Environmental factors affecting the Irrawaddy Dolphin (*Orcaella brevirostris*) distribution in the Mahakam River, East Kalimantan, Indonesia

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Abstract

Tropical rivers are known to support high biodiversity, and are often characterised by vast floodplain areas and seasonal inundation patterns (Dudgeon, 1992). These rivers are places for many important terrestrial and freshwater species such as three true river dolphins species (*Platanista gangetica, Platanista minor and Lipotes vexillifer*) and the facultative freshwater dolphin – the Irrawaddy dolphins (*Orcaella brevirostris*). The Mahakam River in East Kalimantan, Indonesia, is typical of other tropical rivers in Southeast Asia but is distinguished by a riverine population of the iconic Irrawaddy dolphins, known locally as *Pesut*. This freshwater population is classified as “Critically endangered” by the International Union for Conservation of Nature (IUCN). Like many other tropical rivers in Southeast Asia, the Mahakam River is also facing problems from rapid development in rural areas, characterised by a massive conversion of peatland forest to oil palm plantation, an increasing number of mining activities, and ongoing development of settlements. These developments are likely to have had both direct and indirect effects on the Irrawaddy dolphins.

Water quality parameters and land use type from sites in the upper, middle, and lower sections of the Mahakam River were used to quantify relationships with between broadscale catchment land-use changes and river habitat changes while anthropogenic factors such as fishing pressure and other forms of human disturbance were also assessed in relation to dolphin distribution. The objectives of this analysis were to (i) quantify changes in water quality in relation to land use, (ii) investigate the key environmental factors associated with Irrawaddy dolphin distribution and abundance in the Mahakam River, and (iii) integrate these findings with other information on dolphin ecology to make recommendations that support dolphin conservation management.

Over 1996–2017, the land use in the sub-catchments of government water quality monitoring sites demonstrated changes that reflected decreasing forestland and increasing estate cropland, mainly due to the development

of the oil palm plantations in Indonesia. The downstream section of the river also received disturbance from a high proportion of agricultural and settlement land. These land-use changes were shown to be related to the state of water quality in the Mahakam River. Increasing TDS and SO_4 were associated with increasing estate cropland and agricultural intensification, respectively, while decreasing COD and BOD concentration were related to changes in swampland area.

The middle reach of the Mahakam River was indicated as the primary habitat for the Irrawaddy dolphins. Several land-use related water quality parameters appeared to influence dolphin distribution through indirect effects on prey distribution. However, other forms of human disturbances such as settlements and boat traffic likely had direct effects on dolphins, contributing to their absence from the lower reach of the river. Accordingly, conservation management of Irrawaddy dolphins in the Mahakam River should focus on factors influencing prey species productivity in the river, such as the formation of fish reserves.

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Chapter 1

General Introduction

1.1 Tropical river ecology

Tropical rivers are complex ecosystem and support a high percentage of global biodiversity. It becomes a critical habitat for many freshwater and terestrial species living within rivers and their associated flooplains, (Dugeon et al., 2006; Winnemiller et al., 2008). In Asia for instance, some terrestrial mammals such as the orang utan (*Pongo pygmaeus*), other primates and crocodiles use river floodplains as habitat (Dudgeon, 2000a; 2000b). In addition, more than 100 families of freshwater fishes are found in tropical Asian rivers alone (Dudgeon, 2000a), including three out of five true river dolphin species (*Platanista gangetica, Platanista minor and Lipotes vexillifer*) and the facultative freshwater Irrawaddy dolphin (Dudgeon, 2000a).

Geological history, geomorphology, forest type, climate and flow regime differentiate tropical rivers from temperate rivers (Boulton et al., 2008). These factors also determine the function and structure of biodiversity in each river ecosystem (Thorp et al., 2006). For example, tropical rivers are characterised by warmer water temperatures and seasonal annual flooding driven by intense monsoonal rainfall. Further, some of the tropical rivers may have a low concentration of nutrients and minerals during low discharge and increases during floodplain inundation, showing the influence of the flow regime on river water quality (Dudgeon, 1992). These features contribute to the uniqueness of tropical rivers in terms of community structure, species diversity and ecological function (Dudgeon, 2000a; Boyero et al., 2009; Moss, 2010).

However, Boulton et al. (2008) argue, based on various studies, that tropical rivers are not different from temperate rivers in terms of the prevailing ecological processes which are driven by the same external variables, although the organisms mediating these processes may be different. In addition, the productivity in both types of river is limited by nutrients, canopy cover and food web structure (Boulton et al., 2008).

Many studies of river ecosystems in temperate regions of the world have provided comprehensive knowledge on their structure and function (e.g. Benda & Dunne, 1997; Benda et al., 2004; Mantel et al., 2004; Layman and Winemmiler, 2004; Kaushal et al., 2010). However, tropical rivers have not received the same attention and consequently little is known about their ecology (Dudgeon, 2000b). Given the differences between tropical and temperate systems, there is a significant opportunity to test and develop ecological theories for large rivers in these poorly known tropical river systems (Thorp et al., 2006).

1.1.1 Anthropogenic threats to tropical rivers

Allan (2004) states that the land use and landscape surrounding rivers has a disproportionately large influence on aquatic ecosystem processes and biodiversity. The landscape affects geomorphological processes that create different habitats for organisms and maintains connectivity amongst habitats, while land use change can have adverse impacts on water quality. Disturbances to land cover and connectivity can alter and degrade habitats, causing loss of biodiversity (Allan, 2004).

Although temperate rivers experience the same threats, tropical rivers, and particularly those in Asia, receive more intense disturbance due to high population density and poor river management. Well-known river ecosystem disturbances caused by the human activities are flow alternation, water pollution, degradation of habitat and overfishing (Dudgeon, 2000b; Dudgeon, 2003). Flow modification is often caused by channel regulation for navigation and flood control, and construction of dams and abstraction for irrigation, drinking water and energy (Moss, 2010). These disturbances alter annual flows and seasonal flooding regimes to which some river and floodplain organisms are adapted. Flow modification also impedes the movement of migratory species from downstream to upstream for spawning, rearing and feeding, as well as fragmenting their habitat (Dudgeon, 2000b).

In many parts of Asia, water pollution and habitat degradation are mainly caused by the changing land use in the catchment. Indeed, the Asian region is synonymous with high rates of deforestation and rapid development of settlements and agricultural land in rural areas (Dudgeon, 2003). The deforestation and conversion of land use into agriculture and settlements influences river water quality and ecological processes, which in turn can affect aquatic organisms causing decreases in biodiversity (Boyero et al., 2009; Rodríquez-Romero et al., 2018). In this regard, there is concern over human impacts on the distribution and abundance of the iconic Irrawaddy dolphin (*Orcaella brevirostris*, Delphinidae) which occurs in several large Asian rivers, including the Mahakam River in Kalimantan, Indonesia. Understanding human-induced threats to this species was a key driver of the present study, so existing knowledge of this species is summarised below.

1.2 Irrawaddy dolphin

Irrawaddy dolphins are intermittently distributed in shallow coastal areas, brackish water, and turbid water near to river mouths, as well as in freshwater habitats, mostly in an area from Northwest Bengal to Northeast Australia (Rice, 1998; Stacey & Arnold, 1999). In 2005, Irrawaddy dolphins were separated into two species with the Australian population classified as a different species, namely Snubfin dolphin (*Orcaella heinsohni*) (Beasley et al., 2005). Three freshwater populations of Irrawaddy dolphin occur in three major rivers: Mahakam River, Ayeyarwady River and Mekong River in Southeast Asia, and two brackish or freshwater lake populations inhabit Sonkhla, Thailand and Chilika Lake, India (Stacey & Arnold, 1999; Stacey & Hvenegaard, 2002; Smith, 2008).

In Indonesia, the Irrawaddy dolphin has been protected by government regulations since 1990. However, this protection only prohibits the exploitation of animals and does not regulate the activities on or alongside the river that influence dolphin habitat. Intensive study of Irrawaddy dolphins in Indonesia started in 1997 with the main focus on the distribution, abundance and identification of threats from human activities. This work was derived from the need to provide evidence and a conceptual framework that could be used to monitor and protect Irrawaddy dolphins in the Mahakam River (Kreb, 2004). However, despite these efforts, the impacts of environmental factors on the Irrawaddy dolphin distribution have not been well documented. Thus, information on human threats and pressures that can influence dolphin distribution and abundance is limited to support the protection and management of Irrawaddy dolphin.

1.2.1 Biology and ecology

Irrawaddy dolphins have a small triangular dorsal fin and are very challenging to identify especially in the murky river water due to their grey to bluish-grey color, with a lighter color on the belly. They tend to show only a small portion of the dorsal fin on the surface when they are travelling or resting at the surface without moving forward (Smith, 2008). Adult Irrawaddy dolphins have a length range from 2 to 2.75 m (length average of 2.05 m) with a length at birth of 1 m (Jefferson et al., 1993; Jefferson et al., 2007). This physical appearance and behaviour makes it difficult to spot them and may contribute to the lack of data and information on their habitat preferences.

Like other cetaceans, Irrawaddy dolphins only give birth to a single offspring for each reproduction cycle, with birth probably occuring during April to August after a gestation period of fourtheen months to two years (Jefferson et al., 2007; Smith, 2008). Low reproduction rate makes dolphins more prone to human-induced threats, which can lead to population decreases due to their slow recovery. Longevity of Irrawaddy dolphins is about 30 years (Evans & Stirling, 2001; Jefferson et al., 2007).

