC
	Uvaria siamensis (Scheff.) L.L.Zhou, Y.C.F.Su & R.M.K.Saurnders	WC
Apocynaceae	*Aganonerion polymorphum* Pierre ex Spire	C
	Aganosma marginata (Roxb.) G.Don	WC
	Alstonia scholaris (L.) R.Br.	T
Acanthaceae	*P. latifolium* (Vahl) B.Hansen	S
	Peristrophe lanceolaria (Roxb.) Nees	H
	Pseuderanthemum graciliflorum (Nees) Ridl.	S
	Ruellia tuberosa L.	ExH
	Thunbergia fragrans Roxb. var. *fragrans*	C
Aizoaceae	*Trianthema portulacastrum* L.	H
Alangiaceae	*Alangium indochinense* W.J.de Wilde & Duyfjes	ST/T
Amaranthaceae	*A. sessilis* (L.) DC.	H
	A. viridis L.	H
	Achyranthes aspera L.	US
	Alternanthera philoxeroides (Mart.) Griseb.	AqH
	Amaranthus spinosus L.	H
	Celosia argentea L.	H
Apocynaceae	*Amalocalyx microlobus* Pierre ex Spire	C
	Holarrhena pubescens Wall. ex G.Don	ST/T
	Ichnocarpus frutescens (L.) W.T.Aiton	WC
	W. religiosa Benth. ex Kurz	S/ST
	Willughbela edulis Roxb.	WC
	Wrightia arborea (Dennst.) Mabb.	T
Araceae	*Amorphophallus paeoniifolius* (Dennst.) Nicolson	H
	Colocasia esculenta (L.) Schott	H
	Lasia spinosa (L.) Thwaites	H
	Pistia stratiotes L.	AqH
	Typhonium trilobatum (L.) Schott.	H

Family	Species	Life from
Aristolochiaceae	*A. pothiei* Pierre ex Lecomte	C
	Aristolochia indica L.	C
Asclepiadaceae	*Calotropis gigantean* (L.) Dryander ex W.T.Aiton	ExS
	Crptolepis buchanani Roem. & Schult.	WC
	Dischidia nummularia R.Br.	CrH
	Dregea volubilis (L.f.) Hook.f.	WC
	Heterostemma piperifolium King & Gamble	C
	Hoya verticillata (Vahl) G.Don	EC
	Marsdenia glabra Cost.	C
	Marsdenia tinctoria R.Br.	C
	Raphistemma hooperiana (Blume) Decne.	C
	Sacrostemma secamone (L.) Bennet	C
	Streptocaulon juventas (Lour.) Merr.	C
	Toxocarpus villosus (Blume) Decne.	WC
Bignoniaceae	*Radermachera ignea* (Kurz) Steenis	T
Blechnaceae	*Stenochlaena palustris* (Burm.f.) Bedd.	CF
Bombacaceae	*Bombax ceiba* L.	T
Boraginaceae	*Ehretia laevis* Roxb.	ST
	Heliotropium indicum L.	H
Burmaniaceae	*Burmania coelestis* D.Don	H
Burseraceae	*Canarium subulatum* Guillaumin	T
	Garuga pinnata Roxb.	T
Cannaceae	*Canna indica* L.	ExH
Capparaceae	*C. rutidosperma* DC.	H
	C. viscosa L.	H
	Capparis micracantha DC.	S
	Celastrus paniculata Willd.	WC
	Cleome gynandra L.	H
	Crateva magna (Lour.) DC.	T
	Siphonodon celastrineus Griff.	T
Chrysobalanaceae	*Parinari anamense* Hence	T
Combretaceae	*C. quadrangulare* Kurz	T
	C. tetralophum C.B.Clarke	WC
	C. trifoliatum Vent.	WC
	Combretum latifolium Blume	WC
	Combretum latifolium Blume	WC
	Getonia floribunda (Roxb.) Lam.	WC
	T. catappa L.	T
	Terminalia alata Heyne ex Roth	T
Compositae	*Bidens bipinnata* L.	ExH
	Blumea balsamifera (L.) DC.	S
	Centipeda minima (L.) A.Braun & Asch.	H
	Chromolaena odorata (L.) R.M.King & H.Rob.	ExS
	Crassocephalum crepidioides (Benth.) S.Moore	H
	Cyanthillium cinereum (L.) H.Rob.	H
	Eclipta angustata Umemoto & H.Koyama	H
	Emilia sonchifolia (L.) DC. ex Wight	H
	Enydra fluctuans Lour.	AqH
	Grangea maderaspatana (L.) Poir.	H
	Lagascea mollis Cav.	ExH
	Mikania cordata (Burm.f.) B.L.Rob.	ExC
	Sphaeranthus africanus L.	H
	Tarlmounia elliptica (DC.) H.Rob.	WC
	Tithonia diversifolia (Hemsl.) A.Gray	ExUS
	Tridax procumbent L.	H

Family	Species	Life from
	Connarus semidecandrus Jack	WC
Convolvulaceae	*Aniseia martinicensis* (Jacq.) Choisy	C
	Argyreia breviscapa (Kerr) Ooststr.	C
	Evolvulus nummularius (L.) L.	H
	I. rubens Choisy	C
	Ipomoea aquatica Forssk.	CrH
	M. hirta (L.) Merr.	HC
	Merremia hederacea (Burm.f.) Hallier f.	HC
	Operculina turpethum (L.) Silva Manso	HC
Costaceae	*Cheilocostus speciosus* (J.König) C.D.Specht	H
Crypteroniaceae	*Crypteronia paniculata* Blume	T
Cucurbitaceae	*Coccinia grandis* (L.) Voigt	H
	G. scabrum (Lour.) W.J.de Wilde & Duyfjes	HC
	Gymnopetalum chinense (Lour.) Merr.	HC
	Luffa aegyptiaca Mill.	HC
	Mukia maderaspatana (L.) M.Roem.	HC
	Solena heterophylla Lour. subsp. *heterophylla*	HC
Cyperaceae	*C. cyperoides* (L.) Kunze	H
	C. digitatus Roxb.	H
	C. haspan L.	H
	C. imbricatus Retz.	H
	C. mitis Steud.	H
	C. platystylis R.Br.	H
	C. rotundus L.	H
	Cyperus corymbosus Rottb.	H
	F. umbellata Rottb.	H
	Fimbristylis dichotoma (L.) Vahl subsp. *dichotoma*	H
	Fuirena ciliaris (L.) Roxb.	H
	Scleria poaeformis Retz.	H
Datiscaceae	*Tetrameles nudiflora* R.Br.	T
	Dlinia obovata (Blume) Hoogland	T
	Tetracera loureiri (Finet. & Gagnep.) Pierre ex Craib	WC
Dioscoreaceae	*D. bulbifera* L.	HC
	Dioscorea birmanica Prain & Burkill	HC
Dipterocarpaceae	*Dipterocarpus alatus* Roxb. ex G.Don	T
	Hopea odorata Roxb.	T
Droseraceae	*D. indica* L.	H
	Drosera burmannii Vahl	H
Drypteridaceae	*Diplazium esculentum* (Retz.) Sw.	TerF
Ebenaceae	*D. montana* Roxb.	T
	Diospyros ehretioides Wall. ex G.Don	T
Elaeagnaceae	*Elaeagnus latifolia* L.	WC
Elaeocarpaceae	*Elaeocarpus hygrophilus* Kurz	T
Eriocaulaceae	*Eriocaulon ubonense* Lecomte f. *kraduengensis* A.Prajaksood	H
Euphorbiaceae	*A. ghaesembilla* Gaertn.	S/ST
	Acalypha indica L.	H
	Antidesma acidum Retz.	S
	Aporosa villosa (Wall. ex Lind.) Bail.	ST
	B. tomentosa Blume	S/ST
	Baccaurea ramiflora Lour.	ST/T
	Balakata baccata (Roxb.) Esser	T
	Bischofia javanica Blume	T
	Breynia glauca Craib	S
	Bridelia retusa (L.) A.Juss	ST

Family	Species	Life from
	Cladogynos orientalis Zipp. ex Span.	S
	Claoxylon indicum (Reinw. ex Blume) Endl. ex Hassk.	ST
	Croton roxburghii N.P.Balakr.	T
	E. hirta L.	H
	Euphorbia heterophylla L.	ExH
	Flueggea virosa (Roxb. ex Willd.) Voigt	S
	Glochidion hirsutum (Roxb.) Voigt	ST
	Hymenocardia wallichii Tul.	S/ST
	M. paniculatus Müll.Arg.	T
	M. philippensis Müll.Arg.	T
	Macaranga denticulata (Blume) Müll.Arg.	ST
	Mallotus barbatus Müll.Arg.	ST
	P. reticulatus Poir.	S/ST
	P. virgatus G.Forst.	H
	Phyllanthus amarus Schumach. & Thonn.	H
	Ricinus communis L.	ExS/ST
	Sauropus androgynus (L.) Merr.	S
	Suregada multiflorum (A.Juss.) Baill.	T
Fagaceae	*Lithocarpus polystachyus* (A.DC.) Rehder	T
Flacourtiaceae	*Flacourtia indica* (Burm.f.) Merr.	T
Flacourtiaceae	*Hydnocarpus ilicifolia* King	T
Flagellariaceae	*Flagellaria indica* L.	WC
Gramineae	*Arundo donax* L.	G
	Cenchrus echinatus L.	G
	Chrysopogon aciculatus (Retz.) Trin.	G
	Coix aquatica Roxb.	AqG
	Cynodon dactylon (L.) Pers.	G
	D. nuda Schumach.	G
	D. violascens Link	G
	Dactyloctenium aegyptium (L.) P.Beauv.	G
	Dendrocalamus stratus (Roxb.) Nees	B
	Digitaria ciliaris (Retz.) Koeler	G
	E. unioloides (Retz.) Nees	G
	Echinochloa stagnina (Retz.) P.Beauv.	G
	Eragrostis nutans (Retz.) Nees ex Steud.	G
	H. pseudointerrupta C.Muell.	G
	Hygroryza aristata Nees	G
	Hymenachne amplexicaulis (Rudge) Nees	G
	I. rugosum Salisb.	G
	Imperata cylindrical (L.) P.Beauv.	G
	Isachne globosa (Thunb.) Kuntze	G
	Ischaemum magnum Rendle	G
	Leersia hexandra Sw.	G
	O. sativa L.	G
	Oryza rufipogon Griff.	G
	Ottochloa nodosa (Kunth) Dandy	G
	Panicum repens L.	G
	Pennisetum polystachyon (L.) Schult.	ExG
	Phragmites vallatoria (Pluk. ex L.) Veldkamp	G
	S. geniculata (Lam.) P.Beauv.	G
	Saccharum arundinaceum Retz.	G
	Setaria flavidum (Retz.) A.Camus	G
	Thyrsostachys siamensis Gamble	B
Guttiferae	*C. formosum* (Jack) Dyer	T
	Cratoxylum cochinchinensis (Lour.) Blume	T
	Hypericum japonicum Thunb. ex Murraz	H