Dolphin abundance is mostly influenced by slow recruitment and high mortality rates. Slow recruitment due to its long reproductive cycle combined with human-induced habitat fragmentation, which can cause inbreeding depression that accelerates population decline (Beasley et al., 2013). High mortality rates occur in every stage of life, i.e. newborn, juvenile and adult. Frequently, it is caused by entanglement in fish nets and destructive fishing activities. For instance, in the Mahakam River, 74% of 38 cases of Irrawaddy dolphin deaths over 1995 to 2001 were caused by entanglement in gillnets, with 81% of these being adult dolphins (Kreb & Budiono, 2005). Meanwhile, in the Mekong River, dolphin mortalities caused by gillnets accounted for 52% of 23 cases (Beasley et al., 2007). In addition, the Mekong River has a high newborn mortality, which accounts for 54% of 46 mortality cases, although the reasons for deaths are unknown (Beasley et al., 2013).

Compared to other oceanic dolphins that occur in large groups of more than 100 individuals, it is common to find Irrawaddy dolphins in small groups of less than six individuals. Groups of 25 dolphins have been recorded in the Mekong River where they are found in deep pools during the dry season (Smith, 2008; Jefferson et al., 2007), compared to the Mahakam River where Irrawaddy dolphins can be found in groups of 3 to 7 individuals (Kreb, 2002). In the Mahakam River, Irrawaddy dolphins mainly inhabit the middle segment between 180 km to 480 km from the river mouth, with the highest density found within a 195-km river segment (Kreb, 2002). Irrawaddy dolphins in the Mahakam and Mekong Rivers, as well as the Ganges River dolphin, prefer deep pools in confluence areas in the mainstem (Kreb & Budiono, 2005; Beasley et al., 2013; Bashir et al., 2010).

1.2.2 Threats

Current studies have identified several factors that influence dolphin population decline. The main factors that are considered as threats to freshwater dolphin populations are entanglement by gillnets, electrofishing, dam construction, boat noise, live capture for bait and display, exposure to pollutants from mining activities and industries, and general habitat degradation and loss. The relative importance of these threats may vary in each location, however, entanglement in gillnets as well as habitat degradation and loss are major concerns in all locations (Beasley et.al, 2007; Kreb & Budiono, 2005; Smith & Tun, 2007; Smith et al., 2007).

The anthropogenic impacts that cause habitat degradation for cetaceans can be classified into five categories: 1) physical damage; 2) chemical pollution; 3) prey removal due to fisheries pressure; 4) noise disturbance; and 5) global climate change. For the Irrawaddy dolphin, alteration of rivers can cause habitat change and physical damage to their environment, and fragmentation contributes to impeded dolphin movement (Evans, 2008). For example, construction of two hydroelectric dams in the mainstream and upstream areas of the Mekong River has reduced the ability of dolphins to forage and commute within the river leading to population isolation. Dam construction also contributes to decreased fish abundance and thereby influences the availability of dolphin food resources (Baird & Beasley, 2005; Blachet et al., 2010).

Riverine dolphin populations are facing numerous problems from the land caused by human activities as part of rural development. It is widely known that land use change causes habitat degradation and habitat loss for many species, and also influences river water quality that may directly and indirectly affect riverine dolphins through effects on population health and prey abundance. Each land use type has different levels of impact on river water quality. Increased amounts of contaminants and heavy metals in water are derived from industrial land discharges, while agriculture contributes sediment and nutrients. Catchment and riparian deforestation influences seasonal patterns in water quality (Cassens et al., 2000; Bu et al., 2014), and also can influence the abundance and composition of fish in the river by modifying river substrate and interfering with riffles and pools that provide habitat diversity for fish and invertebrate prey (Jones et al., 1999; Meserindino et al; 2011). Nutrient discharges from agriculture, industrial waste and community waste water increase nutrient concentrations and cause eutrophication, which adversely affects aquatic ecosystem health.

Another threat that can have a direct effect on dolphin survival is the level of water pollution and disease (Beasley et al., 2013; Kreb and Budiono, 2005). Evidence from other species shows that cetaceans may be exposed to pollutants such as PCB, DDT and PAHs (Evans, 2008). Mercury also has been found in the tissue of Irrawaddy dolphin carcases in the Mekong River and has been a potential threat to dolphins in the Ayeyarwady River, as well as to the fish prey population in that river. This contaminant results from gold mining in upstream areas and along the river. Since Irrawaddy dolphins are the top predator in the river, biomagnification of persistant contaminants would be a major concern (Smith et al., 2007). These contaminants can affect the reproductive system, cause tumors and may reduce the resistance to disease that make dolphins prone to viral and bacterial infections (Evans, 2008).

High frequency boat traffic for transportation, fishery activities or dolphin tourism can also influence dolphin distribution due to noise and stress levels experienced from vessel encounters, potentially leading to displacement of dolphins from suitable habitat (Kreb & Rahadi, 2004; Beasley et al., 2013). The Irrawaddy dolphin is highly dependant on echolocation for foraging within and commuting between resource patches due to light attenuation by turbid waters (Ballance, 2008). Echolocation is crucial for them to locate their prey, avoid obstacles under the water, communicate within the group and elude predators using high-frequency sound in the range of 60-80 Khz (Van Parijs et al., 2000; Jensen et al., 2013). A river with regular high boat traffic can produce significant underwater noise that might interfere with dolphin echolocation and affect dolphin behaviour. Kreb & Rahardi (2004) reported that boat traffic in the Mahakam River had changed Irrawaddy dolphin surface behaviour by making the dolphins stop to produce vocalisation during boat encounters, presumably to let the vessel pass by.

1.3 Objective of the research

This thesis aims to quantify the relationship between broadscale catchment and river habitat degradation caused by human activities in relation to dolphin distribution in the Mahakam River, with an emphasis on the associations between land use and river water quality, and the productivity of prey species. It is predicted that changes in dolphin distribution will be directly or indirectly related to water quality due to catchment land use change and associated human pressures. Therefore, it is essential to know which environmental factors related to human activity are associated with dolphin distribution and population numbers, and where efforts can be targeted to reduce the impacts. The results of the study will contribute to future conservation efforts aimed at relieving pressure and enhancing populations of the Irrawaddy dolphin in Mahakam River, East Kalimantan.

To address this aim, the thesis involves three general objectives:

1. Quantify spatial and temporal changes in water quality in the Mahakam River in relation to land use.
2. Investigate the key environmental factors associated with Irrawaddy dolphin distribution and abundance in the Mahakam River.
3. Integrate these findings with other information on dolphin ecology to make recommendations that support dolphin conservation management.

The general hypotheses being tested in this study are:

1. Land use/cover change will be related to the rate of water degradation both in terms of trends over time and longitudinally along the river.
2. The rate of water quality degradation will be correlated with dolphin numbers sighted in the Mahakam River, and will interact with other disturbance factors such as fish prey productivity to influence dolphin distribution and abundance.

1.4 Outline of thesis

This thesis consists of five chapters with two main results chapters presented in the style of scientific manuscripts, leading to some repetition in some parts, especially the study area description. The first chapter reviews tropical river ecosystems and the influence of human activities in the catchment on tropical river health. This chapter also reviews the Irrawaddy dolphin biology and ecology, and environmental factors that influence dolphin occurrence. Chapter 2 gives an outline of the study area with the sampling site description. Chapter 3 examines the spatial and temporal pattern of water quality in the Mahakam River, and links this pattern with land use change in the catchment. Chapter 4 investigates environmental factors that may explain Irrawaddy dolphin distribution in particular river sections, and links with Chapter 3 in terms of potential effects of land use change on water quality. The last chapter summarises the findings from Chapters 3 and 4, and discusses possible recommendations to support Irrawaddy dolphin conservation and river management.

Chapter 2

Study Area

2.1 The river and catchment

The Mahakam River catchment lies between latitude 01^{0}55' North - 01^{0}09' South and longitude 113^{0}49' - 117^{0}41' East on the Kalimantan Island of Indonesia. The river is one of the longest in Indonesia at 980 km and originates from Cemaru Mountains in the centre of Kalimantan Island (Van Bemmelen, 1949), draining in a south-eastern direction through the Kutai wetland area and into the Mahakam Delta in the Makassar Strait (Figure 2.1). The Mahakam River is considered a relatively pristine river system in Indonesia with extensive meanders and intact oxbow lakes. Average widths of the river in the upper, middle and lower sections (see Figure 2.1) are 160 m, 200 m and 360 m respectively, and mean depths are 10 m, 15 m, and 12 m (Kreb, 2002).

According to BLHD (2017), the lower section of the river begins from the delta and stretches c.60 km upstream, while the middle section is c.388 km long, and the upper section is c.532 km. Total catchment area is 7,724,365 ha comprising 37 sub-catchments, seven of which are considered major sub-catchments due to the total area they cover (BPDAS, 2010). Three of the major sub-catchments are located in the upstream section of the river, whilst another three are in the middle section and one in the downstream section of the river (Figure 2.1; see Section 2.3). The river has one major tributary (Sungai Ratah) in the upstream and another four tributaries (Sungai Kedang Pahu, Sungai Belayan, Sungai Kedang Rantau and Sungai Kedang Kepala) in the middle, draining the major sub-catchments described earlier.

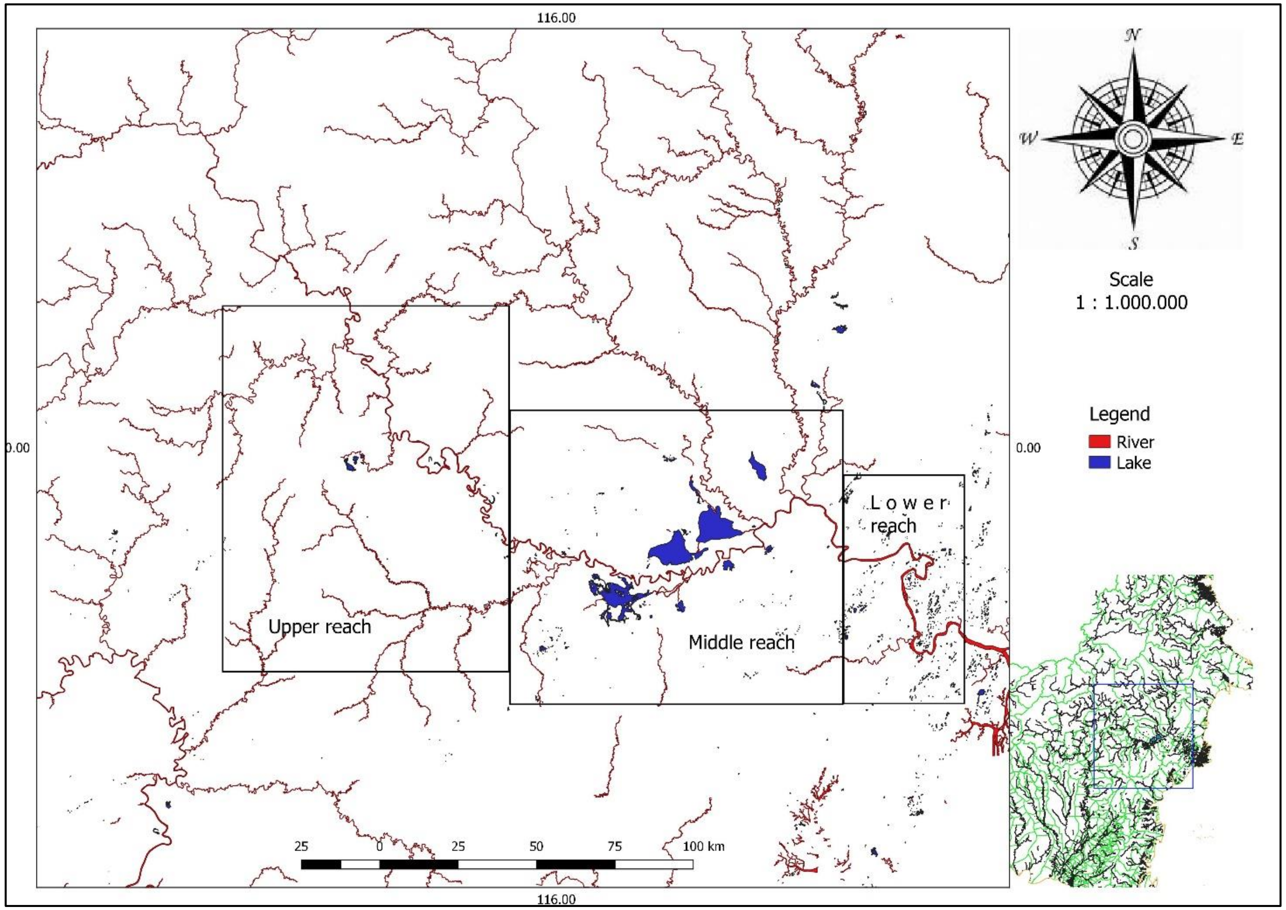

Figure 2-1: Area of study in the Mahakam River showing upper, middle and lower reaches (Inset on the right shows the Island of Kalimantan). The area represents the location of water quality monitoring and dolphin survey areas

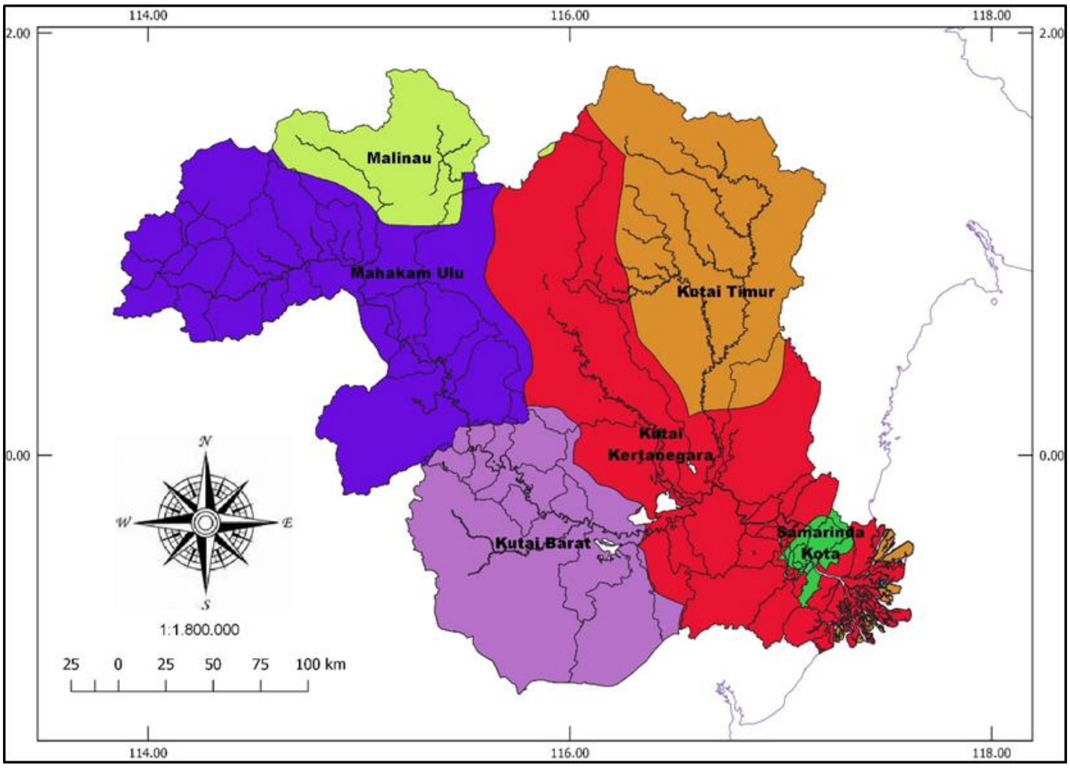

Figure 2-2: The Mahakam River catchment in East Kalimantan showing the administration divisions within the catchment

Administratively, the river catchment covers six districts in two provinces: five districts in East Kalimantan (Kota Samarinda, Kutai Kertanegara, Kutai Timur, Kutai Barat, Mahakam Ulu) and one district in North Kalimantan (Malinau) (Figure 2.2). The upper catchment incorporates Mahakam Ulu and Malinau, while the middle catchment is situated in Kutai Barat and Kutai Timur with part of Kutai Kartanegara, and the lower catchment is covered by another part of Kutai Kertanegara and Kota Samarinda. Although the catchment is located within two provinces, the Mahakam River mainstem only traverses through East Kalimantan province.

The middle catchment areas are situated in the Kutai basin, which forms a vast floodplain area with many swampy and shallow lakes which are believed play an important role in regulating river flow, maintaining a constant discharge for the lower section (Gerven et al., 2009; Hidayat et al., 2016). There are three major lakes in the middle catchment: Lake Melintang (11,000 ha), Lake Semayang (13,000 ha), and Lake Jempang (15,000 ha). A vast floodplain area in the middle catchment, known as the Middle Mahakam Area (MMA) (Christensen, 1993), is surrounded by peat swamps and forested peatlands that are low in nutrients and high in humic acids

(Chokkalingam et al., 2005). The peat swamp has tea-coloured water, known locally as 'blackwater', which is sometimes released into the river during seasonal flooding. These peatlands and lakes play a significant role for inland fisheries (Christensen, 1992; MacKinnon et al., 2013).

Human-induced activities in the Mahakam River catchment are mostly related to land use to fulfill human needs such as settlement, food and transportation. This changing land use and land cover is mainly clustered in the middle and lower catchment areas where it primarily influences the river system. Primary and secondary forests dominate land cover in the upstream catchment, while a vast area of swamp shrubs and dryland agriculture with estate crop plantation covers the middle catchment. The lower catchment is dominated by settlement and dry land agriculture with areas of shrubs (BPDAS, 2010). Some examples of land use and land cover identified in the middle catchment are presented in Figure 2.3, while land cover types and the total land cover area in the Mahakam River catchment are presented in Table 2.1.