Family	Species	Life from
Hydrocharitaceae	*Blyxa aubertii* A.Rich. var. *aubertii*	AqH
	Hydrilla verticillata (L.f.) Royle	AqH
	Ottelia alismoides (L.) Pers.	AqH
	Hydrolea zeylanica (L.) Vahl	H
Icacinaceae	*Gonocaryum lobbianum* (Miers) Kurz	S
Irvingiaceae	*Irvingia malayana* Oliv. ex A.W.Benn.	T
Labiatae	*C. paniculatum* L. var. *paniculatum*	S
	Callicarpa arborea Roxb.	S/ST
	Clerodendrum indicum (L.) Kuntze	S
	Congea tomentosa Roxb.	WC
	G. elliptica Sm.	S/ST
	Gmelina arborea Roxb.	T
	Hymenopyramis brachiata Wall. ex Schauer	ScanS
	Hyptis suaveolens (L.) Poit.	S
	Leucas zeylanica (L.) R.Br.	H
	Tectona grandis L.	T
	V. pinnata L.	T
	Vitex limonifolia Wall.	T
Lauraceae	*Cassytha filiformis* L.	PaHC
	Cinnamomum iners Reinw. ex Blume	T
	Litsea glutinosa (Lour.) C.B.Lob.	T
	Persia kurzii Kosterm.	T
Lecythidaceae	*Barringtonia acutangula* (L.) Gaertn.	ST/T
Leeaceae	*Leea indica* (Burm.f.) Merr.	S
Leguminosae-Caesalpinioideae	*Afzelia xylocarpa* (Kurz) Craib	T
	B. scandens L. var. *horsfieldii* (Miq.) K. & S.S.Larsen	WC
	Bauhinia bracteata (Graham ex Benth.) Baker	WC
	Caesalpinia digyna Rottler	WC
	Cassia fistula L.	T
	Chamaecrista mimosoides (L.) Greene	US
	Delonix regia (Bojor ex Hook.) Raf.	ExT
	Peltophorum dasyrrachis (Miq.) Kurz ex Baker	T
	S. garrettiana (Craib) H.S.Irwin & Barneby	T
	S. spectabilis (DC.) H.S.Irwin & Barneby	ExT
	S. timoriensis (DC.) H.S.Irwin & Barneby	ST
	S. tora (L.) Roxb.	US
	Senna alata (L.) Roxb.	ExS
	Tamarindus indica L.	ExT
Leguminosae-Mimosoideae	*A. concinna* (Willd.) DC.	ScanS
	A. pennata (L.) Willd. subsp. *kerrii* I.C.Nielsen	WC
	Acacia auriculaeformis A.Cunn. ex Benth.	ExT
	Leucaena leucocephala (Lam.) de Wit	ExST/T
	M. pudica L.	US
	Mimosa pigra L.	ExS
	Neptunia oleracea Lour.	AqH
	Pithecellobium dulce (Roxb.) Benth.	ExT
	Xylia xylocarpa (Roxb.) Taub. var. *kerrii* (Craib & Hutch.) I.C.Nielsen	T
Leguminosae-Papilionoideae	*Aeschynomene aspera* L.	US
	Centrosema pubescens Benth.	C
	Crotalaria pallida Aiton	ExS
	D. nigrescens Kurz	T
	D. oliveri Gamble	T

Family	Species	Life from
	Dalbergia cochinchinensis Pierre	T
	Derris scandens (Roxb.) Benth.	WC
	Desmodium triflorum DC.	CrH
	Erythrina fusca Lour.	T
	Milllettia brandisiana Kurz	T
	Mucuna pruriens (L.) DC.	WC
	P. macrocarpus Kurz	T
	Pterocarpus indicus Willd.	T
	S. javanica Miq.	H
	Sesbania grandiflora (L.) Desv.	ExST
	Spatholobus parviflorus (DC.) Kuntze	WC
	Uraria crinita (L.) Desv. ex DC.	US
Lemnaceae	*Lemna perpusilla* Torr.	AqH
Lentibulariaceae	*Utricularia aurea* Lour.	AqH
Limnocharitaceae	*Limnocharis flava* (L.) Buchenau	ExAqH
Loranthaceae	*Dendrophthoe pentandra* (L.) Miq.	PaS
Lygodiaceae	*L. microphyllum* (Cav.) R.Br.	CF
	L. salicifolium C.Presl	CF
	Lygodium flexuisom (L.) Sw.	CF
Lythraceae	*Ammannia baccifera* L.	H
	L. speciosa (L.) Pers.	T
	Lagerstroemia floribunda Jack	T
Malvaceae	*Abutilon indicum* (L.) Sweet subsp. *indicum*	US
	S. rhombifolia L.	US
	Sida acuta Burm.f.	US
	Talipariti macrophyllus (Roxb.) Fryxell	T
	Urena lobata L.	US
Marantaceae	*Schumannianthus dichotomus* (Roxb.) Gagnep.	S
Marsileaceae	*Marsilea crenata* C.Presl	AqF
Melastomataceae	*Melastoma malabathricum* L. subsp. *malabathricum*	S
	Osbecia chinensis L.	S
Meliaceae	*Aphanamixis polystachya* (Wall.) R.Parker	T
	Azadirachta indica A.Juss. var. *siamensis* Valeton	T
	Chukrasia tabularis A.Juss.	T
Menispermaceae	*Tiliacora triandra* (Colebr.) Diels	C
	Tinospora baenzigeri Forman	C
Menyanthaceae	*Nymphoides indicum* (L.) Kuntze	AqH
Mollyginaceae	*Glinus oppositifolius* A.DC.	H
Moraceae	*B. papyrifera* (L.) Vent.	ST
	Broussonetia kurzii (Hook.f.) Corner	WC
	F. heterophylla L.f.	CrUS
	F. hirta Vahl	S/ST
	F. hispida L.f. var. *hispida*	ST
	F. ischnopoda Miq.	S
	F. microcarpa L.f.	ST
	F. rumphii Blume	T
	F. virens Aiton	T
	Ficus benjamina L.	T
	Streblus asper Lour.	T
Myrsinaceae	*Maesa ramentacea* (Roxb.) A.DC.	ST
Myrtaceae	*S. grande* (Wight) Walp. var. *grande*	T
	Syzygium antisepticum (Blume) Merr. & L.M.Perry	T
	Syzygium cumini (L.) Skeels	T
	Syzygium sp.	ST
Nelumbonaceae	*Nelumbo nucifera* Gaertn.	AqH
Nyctaginaceae	*Boerhavia erecta* L.	H

Family	Species	Life from
Nymphaeaceae	*Barclaya longifolia* Wall.	AqH
	N. nouchali Burm.f.	AqH
	Nymphaea lotus L.	AqH
Olacaceae	*Olax psittacorum* (Willd.) Vahl	ScanS
Oleaceae	*Jasminum anodontum* Gagnep.	WC
Onagraceae	*L. hyssopifolia* (G.Don) Exell	H
	L. octovalvis (Jacq.) P.H.Raven	H
	Ludwigia adscendens (L.) H.Hara.	AqH
Ophioglossaceae	*Helminthostachys zeylanica* (L.) Hook.	TerF
Orcidaceae	*Cymbidium aloifolium* (L.) Sw.	EO
Oxalidaceae	*Oxalis corniculata* L.	CrH
Palmae	*Caryota mitis* Lour.	P
	Licuala spinosa Thunb.	P
Pandanaceae	*Dianella ensifolia* (L.) DC.	H
	Pandanus sp.	S
Passifloraceae	*Passiflora foetida* L.	C
Piperaceae	*Peperomia pellucida* (L.) Kunth	H
Polygalaceae	*Salomonia cantoniensis* Lour.	H
Polygonaceae	*Persicaria attenuat*a (R.Br.) Soják subsp. *pulchera* (Blume) K.L.Wilson	H
Polypodiaceae	*Drynaria quercifolia* (L.) J.Sm.	EF
	P. longifolia (Burm.f.) Morton	EF
	Pyrrosia adnascens (Sw.) Ching	EF
Pontederiaceae	*Eichhornia crassipes* (C.Mart.) Solms	ExAqH
	M. vaginalis (Burm.f.) C.Presl ex Kunth	AqH
	Monochoria elata Ridl.	AqH
	M. hastata (L.) Solms	AqH
Portulaceae	*Portulaca oleracea* L.	H
Rhamnaceae	*Ventilago harmandiana* Pierre	WC
	Z. oenoplia (L.) Mill. var. *oenoplia*	WC
	Ziziphus mauritiana Lam.	T
Rhizophoraceae	*Carallia brachiata* (Lour.) Merr.	T
Rubiaceae	*Anthocephalus chinensis* (Lam.) A.Rich. ex Walp.	T
	Aphaenandra uniflora (Wall. ex G.Don) Bremek.	C
	Cephalanthus tetrandra (Roxb.) Ridsdale & Bakh.f.	ST
	Clausena excavata Burm.f.	S/ST
	Glycosmis pentaphylla (Rotz.) DC.	S
	Haldina cordifolia (Roxb.) Ridsdale	T
	Hymenodictyon orixense (Roxb.) Mabb.	T
	Micromelum falcatum (Lour.) Tanaka	S/ST
	Mitragyna diversifolia (Wall. ex G.Don) Havil	S/ST
	Murraya paniculata (L.) Jack	S/ST
	Nauclea orientalis (L.) L.	T
	O. corymbosa L.	H
	Oldenlandia biflora L.	H
	Paederia pilifera Hook.f.	C
	S. remota Lam.	ExH
	Spermacoce articularis L.f.	H
Salicaceae	*Salix tetrasperma* Roxb.	T
Salviniaceae	*Salvinia cucullata* Roxb. ex Bory	AqF
Sapindaceae	*Cardiospermum halicacabum* L.	C
Sapindaceae	*Lepisanthes rubiginosa* (Roxb.) Leenh.	S/ST
Scrophulariaceae	*L. ciliata* (Colsm.) Pennell	H
	L. crustacea (L.) F.Muell. var. *crustacea*	H
	Limnophila repens (Benth.) Benth.	H
	Lindernia anagallis (Burm.f.) Pennell	H

Family	Species	Life from
	Scoparia dulcis L.	H
	Torenia fourneri Lind. ex E.Fourn.	H
Simaroubaceae	*Ailanthus triphysa* (Dennst.) Alston	T
	Harrisonia perforata (Blanco) Merr.	ScanS
Solanaceae	*Physalis minima* L.	H
	S. stramonifolium Jacq.	ExUS
	Solanum erianthum D.Don	S
Sphenocleaceae	*Sphenoclea zeylanica* Gaertn.	H
Sterculiaceae	*H. hirsuta* Lour.	S
	Helicteres angustifolia L.	S
	Pterocymbium tinctorium (Blanco) Merr.	T
Thelypteridaceae	*T. interrupta* (Willd.) K.Iwats.	TerF
	Thelypteris dentata (Forssk.) St.John	TerF
Tiliaceae	*C. capsularis* L.	H
	Corchorus aestuans L.	H
	Microcos tomentosa Sm.	T
Typhaceae	*Typha angustifolia* L.	H
Ulmaceae	*Trema orientalis* (L.) Blume	ST
Umbelliferae	*Centella asiatica* (L.) Urb.	H
	Hydrocotyle umbellata L.	ExH
Urticaceae	*Pouzolzia zeylanica* (L.) Benn. & N.E.Br.	H
Verbenaceae	*Lantana camara* L.	ExS
	Phyla nodiflora (L.) Greene	CrH
	Stachytarpheta jamaicensis (L.) Vahl	H/US
Vitaceae	*Ampelocissus martini* Planch.	C
	Cayratia trifolia (L.) Domin	C
	Cissus javana DC.	C
Xyridaceae	*X. pauciflora* Willd.	H
	Xyris indica L.	H
Zingiberceae	*Curcuma aerugginosa* Roxb.	H

Source: Thailand Institute of Scientific and Technological Research, 2017

Remark: AqH= Aquatic Herb, B= Bamboo, C= Climber, CR= Critically Endangered

CrH= Creeping Herb, Ex= Exotic, EN= Endangered, G= Grass, H= Herb,

HC= Herbaceous Climber, NT= Near Threatened, LC= Least Concern, R= Rare

S= Shrub, ST= Shrubby Tree, ScanS= Scandent Shrub, T= Tree, US= Undershrub

VU= Vulnerable, WC= Woody Climber

Appendix 2 Species lists of the birds in the Nong Bong Khai lake.

Family	Species
Acciptridae	*Accipiter badius*
	Aquila clanga
	Butastur liventer
	Buteo buteo
	Circus aeruginosus
	Circus melanoleucos
	Elanus caeruleus
	Milvus migrans
	Pandion haliaetus
	Pernis ptilorhyncus
	Spilornis cheela
Alcedinidae	*Alcedo atthis*
	Ceryle ruduis
	Halcyon pileata
	Halcyon smyrnensis
Anatidae	*Aix galericulata*
	Anas acuta
	Anas clypeata
	Anas crecca
	Anas falcata
	Anas formosa
	Anas penelope
	Anas platyrhynchos
	Anas poecilorhyncha
	Anas querquedula
	Anas strepera
	Aythya baeri
	Aythya ferina
	Aythya fuligula
	Aythya marila
	Aythya nyroca
	Clangula hyemalis
	Dendrocygna javanica
	Nettapus coromandelianus
	Sarkidiornis melanotos
	Tadorna ferruginea
	Tadorna tadorna
Anhingidae	*Anhinga melanogaster*
	Anhinga melanogaster
Apodidae	*Cypsiurus balasiensis*
Ardeidae	*Ardea cinerea*
	Ardea cinerea
	Ardea purpurea
	Ardea purpurea
	Ardeola bacchus
	Ardeola bacchus
	Bubulcus ibis

Family	Species
	Bubulcus ibis
	Casmerodius albus
	Dupetor flavicollis
	Egretta garzetta
	Egretta garzetta
	Ixobrychus sinensis
	Mesophoyx intermedia
Artamidae	*Artamus fuscus*
Campephagidae	*Coracina melaschistos*
	Pericrocotus solaris
Caprimulgidae	*Caprimulgus macrurus*
Charadriidae	*Charadrius dubius*
	Vanellus cinereus
	Vanellus vanellus
Chloropseidae	*Aegithina tiphia*
Ciconiidae	*Mycteria leucocephala*
Coraciidae	*Coracias benghalensis*
Corvidae	*Cissa chinensis*
	Corvus macrorhynchos
	Crypsirina temia
Coumbidae	*Columba livia*
	Ducula aenea
	Geopelia striata
	Streptopelia chinensis
	Streptopelia transquebarica
Cuculidae	*Cacomantis merulinus*
	Centropus bengalensis
	Centropus sinensis
	Cuculus canorus
	Endynamys scolopacea
	Phaenicophaeus tristis
Dicaeidae	*Dicaeum cruentatum*
Dicruridae	*Dicrurus leucophaeus*
	Dicrurus macrocercus
Emberizidae	*Emberiza aureola*
	Emberiza fucata
	Emberiza pusilla
	Emberiza rutila
	Melophus lathami
Estrildidae	*Amandava amandava*
	Lonchura malacca
	Lonchura punctulata
	Lonchura striata
Falconidae	*Falco peregrinus*
	Falco tinnunculus
Glareolidae	*Glareola lactea*
	Glareola maldivarum
Gruidae	*Grus grus*
	Grus virgo

Family	Species
Hirundinidae	*Hirundo daurica*
	Hirundo rustica
	Hirundo striolata
Jacanidae	*Hydrophasianus chirurgus*
Laniidae	*Lanius collurioides*
	Lanius cristatus
	Lanius schach
	Lanius tephronotus
Laridae	*Larus brunnicephalus*
	Larus ichthyaetus
	Larus ridibundus
	Sterna aurantia
Megalaimidae	*Megalaima haemacephala*
	Megalaima lineata
	Megalaima virens
Meropidae	*Merops leschenaulti*
	Merops orientalis
	Merops philippinus
Monarchidae	*Hypothymis azurea*
Motacillidae	*Anthus cervinus*
	Anthus hodgsoni
	Anthus richardi
	Anthus rufulus
	Dendronanthus indicus
	Motacilla alba
	Motacilla citreola
	Motacilla flava
Muscicapidae	*Culicicapa ceylonensis*
	Cyornis banyumas
	Cyornis rubeculoides
	Cyornis tickelliae
	Cyornis unicolor
	Ficedula parva
	Muscicapa dauurica
Nectaniidae	*Nectarinia asiatica*
	Nectarinia jugularis
Oriolldae	*Oriolus chinensis*
Passeridae	*Passer flaveolus*
	Passer montanus
Phalacrocoracidae	*Phalacrocorax carbo*
	Phalacrocorax carbo
Phasianidae	*Francolinus pintadeanus*
	Gallus gallus
Picidae	*Celeus brachyurus*
	Dendrocopos macei
	Jynx torquilla
	Picus flavinucha
Pittidae	*Pitta moluccensis*
Ploceidae	*Ploceus philippinus*

Family	Species
Podicipedidae	*Podiceps cristatus*
	Podiceps cristatus
	Podiceps nigricollis
	Podiceps nigricollis
	Tachybaptus ruficollis
	Tachybaptus ruficollis
Pycnonotidae	*Pycnonotus atriceps*
	Pycnonotus aurigaster
	Pycnonotus aurigaster
	Pycnonotus blanfordi
	Pycnonotus jocosus
	Pycnonotus melanicterus
Rallidae	*Amaurornis phoenicurus*
	Fulica atra
	Gallicrex cinerea
	Gallinura chloropus
	Gallirallus striatus
	Porphyrio porphyrio
	Porzana cinerea
	Porzana fusca
	Porzana pusilla
	Rallus aquaticus
Recurvirostridae	*Himantopus himantopus*
	Recurvirostra avosetta
Rostratulidae	*Rostratula benghalensis*
Scolopacidae	*Actitis hypoleucos*
	Calidris temminckii
	Gallinago gallinago
	Gallinago nemoricola
	Tringa erythropus
	Tringa glareola
	Tringa nebularia
	Tringa ochropus
	Tringa stagnatilis
	Tringa totanus
Strigidae	*Otus lempiji*
Strurnidae	*Acridotheres grandis*
	Acridotheres tristis
	Sturnus contra
	Sturnus malabaricus
	Sturnus nigricollis
Sylviidae	*Acrocephalus aedon*
	Acrocephalus bistrigiceps
	Acrocephalus orientalis
	Bradypterus thoracicus
	Locustella lanceolata
	Megalurus palustris
	Phylloscopus fuscatus
	Phylloscopus fuscatus

Family	Species
	Phylloscoups inornatus
	Prinia hodgsonii
	Prinia inornata
	Prinia rufescens
	Seicercus burkii
Threskiornithidae	*Platalea minor*
	Plegadis falcinellus
Timaliidae	*Garrulax chinensis*
	Pellorneum ruficeps
	Pomatorhinus schisticeps
	Timalia pileata
Turdidae	*Copsychus malabaricus*
	Copsychus saularis
	Luscinia calliope
	Luscinia svecica
	Monticola solitarius
	Saxicola caprata
	Saxicola ferrea
	Saxicola yorquata
	Turdus merula
Turnicidae	*Turnix suscitator*
	Turnix tanki
Tytonidae	*Tyto alba*
Upupidae	*Upupa epops*
Zosteropidae	*Zosterops japonicus*

Source: Thailand Institute of Scientific and Technological Research, 2017

Appendix 3 Species lists of the fishes in the Nong Bong Khai lake.

Family	Species
Ambassidae	*Parambassis siamensis* (Fowler,1937)
Bandidae	*Badis ruber Schreitmüller, 1923*
Bandidae	*Badis ruber* Schreitmüller, 1923
Belonidae	*Indostomus spinosus* Britz & Kottelat, 1999
Belonidae	*Xenentodon cancila* (Hamilton,1822)
Channidae	*Channa gachua* (Hamilton, 1822)
Channidae	*Channa micropeltes* (Cuvier, 1831)
Channidae	*Channa striata* (Bloch, 1795)
Cichlidae	*Oreochromis niloticus* (Linnaeus, 1758)
Clariidae	*Clarias batrachus* (Linnaeus,1758)
Clariidae	*Clarias gariepinus* (Burchell, 1822)
Clariidae	*Clarias macrocephalus* Günther,1864
Clariidae	*Clarias macrocephalus* x *Clarias gariepinus*
Clupeidae	*Clupeichthys aesarnensis* Wongratana,1983
Cyprinida	*Cyclocheilichthys repasson* (Bleeker, 1853)
Cyprinida	*Mystacoleucus marginatus* (Valenciennes, 1842)
Cyprinidae	*Albulichthys albuloides* (Bleeker, 1855)
Cyprinidae	*Amblypharyngodon chulabhornae* Vidthayanon & Kottelat, 1990
Cyprinidae	*Amblyrhynchichthys truncatus* (Bleeker, 1851)
Cyprinidae	*Barbonymus altus* (Günther,1868)
Cyprinidae	*Barbonymus gonionotus* (Bleeker,1850)
Cyprinidae	*Barbonymus schwanenfeldii* (Bleeker, 1853)
Cyprinidae	*Cirrhina molitorella* (Valenciennes, 1844)
Cyprinidae	*Cirrhinus microlepis* Sauvage, 1878
Cyprinidae	*Cirrhinus mrigala* (Hamilton, 1822)
Cyprinidae	*Ctenopharyngodon idellus* Valenciennes, 1844
Cyprinidae	*Cyclocheilichthys enoplos* (Bleeker,1850)
Cyprinidae	*Cyprinus carpio* Linnaeus, 1758
Cyprinidae	*Esomus metallicus* Ahl, 1924
Cyprinidae	*Hampala dispar* Smith,1934
Cyprinidae	*Hampala macrolepidota* (Valenciennes,1842)
Cyprinidae	*Henicorhynchus siamensis* (de Beaufort,1927)
Cyprinidae	*Hypophthalmichthys molitrix* (Valenciennes, 1844)
Cyprinidae	*Labeo chrysophekadion* (Bleeker, 1850)
Cyprinidae	*Labeo rohita* (Hamilton, 1822)
Cyprinidae	*Labiobarbus siamensis* (SAUVAGE, 1881)
Cyprinidae	*Leptobarbus hoeveni* (Bleeker, 1851)
Cyprinidae	*Mekongina erythrospila* Fowler, 1937
Cyprinidae	*Osteochilus hasselti* (Valenciennes,1842)
Cyprinidae	*Osteochilus schlegeli* (Bleeker, 1851)
Cyprinidae	*Probarbus jullieni* Sauvage, 1880
Cyprinidae	*Puntius brevis* (Bleeker,1860)
Cyprinidae	*Puntius orphoides* (Valenciennes, 1842)
Cyprinidae	*Puntius partipentazona* (Fowler,1934)
Cyprinidae	*Rasbora borapetensis* Smith,1934
Cyprinidae	*Rasbora myersi* Brittan, 1954