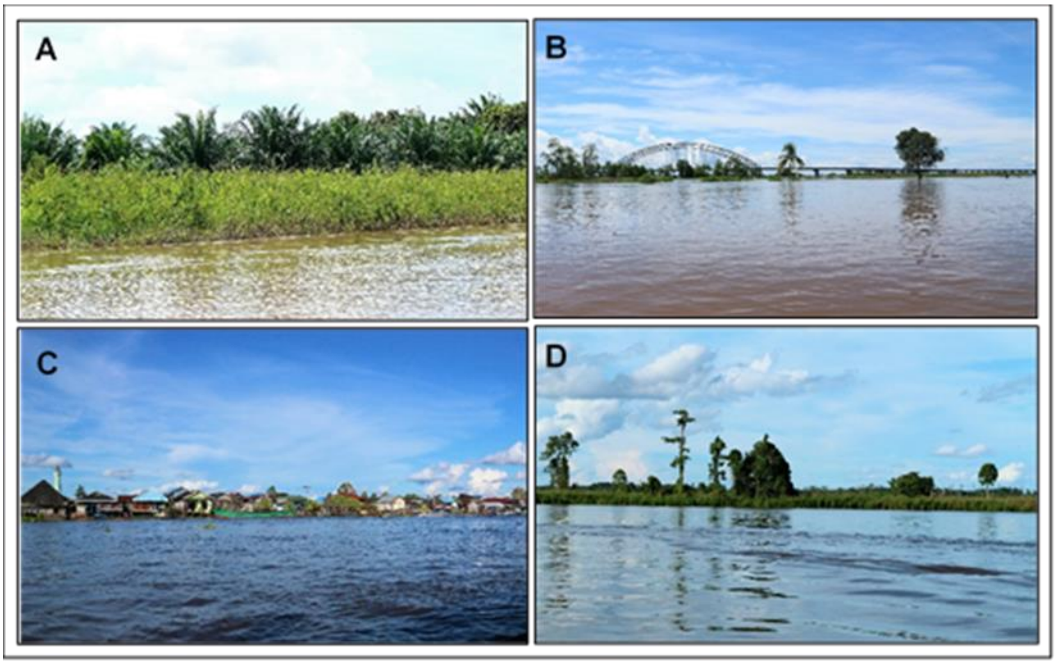

Figure 2-3: Examples of land use and land cover types that can be found in the Mahakam River catchment. A = palm oil plantation in the upstream floodplain; B = Road and bridge across the floodplain; C = settlement along the river bank; D = grassland/shrub swamps. Photos by author

Table 2.1. Land cover types and total areas in the Mahakam River catchment based on satellite imagery analysis in 2004 (BPDAS, 2010). Only those comprising >0.1% of area are shown.

Land cover type	**Total land cover**	
	Total area (ha)	**Percentage**
Secondary forest	2,285,924	29.59%
Shrubs	1,945,880	24.36%
Primary forest	1,807,157	23.40%
Swamps shrubs	450,347	5.83%
Plantation forest	281,507	3.64%
Barren land	168,171	3.47%
Paddy field	143,028	1.85%
Airport	113,253	1.47%
Plantation	107,943	1.40%
Swamps	84,424	1.09%
Mixed agriculture	79,163	1.02%
Secondary swamp forest	72,251	0.94%
Primary swamp forest	25,348	0.33%
Settlement	21,916	0.28%
Dryland agriculture	21,647	0.28%
TOTAL AREA	**7,724,365**	

Based on the classification and assessment conducted by the Catchment Management Agency (Balai Pengelolaan Daerah Aliran Sungai – BPDAS), the Mahakam River catchment has been identified as needing restoration to recover its condition (BPDAS, 2014). This classification is based on problems identified within the catchment such as high sedimentation rate, water quality deterioration and increased risk of fire events.

2.1.1 Climate

Based on the Koppen - Geiger climate classification, Kalimantan Island has a tropical rainforest climate type (Af) with annual temperature >18^{0}C and precipitation >60 mm (Peel et al., 2007). The catchment climate is influenced every year by the Southeast monsoon, which occurs between May to October during the dry season, and the Northwest monsoon during the wet season over November to April (MacKinnon et al., 2013). During the peak of the wet season in December through to January, the water level in the river and the lakes expands and inundates the adjacent peat swamp forest, surrounding the villages alongside the river bank. This inundation occurs in the middle and downstream areas of the river. Meanwhile, in the dry season, the river water level can drop by 6 m and in some lakes down to 1 m depth (Chokkalingam et al., 2005), while others can totally dry up (Figure 2.4). Inundation of this floodplain area is influenced by the level of precipitation in the upstream catchment and the tidal motion in the downstream catchment (Hidayat et al., 2013).

2.1.2 Topography and hydrology

As a result of geological history, the landscape of the Mahakam River catchment is different from upstream to downstream. The western part of the island is hilly while the eastern part comprises lowlands. Accordingly, the upper catchment is located in an area with elevation ranging from 65 m to 2000 m above sea level (asl) and slopes between 15% to >40%. On the other hand, the middle and lower catchments have elevations <65 m asl down to sea level with slopes between 0% to <15% (BPDAS, 2010; Hidayat et al., 2016). The upper catchment is also challenging to reach due to steep contours, limited road access and narrow, rocky river substrate with rapid flow. The peat swamp forest and floodplain in the Mahakam River catchment are considered less developed (Chokkalingam et al., 2005; MacKinnon et al., 2013) with limited road networks, and can only be accessed using a canoe or small motorised boat.

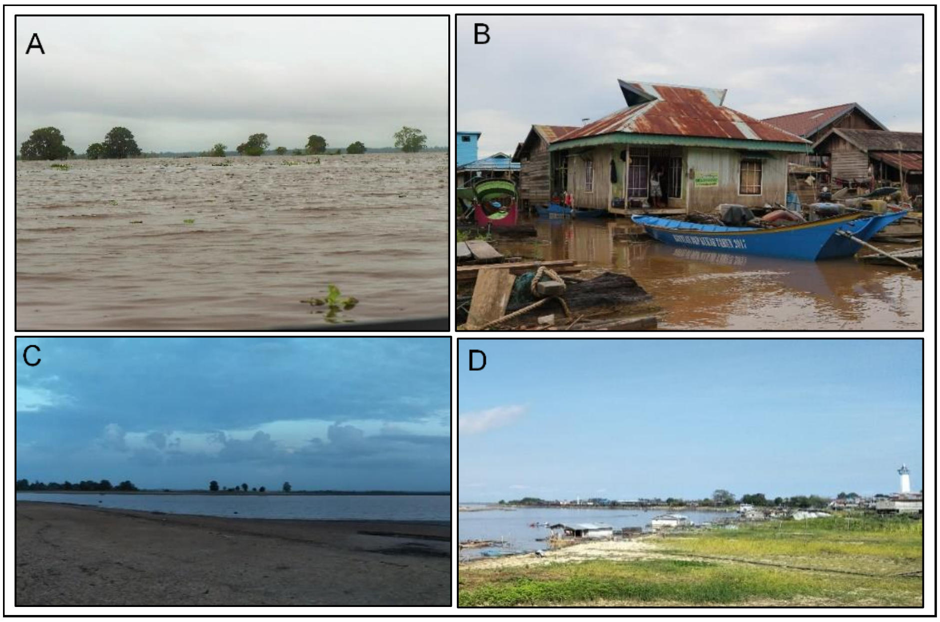

Figure 2-4: Flood during wet season (December 2017) in Semayang Lake (A); The different colour on the house wall shows the water level during floods (B); Semayang Lake in dry season (July 2018), with some parts entirely dried out (C); The river bank during dry season (July 2018) (D). Photo A and B by author; Photo C and D courtesy of Innal Rahman (Save Mahakam Dolphin).

Since Kalimantan lies on the equator, the rainfall has a significant role in determining the distribution of plants and animals, which form diverse ecosystems (MacKinnon et al., 2013). In 2016, average precipitation was 223.6 mm with 18.9 rain days and temperature was between 23^{0}C to 34^{0}C, consistent with tropical rainforest criteria (BPS East Kalimantan, 2017). The precipitation distribution in upstream to downstream parts of catchment is presented in the Figure 2.5. The Mahakam River mean annual discharge for the upstream is 2000 m^3/s and fluctuates seasonally, while the downstream discharge is 8000 m^3/s (Sassi et al., 2011; Hidayat et al., 2016).

2.1.3 Geology and soil types

According to MacKinnon et al. (2013), the geological structure of the Mahakam River catchment is represented by sedimentary rocks, alluvial and peat deposits, melange (a combination of broken rock fragments of different origin) and old volcanic rocks. Sedimentary rocks account for almost three-quarters of catchment area from the middle to the downstream end of the catchment, which is underlain by coal and oil reserves. Alluvial and peat deposits are associated with the sedimentary rocks in the middle catchment, while the upstream catchment is represented by melange and volcanic rock.