Family	Species
Cyprinidae	*Rasbora paviana* Tirant, 1885
Cyprinidae	*Rasbora trilineata* Steindachner,1870
Cyprinidae	*Sikukia gudgeri* (Smith, 1934)
Eleotridae	*Oxyeleotris marmorata* (Bleeker,1852)
Gobiidae	*Brachygobius mekongensis* Larson & Vidthayanon, 2000
Loricariidae	*Pterygoplichthys pardalis* (Castelnau, 1855)
Nandidae	*Pristolepis fasciata* (Bleeker,1851)
Notopteridae	*Chitala ornata* (Gray, 1831)
Notopteridae	*Notopterus blanci* (D'Aubenton, 1965)
Notopteridae	*Notopterus notopterus* (Pallas,1780)
Osphronemidae	*Betta splendens* Regan, 1910
Osphronemidae	*Trichogaster trichopterus* (Pallas, 1770)
Osphronemidae	*Trichopodus microlepis* (Günther, 1861)
Osphronemidae	*Trichopsis vittata* (Cuvier, 1831)
Osphronemidae	*Tricrogaste pectoralis* (Gunther, 1861)
Pangasiidae	*Hemibagrus filamentus* (Fang & Chaux, 1949)
Pangasiidae	*Hemibagrus nemurus* (Valenciennes, 1840)
Pangasiidae	*Heterobagrus bocourti* Bleeker, 1864
Pangasiidae	*Mystus mysticetus* Roberts,1992
Pangasiidae	*Pangasianodon gigas* Chevey, 1931
Pangasiidae	*Pangasianodon hypophthalmus* (Sauvage, 1878)
Pangasiidae	*Piaractus brachypomus* (Cuvier, 1817)
Siluridae	*Kryptopterus bicirrhis* (Valenciennes, 1840)
Siluridae	*Ompok krattensis* (Fowler, 1934)
Siluridae	*Phalacronotus apogon* (Bleeker, 1851)
Synbranchidae	*Macrognathus siamensis* (Günther,1861)
Synbranchidae	*Mastacembelus armatus* (Lacepède,1800)
Synbranchidae	*Mastacembelus erythrotaenia* Bleeker, 1850
Synbranchidae	*Mastacembelus favus* Hora, 1924
Synbranchidae	*Monopterus albus* (Zuiew,1793)
Tetraodontidae	*Tetraodon suvattii* Sontirat, 1990

Source: Thailand Institute of Scientific and Technological Research, 2017

Appendix 4 List of the aquatic plant species found in the Nong Bong Khai lake in March 2019.

Family	Species	Life form	Habitat
Ancistrocladaceae	*Ancistrocladus tectorius* (Lour.) Merr	Herb	Terrestrial
Apiaceae	*Oenanthe javanica* (Blume) DC	Herb	Marginal
Apocynaceae	*Marsdenia tinctoria* R.Br.	Climber	Terrestrial
Araceae	*Colocasia esculenta* (L.) Schott	Herb	Marginal
Araceae	*Lasia spinosa* (L.) Thwaites	Herb	Marginal
Araceae	*Pistia stratiotes* L.	Aquatic	Floating
Asteraceae	*Ageratum conyzoides* L	Herb	Terrestrial
Asteraceae	*Crassocephalum crepidioides* (Benth)S.Moore	Herb	Terrestrial
Asteraceae	*Enhydra fluctuans* Lour	Aquatic	Marginal
Asteraceae	*Mikania micrantha* kunth	Climber	Terrestrial
Athriaceae	*Diplazium esculentum* (Retz.) Sw	Terrestrial ferns	Marginal
Combretaceae	*Getonia floribunda* Roxb.	Climber	Terrestrial
Convolvulaceae	*Ipomoea aquatica* Forssk	Herb	Marginal
Cyperaceae	*Cyperus pulcherrimus* Willd. ex Kunth	Herb	Marginal
Cyperaceae	*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch.	Herb	Emergent
Eriocaulaceae	*Eriocaulon cinereum* R.Br.	Herb	Marginal
Fabaceae	*Mimosa pigra* L.	Shurb	Marginal
Fabaceae	*Mucuna pruriens* (L.) DC.	Climber	Terrestrial
Fabaceae	*Senna alata* (L.) Roxb.	Shrub	Terrestrial
Linderniaceae	*Lindernia anagallis* (Burm.f.) Pennell	Herb	Marginal
Lygodiaceae	*Lygodium microphyllum* (Cav.) R. Br	Climber	Terrestrial
Malvaceae	*Sida acuta* Burm.f.	Undershrub	Terrestrial
Melastomataceae	*Osbeckia stellata* Buch-Ham. ex Ker Gawl	Shrub	Terrestrial
Molluginaceae	*Glinus oppositifolius* (L.) A.DC.	Herb	Terrestrial
Nelumbonaceae	*Nelumbo nucifera* Gaertn	Aquatic	Floating
Onagraceae	*Ludwigia adscendens* (L.) H. Hara	Aquatic	Marginal
Onagraceae	*Ludwigia hyssopifolia*	Herb	Marginal
Onagraceae	*Ludwigia octovalvis* (Jacq.) P. H. Raven	Herb	Marginal
Orchidaceae	*Thrixspermum amplexicaule* (Blume) Rchb.f	Epiphytic	Terrestrial
Phyllanthaceae	*Glochidion sphaerogynum* (Mull.Arg.) Kurz	Shrub	Terrestrial
Phyllanthaceae	*Phyllanthus amarus* Schumach. & Thonn.	Herb	Terrestrial
Poaceae	*Arundo donax* L	Grass	Emergent
Poaceae	*Chrysopogon zizanioides* (L.) Roberty	Grass	Terrestrial
Poaceae	*Cynodon dactylon* (L.) Pers	Grass	Terrestrial
Poaceae	*Dendrocalamus strictus* (Roxb.) Nees	Bamboo	Terrestrial

Family	Species	Life form	Habitat
Poaceae	*Echinochloa colona* (L.) Link	Grass	Marginal
Poaceae	*Imperata cylindrica* (L.) Raeusch	Grass	Marginal
Poaceae	*Isachne globosa* (Thunb.) Kuntze	Grass	Marginal
Poaceae	*Ischaemum barbatum* Retz	Grass	Marginal
Poaceae	*Leersia hexandra* Sw	Grass	Marginal
Poaceae	*Panicum repens* L	Grass	Terrestrial
Poaceae	*Saccharum arundinaceum* Retz.	Grass	Terrestrial
Poaceae	*Sacciolepis indica* (L.) Chase	Grass	Marginal
Poaceae	*Stenotaphrum helferi* Munro ex Hook.f.	Grass	Terrestrial
Polygonaceae	*Persicaria attenuata* (R. Br.) Soják	Herb	Marginal
Polygonaceae	*Persicaria* sp.	Herb	Marginal
Polypodiaceae	*Phymatosorus cuspidatus* (D. Don) Pic.Serm.	Epiphytic	Terrestrial
Pontederiaceae	*Eichhornia crassipes* (Mart.) Solms	Aquatic	Floating
Salicaceae	*Salix tetrasperma* Roxb.	Tree	Marginal
Salviniaceae	*Azolla pinnata* R.Br.	Aquatic	Floating
Salviniaceae	*Salvinia cucullata* Roxb. ex Bory	Aquatic	Floating
Sparganiaceae	*Sparganium eretum* L.	Herb	Marginal
Thelypteridaceae	*Cyclosorus interruptus* (Willd.) H. Itô	Terrestrial ferns	Marginal
Zingiberaceae	*Alpinia* sp.	Herb	Terrestrial

Appendix 5 Covering area of dominant and co-dominant.

Plot No.	Zone	Dominant species	Covering score	Co-Dominant species	Covering score	Co-Dominant species	Covering score
1	A	*Colocasia esculenta* (L.) Schott	4	*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch.	2	*Persicaria* sp.	2
2	A	*Colocasia esculenta* (L.) Schott	3	*Panicum repens* L	3	*Persicaria* sp.	3
3	A	*Colocasia esculenta* (L.) Schott	5	-	-	-	-
4	A	*Cyperus pulcherrimus* Willd. ex Kunth	5	*Isachne globosa* (Thunb.) Kuntze	2	*Enhydra fluctuans* Lour	1
5	A	*Isachne globosa* (Thunb.) Kuntze	5	*Oenanthe javanica* (Blume) DC.	2	*Colocasia esculenta* (L.) Schott	1
6	A	*Panicum repens* L	4	*Leersia hexandra* Sw	3	-	-
7	A	*Enhydra fluctuans* Lour	4	*Isachne globosa* (Thunb.) Kuntze	3	-	-
8	A	*Saccharum arundinaceum* Retz.	3	*Colocasia esculenta* (L.) Schott	3	*Isachne globosa* (Thunb.) Kuntze	2
9	A	*Isachne globosa* (Thunb.) Kuntze	3	*Leersia hexandra* Sw	2	-	-
10	A	*Imperata cylindrica* (L.) Raeusch	4	*Colocasia esculenta* (L.) Schott	2	*Cyclosorus interruptus* (Willd.) H. Itô	2
11	A	*Eichhornia crassipes* (Mart.) Solms	5	-	-	-	-
12	A	*Eichhornia crassipes* (Mart.) Solms	5	-	-	-	-
13	A	*Eichhornia crassipes* (Mart.) Solms	5	-	-	-	-
14	A	*Salix tetrasperma* Roxb.	4	*Enhydra fluctuans* Lour	3	-	-
15	A	*Salix tetrasperma* Roxb.	3	*Enhydra fluctuans* Lour	3	*Leersia hexandra* Sw	2
16	A	*Salix tetrasperma* Roxb.	5	-	-	-	-
17	A	*Isachne globosa* (Thunb.) Kuntze	5	-	-	-	-
18	A	*Isachne globosa* (Thunb.) Kuntze	5	*Imperata cylindrica* (L.) Raeusch	2	-	-
19	A	*Isachne globosa* (Thunb.) Kuntze	5	*Colocasia esculenta* (L.) Schott	2	-	-
20	A	*Leersia hexandra* Sw	5	-	-	-	-
21	A	*Leersia hexandra* Sw	5	*Colocasia esculenta* (L.) Schott	2	*Isachne globosa* (Thunb.) Kuntze	1
22	A	*Leersia hexandra* Sw	3	*Isachne globosa* (Thunb.) Kuntze	3	-	-
23	A	*Enhydra fluctuans* Lour	5	-	-	-	-
24	A	*Enhydra fluctuans* Lour	5	-	-	-	-
25	A	*Enhydra fluctuans* Lour	4	*Cyclosorus interruptus* (Willd.) H. Itô	1	-	-
26	B	*Cyperus pulcherrimus* Willd. ex Kunth	3	*Leersia hexandra* Sw	2	-	-