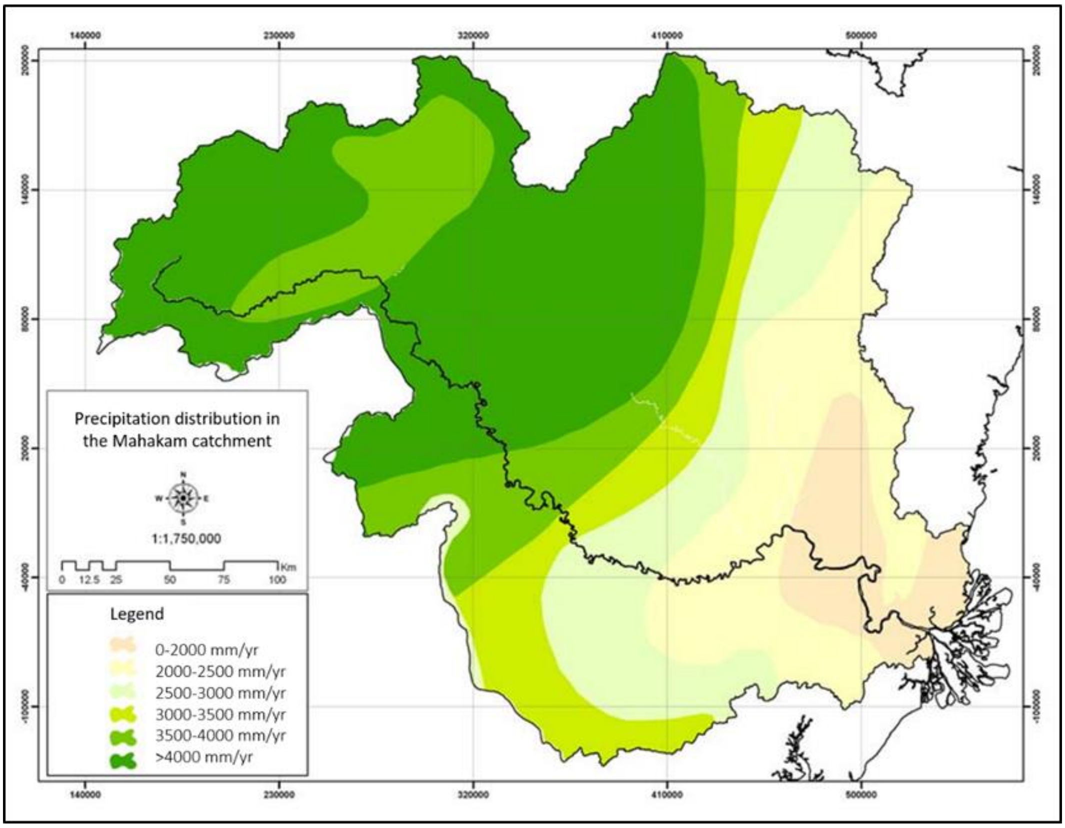

Figure 2-5: The Mahakam River catchment showing precipitation distribution from upstream to downstream (Map adapted from BPDAS, 2010)

According to MacKinnon et al. (2013), extensive dystropepts (inceptisol), characteristic of moderately weathered fertile soil on steep slopes are formed in the upstream catchment. These soils are associated with small areas of tropodults (ultisol) that are categorised as infertile and consist of loam and clay. Meanwhile, the middle catchment is mainly covered by tropohemists (histosol) and tropoquepts (inceptisol). Tropohemists are mainly organic soils (peat) formed on the floodplain area. Almost all tropohemists have high acidity and low nutrient concentration which make this soil type difficult to cultivate (MacKinnon et al., 2013). On the other hand, the tropoquepts are formed on river sediment resulting from erosion of siliceous sandstones. These soils type are poorly drained and less fertile compared to dystropepts. Tropodults cover a vast area from the downstream section to the middle catchment in the Mahakam River. These soils are strongly weathered with high aluminium concentration and strong acidity. The distribution of soils within the catchment defines the distribution of plants, animals, and human settlement and development (MacKinnon et al., 2013).

2.2 Human activities associated with the Mahakam River

The people use the river as the main transportation route and transports their basic daily needs from downstream to upstream, and vice versa (Kreb, 2004, MacKinnon et al., 2013; *pers. observation*). Coal barges traverse the river from the upstream mining area to the downstream end the river where the port is located. The traffic volume in the river, particularly in the middle section, is high with small motorised canoes, speedboats, coal barges and medium-sized wooden boats passing frequently. The average number of all boat types travelling in the middle section of the Mahakam River is approximately 20 boats per hour (Kreb & Rahardi, 2004) (Figure 2.6)

The Mahakam River floodplain is a major inland fisheries area in Indonesia. In 1985 the inland fish production from the river was 25,000 to 35,000 metric tons, with four species dominating catch composition: Kissing gourami (*Helostoma temmincki* - Helostomidae), the banded snakehead (*Channa striata* – Chanidae), the snakeskin gourami (*Trichogaster pectoralis* – Trichopodus) and a small cyprinid (*Thynnichthys vaillanti* - Cyprinidae) (Christensen, 1993a). By 2016, the fish production had increased to around 89,000 tonnes (BPS East Kalimantan, 2017). Four main fishing gears are used in the Mahakam River: gillnets, lift nets, handlines and traps, with gillnets the most popular gear used in the Mahakam floodplain (Christensen, 1993a; BPS East Kalimantan, 2017). The fisheries activities in the river are not only wild-capture but also aquaculture fisheries. Fish ponds are commonly found alongside the river where settlements occur, mainly located alongside the river bank as well as near industry. The lower section is highly populated and well developed compared to the upper and middle sections where saw mills, coal shelters and palm oil processing industries can be found (*pers. observation*).

A 2016 water quality assessment by Ministry of Environmental and Forestry categorised the Mahakam River as having medium to heavy pollution (DJPPKL, 2016). Based on the STORET method for physical, chemical and biological parameters, heavy pollution is observed in the upper reach, upstream parts of the middle reach and in the lower reach, while medium pollution is observed in downstream parts of the middle reach and the middle area of lower reach (DJPPKL, 2016). These conditions may result from activities in the catchment area such as logging, coal mining, and conversion of forest land into plantation or agriculture, activities that change the soil structure as well as creating domestic and industrial discharges.

Figure 2-6: Activities in the Mahakam River. A: fisheries; B: coal barge transportation; C: settlement; D: saw mills. Photos by author.

2.3 Study area boundaries

For this study, the area of interest in the Mahakam River was based on (i) water quality monitoring sites retrieved from the East Kalimantan Province Environmental Agency, and (ii) the main area of dolphin distribution retrieved from Rare Aquatic Species Indonesia (RASI) foundation. For the dolphin study (see Chapter 4), the area of interest covered the upper (Melak to Laham), middle (Muara Kaman – Muara Pahu) and lower (Samarinda Kota – Sebulu) reaches of the river. Meanwhile, for the water quality study (Chapter 3) the coverage area was from Melak to Samarinda Kota encompassing nine water quality monitoring sites (see Table 2.2, Figure 2.1). For land use and land cover analysis purposes, the area of study focused on the catchment area associated with water quality monitoring sites within the upper, middle and lower sections of the river.

Table 2.2 The area of study based on the length of the river and subdistrict.

River section	Subdistrict	Length* (km)
Upper	Melak to Laham	312
Middle	Muara Kaman to Muara Pahu	542
Lower	Samarinda Kota to Sebulu	105
The total length of area study		**959**

*Length = main river + major tributary length

Chapter 3

Spatial and temporal assessment of Mahakam River water quality in relation to changing land use

3.1 Introduction

The definition of 'river health' has been the subject of considerable debate in terms of appropriate assessment methods and indicators (Norris & Thoms, 1999; Bunn et al., 1999). It can be measured based on physicochemical characteristics, functional processes, and biological responses. In particular, water quality is a key factor affecting the health of river biota, and to assess this it is necessary to quantify the concentrations of key parameters over time along the river to determine spatial and temporal patterns. However, there can be difficulties interpreting water quality parameters within rivers, mainly due to uncontrollable factors such as hydrological processes, the geology of the watershed, and human activities within the catchment (Hildrew & Ormerod, 1995).

The nutrients phosphorus and nitrogen, along with suspended sediment, are key land-use related factors affecting primary production and limiting the growth, distribution and diversity of biota in rivers (Moss, 2010; MacKinnon et al., 2013). The relationship between land use and river water quality has been well documented around the world, with different land use types having varying levels of impact on river water quality. Forested areas with dense vegetation have limited soil erosion, but this is exacerbated by deforestation leading to increases in suspended sediment (Newson, 1997; Bu et al., 2014). Furthermore, catchment and riparian deforestation may disturb the hydrological cycle due to changes in evapotranspiration and runoff, which can influence the seasonal patterns of water quality (Horne & Goldman, 1994; Edward, 1995; Newson, 1997; Moss, 2010).

Changes in the vegetation cover, agricultural fertiliser runoff, sewage discharges and associated development for urban settlement, can increase nitrogen and phosphorus concentrations in rivers (Horne & Goldman, 1994; Shi et al., 2017; Manali & Chang, 2018). Meanwhile, increased concentrations of heavy metals are derived from mining and discharges from industry. Slash and burn activities are commonly used to clear catchments, and this may reduce water quality by mobilising excess ashes and sediment into drainage waters (Horne & Goldman, 1994). For example, the combustion of forest (wood) will increase the deposition of sulphate and nitrate in the river, thereby raising the acidity of water (Horne & Goldman, 1994; Moss, 2010). Silica and granitic bedrock types can also influence the sulphate and nitrate concentrations in rivers (Hildrew & Ormerod, 1995).

The Mahakam River and its catchment comprise one of the critical freshwater habitats with high biodiversity in Indonesia. However, despite the importance of the river for the biodiversity, over two decades the lowlands and catchment of the Mahakam River have been subject to extensive forest clearance, primarily for agriculture and palm oil plantations, along with increases in mining activities for coal, bauxite and some precious stones (MacKinnon et al., 2013). In addition, the Mahakam floodplain, mainly surrounded by peat swamp forest, experienced massive fire events between 1983-1984 and 1997-1998 (Dennis, 1999; Chokkalingam et al., 2005; Hope et al., 2005). These anthropogenic events have contributed to the degradation of the Mahakam River catchment with the potential to adversely affect aquatic organisms living in the river and connected freshwater environments.