Plot No.	Zone	Dominant species	Covering score	Co-Dominant species	Covering score	Co-Dominant species	Covering score
27	B	*Cyperus pulcherrimus* Willd. ex Kunth	4	*Leersia hexandra* Sw	2	*Panicum repens* L	2
28	B	*Senna alata* (L.) Roxb.	5	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
29	B	*Senna alata* (L.) Roxb.	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	*Glochidion sphaerogynum* (Mull.Arg.) Kurz	2
30	B	*Senna alata* (L.) Roxb.	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
31	B	*Salix tetrasperma* Roxb.	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	*Imperata cylindrica* (L.) Raeusch	2
32	B	*Salix tetrasperma* Roxb.	5	-	-	-	-
33	B	*Leersia hexandra* Sw	5	-	-	-	-
34	B	*Leersia hexandra* Sw	5	*Mimosa pigra* L.	2	-	-
35	B	*Leersia hexandra* Sw	5	-	-	-	-
36	B	*Arundo donax* L	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
37	B	*Arundo donax* L	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
38	B	*Salvinia cucullata* Roxb. ex Bory	5	-	-	-	-
39	B	*Nelumbo nucifera* Gaertn	5	-	-	-	-
40	B	*Nelumbo nucifera* Gaertn	5	-	-	-	-
41	B	*Eichhornia crassipes* (Mart.) Solms	5	-	-	-	-
42	B	*Imperata cylindrica* (L.) Raeusch	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
43	B	*Imperata cylindrica* (L.) Raeusch	3	*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch.	2	*Cyclosorus interruptus* (Willd.) H. Itô	2
44	B	*Imperata cylindrica* (L.) Raeusch	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
45	C	*Arundo donax* L	5	*Colocasia esculenta* (L.) Schott	2	*Getonia floribunda* Roxb.	1
46	C	*Mimosa pigra* L	4	*Leersia hexandra* Sw	3	-	-
47	C	*Mimosa pigra* L	4	*Colocasia esculenta* (L.) Schott	2	*Mikania micrantha* kunth	2
48	C	*Colocasia esculenta* (L.) Schott	4	*Mikania micrantha* kunth	2	-	-
49	C	*Colocasia esculenta* (L.) Schott	4	*Leersia hexandra* Sw	3	-	-
50	C	*Isachne globosa* (Thunb.) Kuntze	3	*Leersia hexandra* Sw	2	-	-
51	C	*Isachne globosa* (Thunb.) Kuntze	5	*Eriocaulon cinereum* R.Br.	1	-	-

Plot No.	Zone	Dominant species	Covering score	Co-Dominant species	Covering score	Co-Dominant species	Covering score
52	C	*Imperata cylindrica* (L.) Raeusch	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
53	C	*Imperata cylindrica* (L.) Raeusch	5	-	-	-	-
54	C	*Eichhornia crassipes* (Mart.) Solms	5	-	-	-	-
55	C	*Eichhornia crassipes* (Mart.) Solms	5	*Salvinia cucullata* Roxb. ex Bory	2	-	-
56	C	*Eichhornia crassipes* (Mart.) Solms	5	*Salvinia cucullata* Roxb. ex Bory	1	-	-
57	C	*Dendrocalamus strictus* (Roxb.) Nees	5	-	-	-	-
58	C	*Dendrocalamus strictus* (Roxb.) Nees	5	*Leersia hexandra* Sw	2	-	-
59	C	*Salix tetrasperma* Roxb.	3	*Imperata cylindrica* (L.) Raeusch	3	-	-
60	C	*Cyclosorus interruptus* (Willd.) H. Itô	3	*Phymatosorus cuspidatus* (D. Don) Pic.Serm.	2	*Enhydra fluctuans* Lour	2
61	C	*Colocasia esculenta* (L.) Schott	3	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
62	C	*Imperata cylindrica* (L.) Raeusch	3	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
63	C	*Imperata cylindrica* (L.) Raeusch	5	-	-	-	-
64	D	*Salix tetrasperma* Roxb.	5	*Phymatosorus cuspidatus* (D. Don) Pic.Serm.	2	*Cyclosorus interruptus* (Willd.) H. Itô	1
65	D	*Salix tetrasperma* Roxb.	5	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
66	D	*Cyclosorus interruptus* (Willd.) H. Itô	3	*Phymatosorus cuspidatus* (D. Don) Pic.Serm.	3	*Isachne globosa* (Thunb.) Kuntze	2
67	D	*Cyclosorus interruptus* (Willd.) H. Itô	3	*Phymatosorus cuspidatus* (D. Don) Pic.Serm.	3	-	-
68	D	*Phymatosorus cuspidatus* (D. Don) Pic.Serm	3	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
69	D	*Colocasia esculenta* (L.) Schott	3	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
70	D	*Colocasia esculenta* (L.) Schott	4	-	-	-	-
71	D	*Colocasia esculenta* (L.) Schott	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
72	D	*Isachne globosa* (Thunb.) Kuntze	4	-	-	-	-
73	D	*Isachne globosa* (Thunb.) Kuntze	3	*Enhydra fluctuans* Lour	3	-	-
74	D	*Lasia spinosa* (L.) Thwaites	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
75	D	*Eichhornia crassipes* (Mart.) Solms	5	*Salvinia cucullata* Roxb. ex Bory	2	-	-
76	D	*Eichhornia crassipes* (Mart.) Solms	5	*Pistia stratiotes* L	2	-	-
77	D	*Eichhornia crassipes* (Mart.) Solms	5	*Salvinia cucullata* Roxb. ex Bory	1	-	-

Plot No.	Zone	Dominant species	Covering score	Co-Dominant species	Covering score	Co-Dominant species	Covering score
78	D	*Isachne globosa* (Thunb.) Kuntze	5	-	-	-	-
79	D	*Isachne globosa* (Thunb.) Kuntze	4	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-
80	D	*Isachne globosa* (Thunb.) Kuntze	5	*Cyclosorus interruptus* (Willd.) H. Itô	1	-	-
81	D	*Senna alata* (L.) Roxb.	4	*Colocasia esculenta* (L.) Schott	2	*Cyclosorus interruptus* (Willd.) H. Itô	2
82	D	*Senna alata* (L.) Roxb.	5	*Cyclosorus interruptus* (Willd.) H. Itô	2	-	-

Remark: Index values according to abundance/ dominance Braun-Blanquet scale

Appendix 6 Dominant species lists of the aquatic plants in zone A, zone B, zone C and zone D.

Species Name	Life Form	Habitat	Number of sample plots				Average water Depth (m)
			Zone A	Zone B	Zone C	Zone D	
Phymatosorus cuspidatus (D. Don) Pic.Serm.	Epiphytic ferns	Terrestrial	-	-	-	1	2.9
Lasia spinosa (L.) Thwaites	Herb	Marginal	1	-	-	-	2.85
Cyclosorus interruptus (Willd.) H. Itô	Terrestrial ferns	Marginal	-	-	1	2	2.52
Senna alata (L.) Roxb.	Exotic Shrub	Terrestrial	-	3	-	2	1.8
Eichhornia crassipes (Mart.) Solms	Exotic Aquatic Herb	Floating	3	1	3	3	1.79
Isachne globosa (Thunb.) Kuntze	Grass	Marginal	5	-	2	5	1.78
Cyperus pulcherrimus Willd. ex Kunth	Herb	Marginal	1	2	-	-	1.77
Salix tetrasperma Roxb.	Tree	Marginal	3	2	1	2	1.74
Colocasia esculenta (L.) Schott	Herb	Marginal	3	-	3	3	1.37
Imperata cylindrica (L.) Raeusch	Grass	Marginal	4	3	4	-	1.29
Panicum repens L	Grass	Terrestrial	1	-	-	-	1.15
Enhydra fluctuans Lour	Aquatic Herb	Marginal	4	-	-	-	1.14
Nelumbo nucifera Gaertn.	Aquatic Herb	Floating	-	2	-	-	1.1
Saccharum arundinaceum Retz.	Grass	Terrestrial	1	-	-	-	1.1
Leersia hexandra Sw	Grass	Marginal	3	3	-	-	1.06
Arundo donax L	Grass	Emergent	-	2	1	-	1
Salvinia cucullata Roxb. ex Bory	Aquatic ferns	Floating	-	1	-	-	0.75
Dendrocalamus strictus (Roxb.) Nees	Bamboo	Terrestrial	-	-	2	-	0
Mimosa pigra L.	Exotic Herb	Marginal	-	-	2	-	0

Appendix 7 List of the aquatic plant species found in the Nong Bong Khai lake in March 2019, September 2019 and March 2020.

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Acanthaceae											
Justicia sp.	S	Ter	-	-	-	✓	C	1.2	✓	D	0
Amaranthaceae											
Alternanthera philoxeroides	Aq	Eg	-	-	-	-	-	-	✓	C	0
Alternanthera sessilis (L.) DC.	H	Eg	-	-	-	✓	A, C	0-0.65	-	-	-
Ancistrocladaceae											
Ancistrocladus tectorius (Lour.) Merr.	C	Ter	✓	C	0	✓	C	0	✓	C	0
Apiaceae											
Oenanthe javanica (Blume) DC.	H	M	✓	A, B, C, D	0.60-2.95	✓	A, B, C, D	0.20-2.50	✓	A, B, C, D	0-1.90
Apocynaceae											
Marsdenia tinctoria R.Br.	C	Ter	✓	B, D	0.85-2.90	✓	B, D	0.20-2.50	✓	A, B, C, D	0-2.00
Alstonia scholaris (L.) R. Br.	T	Ter	-	-	-	-	-	-	✓	B	0
Araceae											
Colocasia esculenta (L.) Schott	H	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.5-2.5	✓	A, B, C, D	0-1.95
Lasia spinosa (L.) Thwaites	H	M	✓	C, D	1.30-2.90	✓	D	2.45	✓	D	1.90
Pistia stratiotes L.	Aq	F	✓	C, D	1.40-2.80	✓	B	0.65	✓	C	0.25
Asteraceae											
Ageratum conyzoides L.	H	Ter	✓	C	0	✓	B, C, D	0.55-2.15	✓	C	0
Crassocephalum crepidioides (Benth) S. Moore	H	Ter	✓	C	0	✓	C	0-1.00	✓	A, B, C, D	0-0.70
Enhydra fluctuans Lour	Aq	M	✓	A, C, D	0.83-2.90	✓	A, B, C, D	0-2.45	✓	A, B, C, D	0-2.00
Mikania micrantha Kunth	C	Ter	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.15-2.50	✓	A, B, C, D	0-1.90
Bidens pilosa L.	H	Ter	-	-	-	-	-	-	✓	B, C	0
Chromolaena odorata (L.) R.M.King & H.Rob.	H	Ter	-	-	-	-	-	-	✓	B, C	0-0.30
Athyriaceae											
Diplazium esculentum (Retz.) Sw	TerF	M	✓	D	2.90	-	-	-	-	-	-
Combretaceae											
Getonia floribunda Roxb.	C	Ter	✓	C	0.95	-	-	-	-	-	-
Commelinaceae											
Commelina benghalensis L.	H	Ter	-	-	-	-	-	-	✓	B, C	0-0.50
Commelina diffusa Burm. f.	H	Ter	-	-	-	✓	B	0.25-0.60	-	-	-
Convolvulaceae											
Aniseia martinicensis	C	Ter	-	-	-	✓	B	0.70	-	-	-
Ipomoea aquatica Forssk.	H	M	✓	B, C	0-2.10	✓	A, B, D	0.25-1.25	✓	B	0-0.25
Ipomoea sp.	H	M	-	-	-	✓	A	0.65	-	-	-
Merremia umbellata (L.) Hallier f.	C	Ter	-	-	-	-	-	-	✓	A	0-0.75