This chapter aims to quantify spatial and temporal changes in water quality in the Mahakam River in relation to land use. There have been many studies carried out in the Mahakam River and its floodplain, particularly in the Middle Mahakam Area (MMA), focused on the impacts of fire events, fisheries productivity, Irrawaddy dolphin population abundance, and the hydrology of the river (see Christensen, 1992; Kreb, 2004; Chokkalingam et al., 2005; Sassi et al., 2010; Hidayat et al., 2011; Hidayat, 2013; Vermeulen, 2014). However, there has been limited study of factors affecting the water quality in the Mahakam River (e.g. de Jong et al., 2015 focus in the middle Mahakam lakes). To address the information gap, the specific objectives of this chapter were to:

- Measure trends in water quality from past and present data to determine the changes of the Mahakam River water quality over time. Despite the regular monitoring conducted by local government since 2010, there is no information regarding water quality trends in the Mahakam River (de Jong et al., 2015)
- Identify longitudinal patterns in water quality down the upper, middle and lower sections of the Mahakam River to determine spatial water quality changes associated with increasing human development.
- Relate spatial and temporal patterns in water quality to changes in land cover/use, including any long-term effects of major fire events.

Based on findings from various studies and the literature, the hypotheses of this chapter are: (i) trends of water quality in the Mahakam River will reflect intensification of land use in the catchment; (ii) declining water quality will be more prevalent in the lower section of the river, particularly in the highly developed area, and (iii) an historical fire event was associated with ongoing changes in selected water quality parameters related to mobilisation of ash to the river. The results from this chapter inform Chapter 4 to help identify the factors that may be affecting the iconic Irrawaddy dolphin distribution in the Mahakam River.

3.2 Methods

3.2.1 Study area

The study area encompasses the mainstem of the Mahakam River with some extension to its tributaries. The location of regular water quality monitoring sites was designated by the East Kalimantan Province Environmental Agency (BLHD) covering the mainstem river section from Melak (MS-1) in the upper part to Samarinda Kota (MS-9) in the lower section (Figure 3.1). BLHD chose these monitoring sites to represent stations down the river that meet the following criteria: (i) the upper reach

(MS-1) to provide a baseline of low human activity; (ii) locations in the middle reach (MS-2 to MS-5) to represent frequent human interference and intensive land use, and (iii) specific locations to indicate pollutant sources,including tributaries in the middle reach (not shown on Figure 3.1) and the lower mainstem reach (MS-6 to MS-9) where the industrial or mining activity exist. Nine monitoring sites from eight sub-districts were used in this study (Figure 3.1). Further details about the study area can be found in Chapter 2.

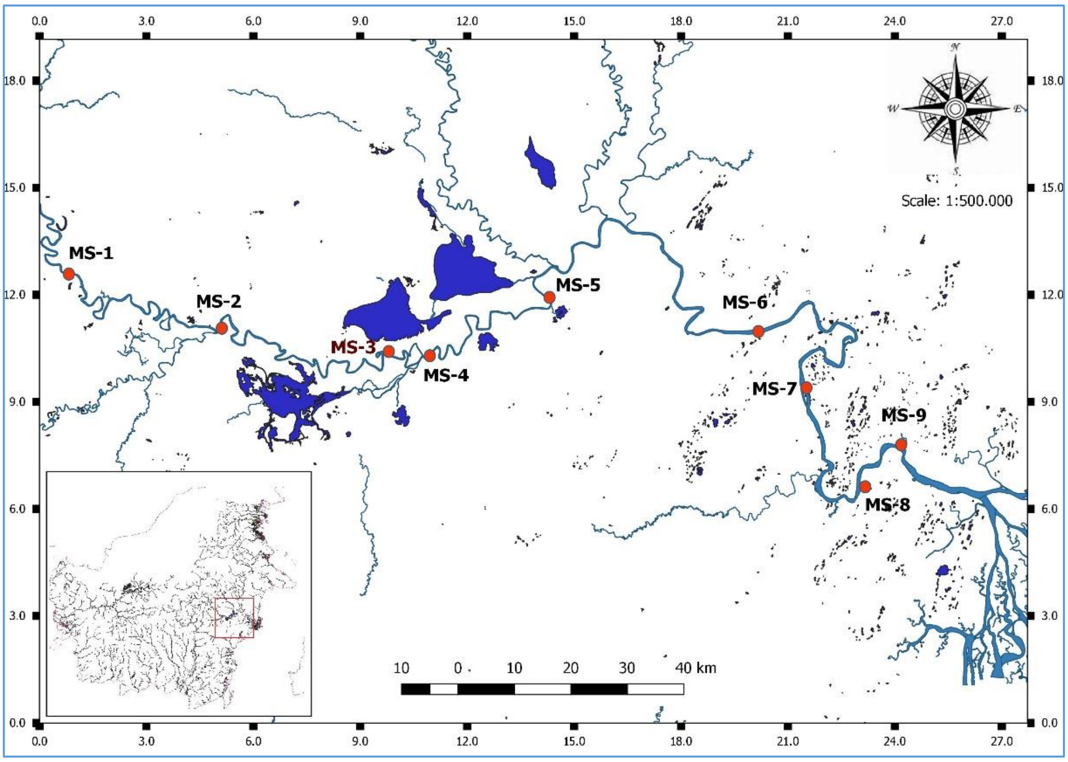

Figure 3-1: The nine water quality monitoring stations (MS) in eight sub-districts of Kalimantan Island (inset), Indonesia

3.2.2 Data collation

3.2.2.1 Water quality parameters

Water quality data were acquired from the District environmental agency (Badan Lingkungan Hidup Daerah – BLHD) and the Water Quality Management Musi and Mahakam (WQMMM) Project report issued by Indonesia-German Government Cooperation (IGGC, 1998). Water quality data were available from 1993 to 1998 and from 2010 to 2017; no data were available from 1999 to 2009. More than 30 chemical, physical and biological variables were recorded, 12 of which are used in this study to represent water quality parameters related to land use (see Table 3.1).

3.2.2.2 Land cover and land use

The land cover data were obtained from East Kalimantan Forestry Agency (DISHUT) for each district and sub-district within the Mahakam River catchment area. The land cover data from DISHUT was in GIS format extracted using the open source software QGIS v. 3.0 (https://qgis.org/en/site/). Land cover classification classes are presented in Table 3.2 following the Ministry of Environmental and Forestry (MoEF) standard. These land cover data were used to identify the land use type within the catchment for the four years when data were available: 1996, 2011, 2014 and 2017.

3.2.2.3 Historical fire event

East Kalimantan province is one of the areas in Indonesia that is prone to fire events because the region is surrounded by peat swamp forest that burns easily during the dry season. The information on fire events (1997-1998) was gathered from available literature (e.g. Dennis, 1999; Chokkalingam et al., 2005). Large fire events happened between 1983-1984 and 1997-1998 (Dennis, 1999). This information was used to explore potential long-term effects of historical land cover changes due to fire on water quality measured in the Mahakam River.

Table 3.1 List of data availability for selected water quality parameters related to land use for the period of 1993-2017 in nine monitoring sites in the Mahakam River.

Parameter	**Upper**		**Middle**	
	MS-1 (Melak)	MS-2 (Muara Pahu)	MS-3 (Batuq-Muara Muntai)	MS-4 (Muara Muntai)
Temperature (^oC)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
pH	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Electrical conductivity (EC) (µS/cm@25^oC)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Total dissolved solids (TDS) (mg/L)	1998 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Dissolved oxygen (DO) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Biological oxygen demand (BOD) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Chemical oxygen demand (COD) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Nitrite-Nitrogen (NO_2-N) (mg/L)	2010 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Nitrate-Nitrogen (NO_3-N) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Ammonium (NH_3-N) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Total phosphorus (TP) (mg/L)	1993 – 2017	2011 – 2017	2011 – 2017	2011 – 2017
Sulphate (SO_4) (mg/L)	2003 – 2017	2011 – 2017	2011 – 2017	2011 – 2017

Table 3.1 continued

Parameter	Middle		Lower		
	MS-5 (Kota Bangun)	MS-6 (MHU Ulu-Sebulu)	MS-7 (Tenggarong)	MS-8 (Kalamur -Loa Janan Ilir)	MS-9 (Kantor Gubernur-Samarinda Kota)
Temperature (^{0}C)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
pH	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Electrical conductivity (EC) (µS/cm@25^{o}C)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Total dissolved solids (TDS) (mg/L)	2011 – 2017	1997 – 2017	1998 – 2017	2010 – 2017	1998 – 2017
Dissolved oxygen (DO) (mg/L)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Biological oxygen demand (BOD) (mg/L)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Chemical oxygen demand (COD) (mg/L)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Nitrite-Nitrogen (NO_2-N) (mg/L)	2011 – 2017	2010 – 2017	2010 – 2017	2010 – 2017	2010 – 2017
Nitrate-Nitrogen (NO_3-N) (mg/L)	1993 – 2017	1997 – 2017	1993 – 2017	2010 – 2017	1993 – 2017
Ammonium (NH_3-N) (mg/L)	1993 – 2017	2003 - 2017	2003 – 2017	2010 – 2017	2003 – 2017
Total phosphorus (TP) (mg/L)	1993 – 2017	1998 – 2017	1993 – 2017	2010 – 2017	1998 – 2017
Sulphate (SO_4) (mg/L)	1993 – 2017	2003 – 2017	2003 – 2017	2010 – 2017	2003 – 2017

Table 3.2 Land cover classification using the Ministry of Environmental and Forestry (MoEF) standard.