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Cucurbitaceae											
Gymnopetalum integrifolium (Roxb.) Kurz.	C	Ter	-	-	-	-	-	-	✓	C	0
Cyperaceae											
Actinoscirpus grossus (L. f.) Goetgh. & D. A. Simpson	H	M	-	-	-	-	-	-	✓	A, B, C, D	0-1.05
Cyperus cephalotes Vahl	H	M	-	-	-	✓	C	1.20	✓	C, D	0.25-1.65
Cyperus compactus Retz.	H	M	-	-	-	✓	D	2.45	-	-	-
Cyperus procerus Rottb.	H	M	-	-	-	✓	B, C	0-0.65	-	-	-
Cyperus pulcherrimus Willd. ex Kunth	H	M	✓	A, B, C, D	0-2.70	✓	A, B, C, D	0.25-2.45	✓	A, B, D	0-1.95
Cyperus rotundus L.	H	M	-	-	-	✓	D	2.30	-	-	-
Eleocharis dulcis (Burm. f.) Trin. ex Hensch.	H	Eg	✓	A, B, C, D	0.63-2.90	✓	A, B, C, D	0.2-2.55	✓	A, B, C, D	0-2.00
Eriocaulaceae											
Eriocaulon cinereum R.Br.	H	M	✓	C	0	-	-	-	✓	C	0
Euphorbiaceae											
Phyllanthus urinaria L.	H	Ter	-	-	-	-	-	-	✓	C, D	0-0.40
Fabaceae											
Acacia auriculiformis A. Cunn. ex Benth.	T	Ter	-	-	-	-	-	-	✓	C	0
Mimosa invisa Mart.	H	M	-	-	-	-	-	-	✓	C	0
Mimosa pigra L.	S	M	✓	B, C	0-0.80	✓	B, C	0-1.20	✓	A, B, C	0
Mimosa pudica L.	H	M	-	-	-	-	-	-	✓	C	0
Mucuna pruriens (L.) DC.	C	Ter	✓	B	0.85-1.25	✓	B, D	0.50-2.30	✓	B, C	0
Senna alata (L.) Roxb.	S	Ter	✓	B, D	0.85-2.95	✓	B, C, D	0-0.25	✓	B, C, D	0-1.80
Senna tora (L.) Roxb.	US	Ter	-	-	-	✓	C	0	✓	C	0
Hydroleaceae											
Hydrolea zeylanica (L.) Vahl	H	M	-	-	-	-	-	-	✓	C	0-0.90
Linderniaceae											
Lindernia anagallis (Burm. f.) Pennell	H	M	✓	B, C, D	0-3.0	✓	A, B, C, D	0-2.55	✓	A, B, C	0-0.90
Lygodiaceae											
Lygodium microphyllum (Cav.) R. Br	C	Ter	✓	D	2.85	-	-	-	-	-	-
Lythraceae											
Rotala rotundifolia (Roxb.) Koehne	H	Eg	-	-	-	✓	C	1.20	✓	C, D	0.5-1.50
Malvaceae											
Sida acuta Burm. f.	US	Ter	✓	C	0	-	-	-	-	-	-
Urena lobata L.	US	Ter	-	-	-	-	-	-	✓	C	0
Waltheria indica L.	US	Ter	-	-	-	✓	C	0	-	-	-
Melastomataceae											
Osbeckia stellata Buch-Ham. ex Ker Gawl.	S	Ter	✓	C, D	1.65-2.95	✓	C	1.20	✓	C	0.70
Molluginaceae											
Glinus oppositifolius (L.) A.DC.	H	Ter	✓	C	0	-	-	-	✓	C	0
Nelumbonaceae											
Nelumbo nucifera Gaertn.	Aq	F	✓	A, B	1.10	✓	A, B	0.30-0.70	✓	B	0.30
Onagraceae											
Ludwigia adscendens (L.) H. Hara	Aq	M	✓	B, C, D	0.80-2.95	✓	A, B, C, D	0-1.55	✓	B, C, D	0-1.80

Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Ludwigia hyssopifolia (G. Don) Exell	H	M	✓	A	1.65	✓	C	0.65	-	-	-
Ludwigia octovalvis (Jacq.) P. H. Raven	H	M	✓	A	1.15	✓	A, B, C	0-2.00	✓	C	0
Orchidaceae											
Thrixspermum amplexicaule (Blume) Rchb. f	E	Ter	✓	C, D	1.85-2.95	✓	D	2.45	✓	D	1.45-1.90
Phyllanthaceae											
Glochidion sphaerogynum (Mull.Arg.) Kurz	S	Ter	✓	B, C	0.90-1.30	✓	B	0.25	✓	B, D	0
Phyllanthus amarus Schumach. & Thonn.	H	Ter	✓	C	1.50	-	-	-	✓	C	0
Plantaginaceae											
Scoparia dulcis L.	H	Ter	-	-	-	✓	B, C	0.50-1.35	✓	B	0.25
Poaceae											
Arundo donax L	G	M	✓	B, C	0.95-1.30	✓	A, B	0.50-0.70	✓	A, B, C, D	0-2.10
Axonopus compuuressus P.Beauv	G	Ter	-	-	-	-	-	-	✓	C	0
Brachiaria mutica	G	Ter	-	-	-	-	-	-	✓	D	0.65
Chrysopogon zizanioides (L.) Roberty	G	Ter	✓	C	0-0.40	-	-	-	-	-	-
Cynodon dactylon (L.) Pers	G	Ter	✓	C	0	✓	C	0	✓	B, C	0
Cyrtococcum oxyphyllum (Steud.) Stapf	G	Ter	-	-	-	-	-	-	✓	C	0
Dendrocalamus strictus (Roxb.) Nees	B	Ter	✓	C	0-1.30	-	-	-	-	-	-
Echinochloa colona (L.) Link	G	M	✓	B, C	0-1.30	✓	B, C, D	0.50-1.45	✓	B, C, D	0-0.50
Echinochloa crus-galli (L.) P. Beauv.	G	Ter	-	-	-	-	-	-	✓	B	0
Eragrostis unioloides (Retz.) Nees ex Steud	G	Ter	-	-	-	-	-	-	✓	C	0
Imperata cylindrica (L.) Raeusch	G	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.55	✓	A, B, C, D	0-1.95
Isachne globosa (Thunb.) Kuntze	G	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.55	✓	A, B, C, D	0-1.95
Ischaemum barbatum Retz	G	M	✓	C, D	0-2.95	✓	B, D	0.20-2.40	✓	C	0-0.90
Ischaemum rugosum Salisb.	G	Ter	-	-	-	✓	C	0	✓	A, B	0
Leersia hexandra Sw	G	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.55	✓	A, B, C, D	0-1.95
Leptochloa chinensis (L.) Nees	G	Ter	-	-	-	-	-	-	✓	A	0
Panicum repens L	G	Ter	✓	A, B, C	0-2.10	✓	C	0-1.20	✓	B, C, D	0-2.00
Pennisetum polystachion (L.) Schult.	G	Ter	-	-	-	-	-	-	✓	B	0
Saccharum arundinaceum Retz.	G	Ter	✓	A	1.10	-	-	-	-	-	-
Sacciolepis indica (L.) Chase	G	M	✓	C, D	0-3.00	✓	A, B, C, D	0-2.20	✓	B, C, D	0-1.80
Stenotaphrum helferi Munro ex Hook.f.	G	Ter	✓	C	1.70	-	-	-	-	-	-
Polygonaceae											
Persicaria attenuata (R. Br.) Soják var.	H	M	✓	C	0-1.30	✓	A, B, C	0-1.00	✓	A, B, C	0
Persicaria sp.	H	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.55	✓	A, B, C, D	0-1.95
Polypodiaceae											
Phymatosorus cuspidatus (D. Don) Pic.Serm.	E	Ter	✓	C, D	1.65-2.90	✓	C, D	0.50-2.50	✓	D	1.95

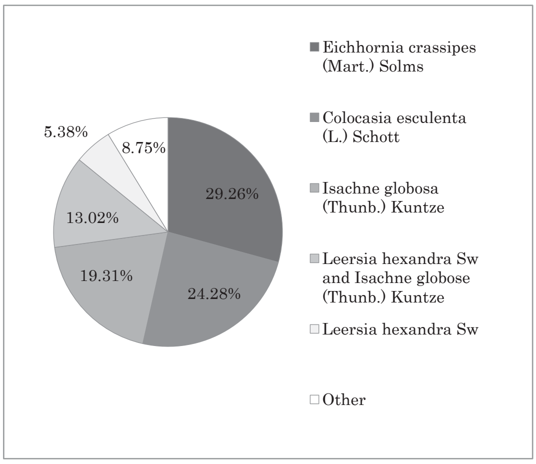
Family/Species	Life form	Habitat	Mar. 2019 (Dry season)	zone	Water Depth (m)	Sep. 2019 (Rainy season)	zone	Water Depth (m)	Mar. 2020 (Dry season)	zone	Water depth (m)
Pontederiaceae											
Eichhornia crassipes (Mart.) Solms	Aq	F	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.50	✓	A, B, C, D	0-1.80
Salicaceae											
Salix tetrasperma Roxb.	T	M	✓	A, B, C, D	0-2.85	✓	A, B, D	0.25-2.35	✓	A, B, D	0-1.85
Salviniaceae											
Azolla pinnata R.Br.	Aq	F	✓	C	1.20	-	-	-	-	-	-
Salviniaceae											
Salvinia cucullata Roxb. ex Bory	Aq	F	✓	A, B, C, D	0-2.85	✓	A, B, C, D	0.50-2.50	✓	B, C, D	0-1.95
Solanaceae											
Solanum torvum Swartz.	S	Ter	-	-	-	-	-	-	✓	C	0
Sparganiaceae											
Sparganium erectum L.	H	M	✓	D	2.90	✓	D	1.45-2.50	✓	A, D	0-2.10
Thelypteridaceae											
Cyclosorus interruptus (Willd.) H. Itô	TerF	M	✓	A, B, C, D	0-2.95	✓	A, B, C, D	0.20-2.50	✓	A, B, C, D	0-1.90
Zingiberaceae											
Alpinia sp.	H	Ter	✓	C	0	-	-	-	-	-	-

Remark: T = Tree, S = Shrub, US = Under Shrub, H = Herb, G = Grass, B = Bamboo, C = Climber, E = Epiphyte, TerF = Terrestrial Ferns, Aq = Aquatic, Ter = Terrestrial, M= Marginal, Eg = Emergent, F = Floating

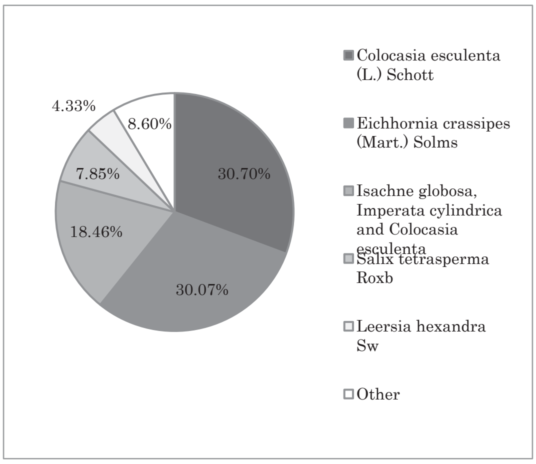
Appendix 8 Coverage area of each plant community in Zones A, B, C, and D in March 2019 (dry season), September 2019 (rainy season), and March 2020 (dry season).