Code	Acronym	Land cover class
2001	Hp	Primary Dry Land Forest
2002	Hs	Secondary Dry Land Forest
2004	Hmp	Primary Mangrove Forest
2005	Hrp	Primary Swamp Forest
20041	Hms	Secondary Mangrove Forest
20051	Hrs	Secondary Swamp Forest
2006	Ht	Plantation Forest
2007	B	Shrubs
2010	Pk	Estate Crop
2012	Pm	Settlement
2014	T	Barren Land
3000	S	Savanna/Grass Land
5001	A	Water
20071	Br	Shrubs Swamp
20091	Pt	Dry Land Agriculture
20092	Pc	Mixed Dry Land Agriculture
20093	Sw	Paddy field
20094	Tm	Fishpond
20121	Bdr	Airport/Port
20122	Tr	Transmigration Area
20141	Pb	Mining
50011	Rw	Swamps

3.2.3 Water quality sample collection and analytical methods

In-situ field measurements were made following the national standards for pH (SNI 06-6989.11-2004), electrical conductivity (EC) (SNI 06-6989.1-2004), temperature (SNI 06-6989.23-2005), and dissolved oxygen (DO)

(SNI 06-6989.14-2004). EC and DO were also measured on water samples in the laboratory, and these results were used for this study. To collect water quality parameters, BLHD used an Indonesia National Standard (SNI) method for surface water sampling (SNI No. 6989.57:2008) applied to the wider and deeper parts of the river. Water samples (0.1-0.5 L in polyethene bottles acid-washed where appropriate) were collected from the true left, middle and true right of the river at 5 m depth. The samples from three points were then combined into one integrated sample for each monitoring site.

Samples were kept at 4^0C to inhibit biological processes and chemical and physical reactions, prior to analysis of water quality parameters presented in Table 3.3 at a commercial water quality laboratory certified by the National Accreditation Committee and with ISO 17025:2005 accreditation. From 1993 to 1998, the information on the methods used to analyse water samples was not available. However, it can be assumed that it conformed to the Indonesia National Standard SNI 06-2421-1991 (revised and replaced with SNI No. 6989.57:2008 in 2008).

Table 3.3 The method used for the analysis of water samples in the laboratory (source BLHD, 2017).

Variables	Method for analysis	Possible source related to land use impact
Electrical conductivity (EC)	SNI 06.6989.1.2004	Open mining, agriculture, barren land
Dissolved oxygen (DO)	SNI 06.6989.14.2004	Settlement, agriculture
Total dissolved solids (TDS)	MUTU – 33304	Barren land, open mining, agriculture
Biological oxygen demand (BOD)	SNI 6989.72-2009	Related to nitrate and phosphorus concentration – agriculture, settlement
Chemical oxygen demand (COD)	SNI 6989.2-2009	Barren land, agriculture (pertaining to sediment concentration)
Nitrite (NO_2-N)	SNI 06-6989.9-2004	Agriculture, settlement wastewater, industrial (Xue et al., 2016)
Nitrate (NO_3-N)	SNI 06-2480-1991	Agriculture, settlement, industrial (Xue et al., 2016)
Ammonia (NH_3-N)	SNI 06-6989.30-2005	Agriculture, settlement wastewater, industrial (Xue et al., 2016)
Total phosphorus (TP)	SNI 06-6989.31-2005	Agriculture, settlement, wastewater (Moss, 2010)
Sulphate (SO_4)	SNI 6989.20-2009	Settlement, industry (pulp mills, textile mills), agriculture, power plant (Moss, 2010)

To classify river water quality according to its suitability for supporting aquatic biota and human uses, water quality parameter values were compared to (i) Indonesian threshold values for river water quality (first class River) based on Government Regulation (PP) No.82/2001; and (ii) the ANZECC (2000) guidelines as a comparison (Table 3.4). The ANZECC guideline was developed for Australia and New Zealand ecosystems, and therefore interpretation for Indonesian ecosystems should me made with caution. However, some values for water quality parameters such as pH, EC and TP were derived from an Australian tropical ecosystem that may represent similar conditions to those encountered in the Mahakam River. For TDS, BOD, COD and DO, an ANZECC trigger value for freshwater aquaculture species protection is used since aquaculture is also common in the Mahakam River. The trigger value for slightly disturbed ecosystems was used for NO_3-N and NH_3-N.

Table 3.4 Threshold values for river water quality. Only parameters that relate to land use impacts are shown. - = not given

Parameters	**Unit**	**Indonesia Government Regulation No.82/2001 – First Class River Category**	**ANZECC (2000)**
		Limit Value	Trigger Value (95%)
pH	-	6 - 9	6 – 8
EC	µS/cm	-	20 – 250
TDS	mg/L	1000	< 3000
DO	mg/L	6	>5
BOD	mg/L	2	< 15
COD	mg/L	10	< 40
NO_2-N	mg/L	0.06	-
NO_3-N	mg/L	10	0.7
NH_3-N	mg/L	0.5	0.9
TP	mg/L	0.2	0.01
SO_4	mg/L	400	-

3.2.4 Data processing

Water quality

Since data acquired from different sources may vary in measurement units and accuracy, procedures have been applied to ensure data consistency. First, the raw data were checked to ensure the same measurement units were used. Next, time series plots were applied to check for apparent errors by examining outliers and extremes using manual observation. Corrections were made only if the data appeared to have an incorrect decimal place; however, some data were omitted entirely if there was no satisfactory explanation to be included in the analysis. The following criteria were applied to select the datasets to include in the analysis of trends or historical comparison (past versus present):

1. Only datasets from the main river sections were included in the analysis (i.e., tributaries were excluded due to inadequate monitoring)
2. Monitoring sites had at least three sampling times in a year and more than five years of data for trend analysis, and at least two years of data for comparison of past (fire-affected) and present state
3. The parameters had more than 24 values to be included in the trend analysis, and at least ten values for the past (fire-affected) and present state analysis.

As environmental datasets often have values reported as below detection limit (“less than" values or censored data), only variables that had <50% of records censored were included in the analysis (Ganser & Hewett, 2010; Larned et al., 2016). This screening mostly affected data from the recent period 2003-2017, and provided nine monitoring sites (eight sub-districts) and 12 parameters that could be included in the analysis (see Table 3.1). Next, procedures were applied to substitute remaining censored data with specific values. One method commonly used is to substitute the value with a fraction of the detection limit, such as half the limit (McBride, 2005). However, this substitution method leads to a high bias in the analysis (Helsel, 2006; Ganser & Hewett, 2010; Larned et al., 2016). Instead, I used a β-substitution method (Ganser & Hewett, 2010) as it has less bias and is easy to apply using a standard spreadsheet. When compared to the Maximum Likelihood Estimation (MLE) and Bayesian methods, β-substitution has a similar level of bias (Ganser & Hewett, 2010; Huynh et al., 2015). To adjust each censored value, the non-censored data were used to calculate the β factor using equations in Ganser & Hewett (2010). The β factor was then multiplied by the detection limit to substitute the censored value.

Land use

The land cover (see Table 3.2) was identified for the sub-district within the river catchment boundaries where the water quality monitoring site was located. Land cover was then classified into six types of land use based on how people mainly utilised the area (Table 3.5). For analysis of the relationship of land use with the selected water quality parameters, the total area of each land use type within each sub-district catchment was measured using QGIS, and the proportion of each land use type was used to assess the relationship of land use changes with the river water quality over time.

Table 3.5 List of Land use categories used in this study

Land use type	**Abbreviation**	**Land cover**
Forest land	FOREST	• Primary and secondary forest • Plantation forest (concession forest)
Agricultural land	AGRICULTURE	• Dryland agriculture • Mixed dryland agriculture • Rice field/Paddy field
Estate crop plantation	ESTATE	• Estate crop plantation (main crops are oil palm, rubber and coconut)
Swamps	SWAMP	• Swamps • Primary and secondary swamp forest • Shrubs swamp • Shrubs
Settlement	SETTLEMENT	• Settlement • Transmigration area
Mining	MINING	• Mining
Others	OT	• Water body • Barren land

3.2.5 Statistical analysis

General statistics

Twelve parameters from nine monitoring sites (period 2010-2017) and eight parameters from five monitoring sites (period 1993-1998) included in the analysis were tested for normality using Shapiro-Wilk test, whereby if the *W* statistic is significant (p-value <0.05) then data are considered not normally distributed. The test revealed that all parameters had non-normal distributions, and therefore a non-parametric test was chosen for statistical analyses. STATISTICA v.13 was used to run the normality tests and to derive descriptive statistics (mean, median, minimum, maximum and standard deviation).

The water quality data from the Mahakam River have inconsistent variation in sampling frequency (i.e., no value for some season(s) in a year or more values in one season in a year); thus, the median value from each season was used in the calculation. Since this study does not have data on river flow, solute data are represented as concentrations rather than annual loads, meaning the analysis does not account for contaminant loads. However, it is the concentrations that are relevant to standards for aquatic life and human use (see Table 3.4). Spearman (r_s) analysis was used to quantify correlations between each water quality parameter to highlight which parameters may influence or covary with other water quality parameters.