Zone A

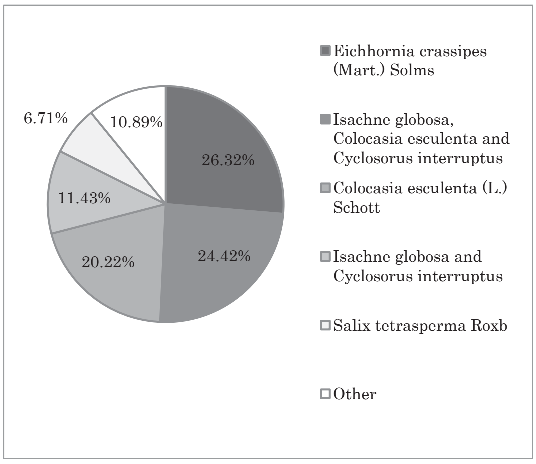
March 2019 (Dry season)



September 2019 (Rainy season)

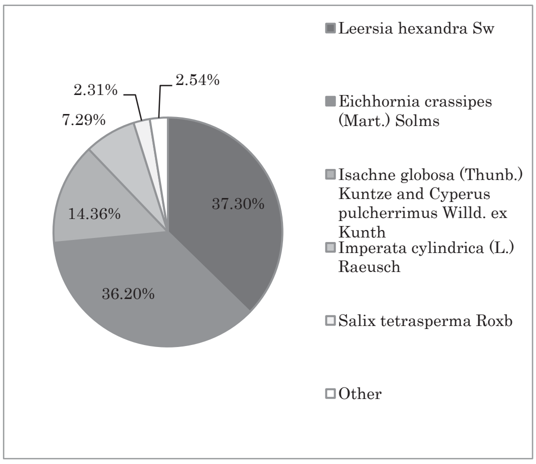


March 2020 (Dry season)

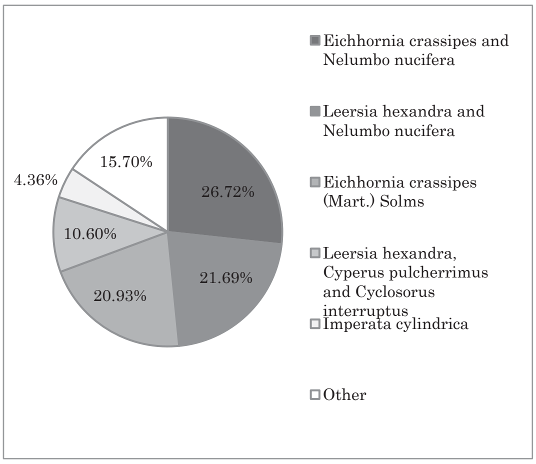


Zone B

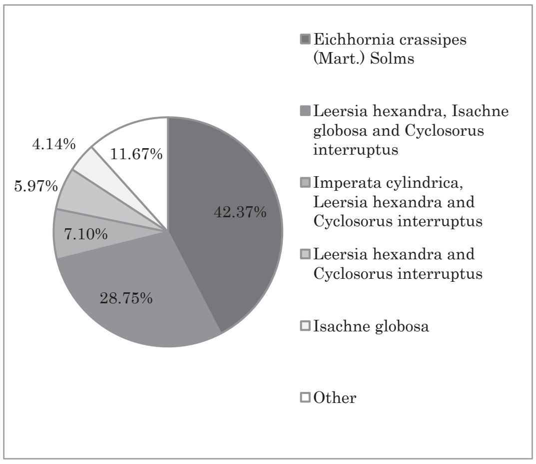
March 2019 (Dry season)



September 2019 (Rainy season)

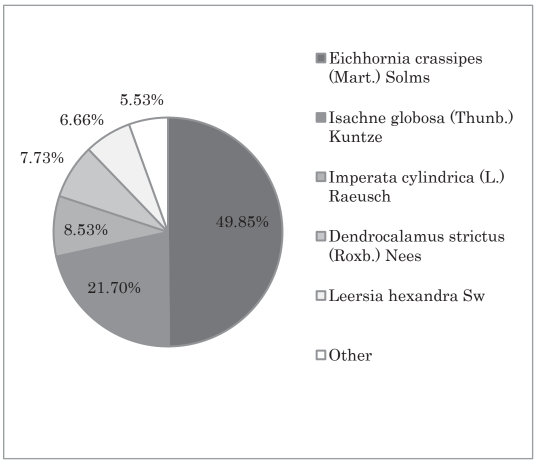


March 2020 (Dry season)

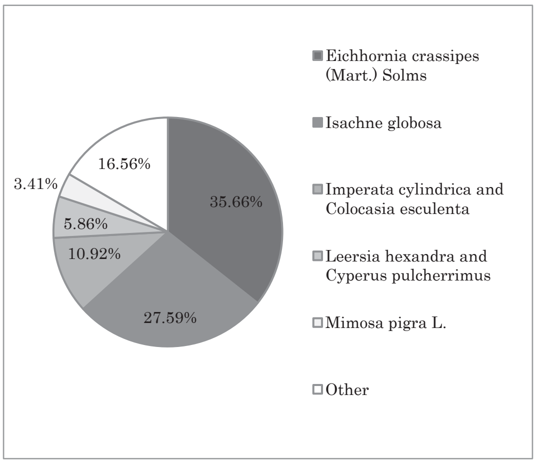


Zone C

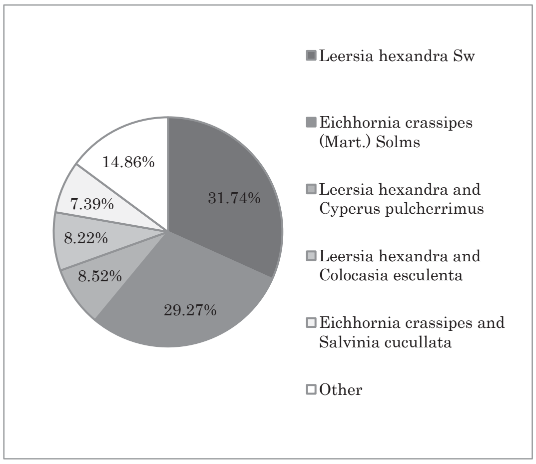
March 2019 (Dry season)



September 2019 (Rainy season)

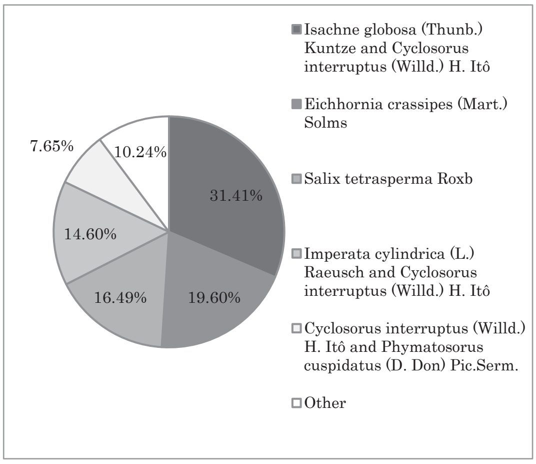


March 2020 (Dry season)

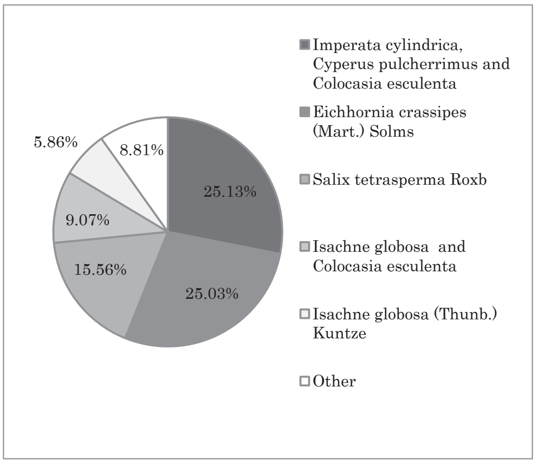


Zone D

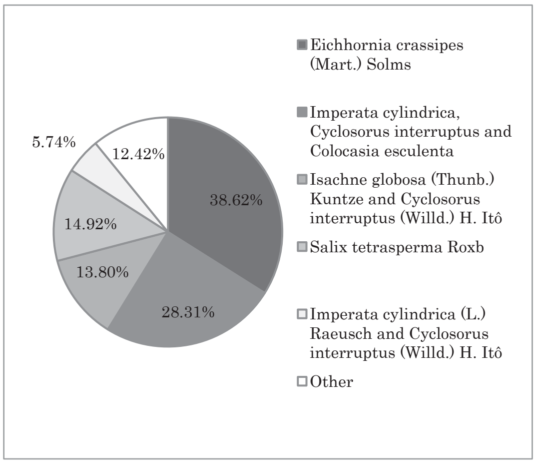
March 2019 (Dry season)



September 2019 (Rainy season)



March 2020 (Dry season)



Summary

Wetlands are ecosystems that are important to human, animal and plant. It consists of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters (Ramsar convention Secretariat, 2013). In 1998, Thailand participated to the 110th Ramsar Convention and registered 15 Ramsar sites, 69 wetlands of international importance, and 47 wetlands of national importance. Currently, Nong Bong Khai wetland is the one of Ramsar site where is threaten by the increase of alien plant species. It seemed that the causes of the increase of alien plant species may be nutrient rich environment affected by changes of land use/land cover. And water level fluctuation from low precipitation also may affect lake vegetation. Then this study aims to (1) Describe background of the increase of alien plants species by analyzing land use/land cover and water quality in the lake. And apply unmanned aerial vehicle (UAV) for non-submerged aquatic vegetation mapping to study their distribution especially Eichhornia crassipes. (2) Describe impacts of water level fluctuation caused by decreased precipitation on the distribution of the non-submerged aquatic vegetation community and the expansion of *Eichhornia crassipes* by applying non-submerged aquatic vegetation and distribution maps based on images from UAV. (3) Describe impacts of changes of the land use and land cover around the lake and the water level fluctuation to the increase of an alien plant species. And propose a measure to manage an alien plant species for improve the lake and maintain the sustainable ecosystem services.

The study is in Nong Bong Khai non-hunting area in Chiang Rai, Northern part of Thailand. It is approximately 5 km apart from the Mekong River. The lake area is registered as the Ramsar site No. 1,101 of wetland of international index on 5th July 2001. The average annual temperature is 24.4 °C. The average rainfall is 1,600-1,800 mm. The lake covers the area around 434 ha. This area has a beautiful scenery and also be an important habitat for local water birds and migratory water birds which migrate to live in this area in winter (November-

February). The lake is surrounded by hills and private areas such as agricultural area, residence and degraded forest.

A land use/land cover map in 2009, 2012, 2016 and 2018 which produced by satellite images showed changes in the watershed of the Nong Bong Khai non-hunting area. The area of field crop continuously increased from 2009 to 2018 by 92.07% while the area of deciduous forest and rangeland continuously decreased by 53.23% and 47.86% respectively. In field crops area, there was an increase in pineapple field and cassava field by 344.48% and 100.25% respectively. The increase in field crop area affected the amount of fertilizers used in agricultural areas, especially in a pineapple field and a cassava field where the highest usage of fertilizers per year rose to 813.43 and 100.19 tons respectively. After rain, soil erosion led to higher levels of fertilizer contamination in the lake which was a cause of high nutrient especially, phosphorous and nitrogen.

The 30 m altitude orthophoto together with 2-10 m single-shot photo gave an adequate resolution to generate the vegetation map. This was similar to that of Andrea (2019), who found that photos at 25 m together with 5 m could identify plant communities and plant species. The vegetation maps of 2019 based on the 30-m data, which were gathered in four study zones, showed that *Eichhornia crassipes* was presented in all of the study zones. The proportion of dominant plant species showed that the covering area of *Eichhornia crassipes* was mostly greater than other native species. Yongyut's (2006)'s study, *Eichhornia crassipes* were not prominently found but they might increase as a result of land use and water quality changes, was similar with interview of officers of Nong Bong Khai non-hunting area which reported that a few *Eichhornia crassipes* were found between the years of 2001 and 2010. The distribution map based on the 90-m orthoimage, which was gathered over the entire lake, showed a large coverage area of *Eichhornia crassipes* by almost 600,000 m^2 (13.82% of total lake area). Water quality data in years 2008, 2011, 2017 and 2019 showed that phosphorous and nitrogen were over standard in 2019 while DO was below the standard. The results of water quality test showed that the nutrients in the water, which mostly came from the agricultural areas, resulted in an increase in the *Eichhornia crassipes*. And their increase resulted in reducing of oxygen in the water.

In September 2018 to December 2020, the water levels in Nong Bong Khai lake fluctuated due to changes in rainfall. Refer to Actual rainfall and water level data, the highest water level was at 1 m in September 2018 and the lowest was at 0.2 m in March and April 2020. Thai Meteorological Department (2020) reported that the occurrence of El Niño in the first half of 2019 caused low actual rainfall. Although El Niño phenomenon did not occur in the second half of 2019, the actual rainfall still low which because of Positive Indian Ocean Dipole. Data of plant species index and water level during 3 surveys (March 2019, September 2019 and March 2020) showed that water level and the number of plant species in March 2019 and September 2020 did not obviously different. But during the lowest water level (0.2 m) in March 2020, high numbers of alien plant species (18 species) were found which was the highest amount in 3 times of survey. The terrestrial plant species also increased because of the increase of terrestrial area. High water levels have a strong negative effect on *Mimosa pigra* (Asyraf and Micheal, 2011). Indeed, Yongyut (2006) stated that a few *Mimosa pigra* was found in 2006 because the water in the lake was maintained at a high level and it could not invade into the lake area.

The vegetation maps based on the 30-m data showed the higher increase of *Mimosa pigra* in March 2020. Refer to the water level data and the 90-m distribution map of *Eichhornia crassipes* in September 2018, March 2019, September 2019 and March 2020, the covering area of *Eichhornia crassipes* was increasing continually during consecutively decline of the water level. Exception was in March 2020, the covering area of *Eichhornia crassipes* decreased due to a heavy hailstorm, which was an irregular natural event, in December 2019. This hailstorm destroyed many plants in the wetlands. An increase of *Eichhornia crassipes* during a decrease of water level shows how well they adapt to the unfavorable environment. They can survive for several months with no water and only moist sediments (Center et al., 2002).

Refer to water quality data in September 2018, March 2019, September 2019 and March 2020, an average water temperature was between 22.57°C and 30.58°C and the pH was between 6.07 and 7.98. The range of these two parameters was suitable for growing *Eichhornia crassipes*. In addition, high levels of phosphorus and nitrogen were detected in dry season (March) 2019 and 2020. Phosphorous and nitrogen are essential for growth of aquatic plants. However, excessive composition of nutrients can over-encourage aquatic plant growth (Paul and James, 2003; Prita et al., 2017). The results from water quality test showed that from March 2019 to March 2020, the water was polluted which was indicated by substandard DO values. The large *Eichhornia crassipes* mats blocked the sunlight and obstructing oxygen exchange which that degraded water quality, altered and reduced the biodiversity (Center et al., 2002; Brendock, 2003). To restore the water quality and maintain the biodiversity, a machine should be applied for get rid of all *Eichhornia crassipes* and *Mimosa pigra* out of the lake. At the same time, for sustainable wetland, vegetation buffer zones should be built all around the lake to reduce the level of fertilizer contamination caused from soil erosion.

Key words: *Eichhornia crassipes* (Mart.) Solms, *Mimosa pigra* L, Non-submerge aquatic plants, Unmanned aerial vehicle (UAV), Vegetation mapping, Nong Bong Khai non-hunting area

Japanese Summary

湿地は、生物多様性保全上きわめて重要な生態系である。1998 年、タイは第 110 番目のラムサール条約加盟国となり、15 のラムサールサイト湿地を登録した。そのうちの１つ、ノン・ボン・カイ湿地は外来植物種の増加によって脅かされている。外来植物種の増加は、土地利用／被覆の変化の影響で生じた栄養塩化した湖水環境のためである可能性がある。また、降水量の減少による水位変動も湖の植生に影響を与える可能性がある。そこで本研究は、(1)湖周辺の土地利用／被覆と湖水の水質を分析し、外来植物種の増加の背景を明らかにすることを目的とした。その際、水生植生の地図化に無人航空機(UAV)を適用し、特にホテイアオイの分布に焦点を当てた。また、(2)水生植物群落の分布に与える降水量の変化に伴う水位変動の影響をとくにホテイアオイとミモザに焦点を当てながら UAV の画像にもとづいて明らかにしようと試みた。

研究対象地は、タイ北部チェンライのノン・ボン・カイ禁漁区であり、ここは 1,101 番目のラムサール登録湿地である。年平均気温は 24.4 °C、平均降水量は 1,600-1,800 mm、面積は約 434ha である。この地域は美しい風景を有し、留鳥と冬季(11 月 -2 月)に渡来する水鳥の重要な生息地となっている。湖は丘陵地に囲まれ、主な土地利用は、農地、住居地、劣化した森林などで、土地所有形態は私有地である。

ノン・ボン・カイ禁漁区の集水域における土地利用／被覆図が、衛星画像から 2009 年、2012 年、2016 年、2018 年について作成された。それによると、畑地面積は 2009 年から 2018 年にかけて 92.07%増加し、落葉樹林と放牧地の面積は各々 53.23%と 47.86%減少した。畑地では、パイナップル畑とキャッサバ畑が各々 344.48%と 100.25%増加した。畑地の増加は、特にパイナップル畑とキャッサバ畑で

使用される肥料の量に影響を及ぼし、年間肥料使用量は各々813.43t と 100.19t に増加した。そのため、降雨時に土壌侵食が起き、栄養塩類であるリンと窒素の湖への流入が湖水の富栄養化を引き起こしたと考えられる。

UAV による撮影高度 30m の正射投影画像と 2-10m の単画像は、植生図を作成するのに十分な解像度で、アンドレア(2019)の「高度 25m と 5m の写真が植物群集や植物種を特定できる」との知見と一致した。4 つの調査区における高さ 30m からの画像にもとづく 2019 年の植生図は、ホテイアオイが全調査区に存在することを示し、同種が自生種を上回って優占種となっていた。2006 年、ヨンユートは同地で、ホテイアオイは目立つ存在ではないが、水質と土地利用／被覆の変化で増加するかもしれないとしており、これは 2001-2010 年の間、ホテイアオイはわずかしか見られなかったとの禁漁区職員と報告と一致する。湖全域を対象にした高さ 90m の画像にもとづく分布図は、ホテイアオイの植被が約 60 万 m^2（湖全体の 13.82%)に広がっていることを示した。2019 年にはリンと窒素は水質基準値を超え、DO は基準値に達していなかった。水質調査の結果は、主に農地から来た栄養塩類が、ホテイアオイの増加をもたらし、溶存酸素を減少させたことを示唆した。

2018 年 9 月から 2020 年 12 月にかけて、降水量の変化に伴ってノン・ボン・カイ湖の水位が変動した。最高水位は 2018 年 9 月の 1m、最低水位は 2020 年 3 月と 4 月の 0.2m であった。タイ気象局(2020)は、2019 年上半期のエルニーニョの発生が降水量の減少をもたらしたと報告した。エルニーニョは、2019 年後半には発生しなかったが、降水量はインド洋の正のダイポールモード現象のため少ないままであった。また、2019 年の 3 月と 2020 年 9 月の水位と植物種数に大きな変化はなかった。しかし、2020 年 3 月の最低水位(0.2m)時には、最多の 18 種の外来植物が見つかった。ま

た、陸上植物の種数も陸域の拡大によって増加した。高水位はミモザ(アサイラフとミシェル、2011)に強い負の影響を与える。実際、ヨンユート(2006)は、湖水の水位が高い状態に維持されている場合、湖の領域に侵入することができなかったので、わずかなミモザしか発見されなかったと述べている。

植生図は、2020 年 3 月時点でミモザの増加が著しいことを示した。また、 2018 年 9 月、2019 年 3 月、同年 9 月、2020 年 3 月の水位とホテイアオイの分布図を照合すると、ホテイアオイの被覆域は、水位の連続的な減少期間中にも継続的に増加していた。例外は 2020 年 3 月で、2019 年 12 月に起きた激しい霰の結果ホテイアオイが減少した。この霰は湿地の多くの植物を損傷させた。水位低下期におけるホテイアオイの増加は、同種が不利な環境に上手く適応できることを示唆した。

2018 年 9 月、2019 年 3 月、同年 9 月、2020 年 3 月の平均水温は 22.57°C-30.58°C、pH は 6.07-7.98 で、ホテイアオイ の成長に適していた。また、2019 年と 2020 年の乾季には、高濃度のリンと窒素が検出された。水生植物の成長にはリンと窒素が必要であるが、過剰な栄養塩類は水生植物の成長を過度に促す (ポールとジェームズ 2003;プリタら 2017)。2019 年 3 月から 2020 年 3 月にかけて、溶存酸素は基準値以下であった。ホテイアオイの大きな塊は、日光を遮断し、酸素の供給を妨げ、生物多様性を減少させる(Centeret al. 2002;ブレンドック 2003)。水質を回復し、生物多様性を維持するためには、機械を使用して湖からホテイアオイとミモザを取り除く必要がある。また、集水域の土壌侵食によって引き起こされる栄養塩類の湖水への流入を防ぐために、湖の全周に植生緩衝帯を構築することが推奨される。

キーワード: ホテイアオイ、 ミモザ、 非水没性水生植物、 無人航空機 (UAV)、 植生図化、 ノン・ボン・カイ禁猟区