Historical change analysis

Two data series referred to as "past" (1996-1997) and "present" (2010-2011), were used in this analysis to identify long-term differences that might be related to a major fire event in 1997-1998. Data used in this analysis came from three monitoring sites (MS-1, MS-5 and MS-6) for each period sampled in the same time/season. MS-1 (Upper reach) represented the location less affected by the fire event, while MS-5 and MS-6 (middle and lower reaches, respectively) represented the area strongly affected by the fire event. Data from MS-5 and MS-6 were combined into one impact site to compare with data from MS-1 (control site) for each period to understand the differences between locations with less fire impact and areas heavily impacted by the fire. Box-whisker plots were used to visualise the differences and spread in data between the two groups (before-after; control-impact), and the Mann-Whitney test was used to determine the significance of past versus present differences and control versus impact site differences.

Water quality trend analysis (temporal pattern)

Trends in water quality parameters within the two time periods, representing present (2010-2017) and past (1993-1998), were analysed using TimeTrend software v.6.30.2017 (http://www.jowettconsulting.co.nz, downloaded 13 April 2018). The water quality trend analysis was carried out separately for the two periods due to missing data in the intervening years. The trend analysis measured whether there were increasing or decreasing parameter values over each time period and quantified the rate of change. Untransformed (raw) data were used for the trend analyses because this nonparametric trend test is indifferent to monotonic transformation, meaning raw or transformed data analysis will have the same result (Helsel & Hirsch, 2002).

The Seasonal Kendall test was used to determine whether statistically significant temporal trends in the water quality data occurred within the two time periods, as this method is suitable for non-parametric data like surface water quality and accounts for missing values (Hirsch et al., 1982). The method also handles seasonality in the data using the Mann Kendall test approach which calculates each season separately and combines the result in the computation of overall trends (Helsel & Hirsch, 2002).

The TimeTrend software produced two sets of results: Sk (Seasonal Kendall value) and Sse (Sen slope estimator). Sk and Sse yield the standard normal statistic (Z), probability ($p<0.05$ indicates a statistically significant trend), slope and magnitude (% of change per year) of the trend. For trend detection, the null hypothesis of no trend is rejected at the significance level $\alpha=0.05$ if the Z value of the seasonal Kendall value (Zsk) is higher than the Z value from statistic normal distribution at $1-\alpha/2$ ($|Z_{sk}|>Z_{1-\alpha/2}$) (Gocic &

Trajkovic, 2013). Therefore, when Zsk > 1.96 at $\alpha = 0.05$, the null hypothesis is rejected, and there is a significant trend in the time series.

Following Vant (2013), a 1% change per year is used to distinguish between an “important” trend or “slight” trend, which is statistically significant but has a lower rate of change. Whether each trend represents an improvement or deterioration will depend on the nature of each parameter.

Water quality longitudinal analysis (spatial pattern)

The spatial pattern within the river mainstem was analysed by comparing each monitoring site using multiple comparisons for independent groups (Kruskal-Wallis test), and data were visualised using box-whisker plots. The post-hoc multiple comparison of mean-ranks test was also carried out for all groups where the test statistic (H) was significant to see which monitoring sites showed pairwise differences (Field et al., 2012; STATISTICA v.13).

Water quality correlation with land use

The correlation between water quality and land use was assessed using non-parametric Spearman correlation (r_s). Three years of water quality monitoring data were correlated with the percentage area of land use for the same period (2011, 2014 and 2017) from nine monitoring sites. The r_s value was used to infer significant ($p<0.05$) or highly significant ($p<0.01$) relationships.

3.3 Results

3.3.1 Catchment land use at monitoring sites

A summary of the proportion of land use categories within the sub-catchment of each sub-district where the monitoring site (MS) was located is presented in Figure 3.2 (see Table 3.1 as a reference for monitoring site number and name). The total catchment area for each monitoring site is given in Appendix 1. Each monitoring site is in one sub-district with the exception of MS-3 and MS-4 which are located in the same sub-district; thus, these sites used the same data for the land use categories and total area.

In general, it can be seen from Figure 3.2 that there was a change in the percentage area of different land use categories from MS-1 to MS-9 over the period 1996 to 2017. For MS-1 to MS-7, swampland dominated sub-catchment land cover on most dates, accounting for 50% to 90% of land use. MS-1 and MS-2 demonstrated a minor change in the percentage of swamps over time. In contrast, MS-3 to MS-6 showed apparent declines in one period (2011) and increases in the following year reflecting the change in land use type within the sub-catchment due to the transformation of forest land and agricultural land to swamps. MS-7 showed swampland replacing forest and agricultural land, which increased the percentage of swampland over time (nearly 75%).

MS-8 and MS-9 showed a different land use pattern to other monitoring sites. While other sites comprised vast areas of swamps that persisted to varying degrees over time, MS-8 showed a significant change in swampland. In 1996, MS-8 land use was dominated by swampland (nearly 60%), however, in the following years (2011 to 2017) it was subsequently converted into agricultural land. Meanwhile, MS-9 (Kantor Gubernur - Samarinda Kota), which is located in an urban area, does not have swampland in its sub-catchment.

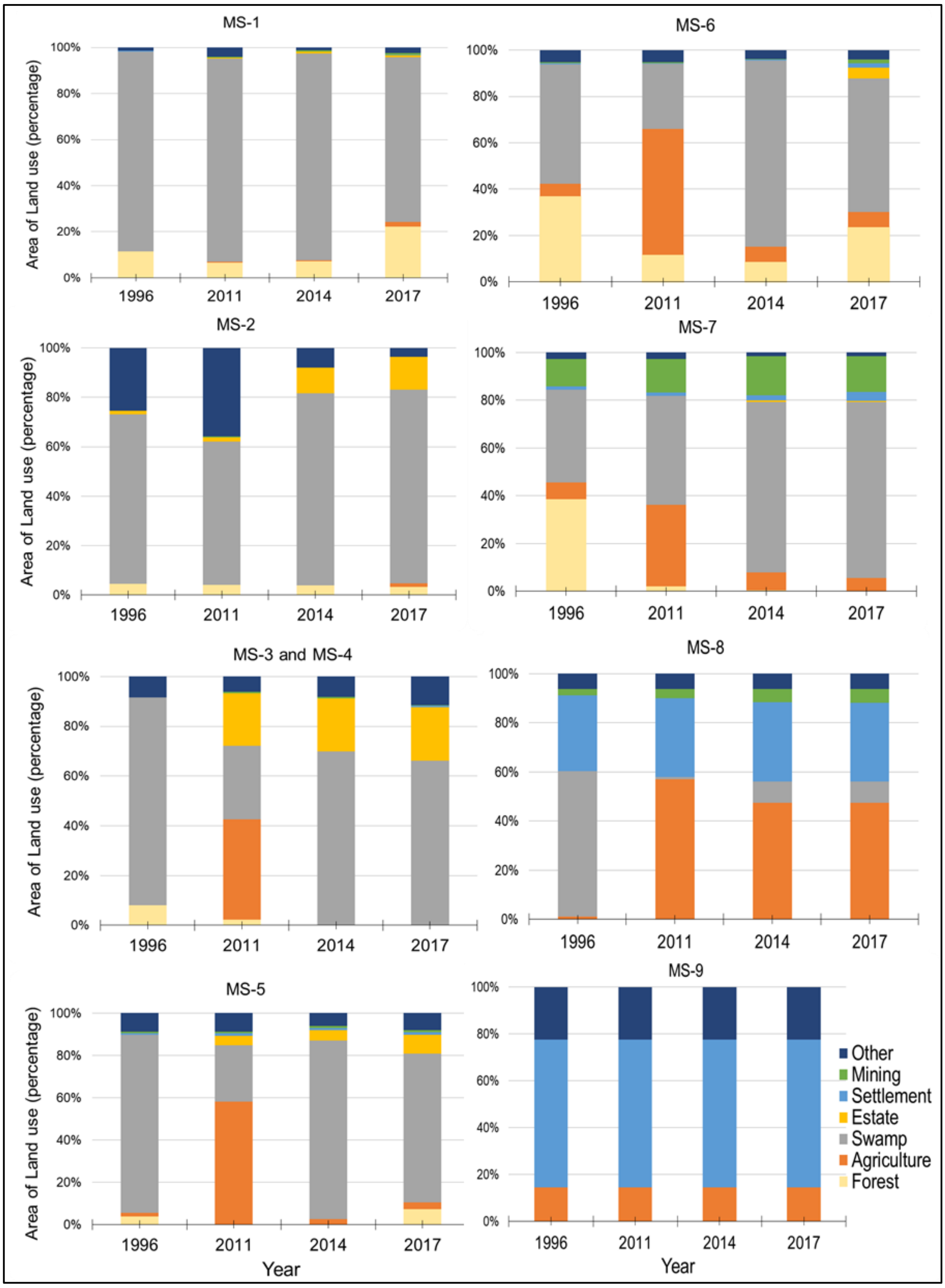

Figure 3-2: The percentage of land use categories in the catchment of each monitoring site for 1996, 2011, 2014 and 2017. The land use was derived from the land cover area within sub-districts where the monitoring site is located. Monitoring site (MS)-1: upper section; MS-2 to MS-5: middle section; MS-6 to MS-9: lower section. See Table 3.2 for details of land use categories

Agricultural land was mainly located in the downstream end of the middle section and the lower section of the catchment, with very small areas in the upper section and upstream end of the middle section's catchment (MS-1 and MS-2; Figure 3.2). MS-3 and MS-4 showed dramatic changes in 2011 when agriculture comprised around 40% of land use, before plummeting over 2014 to 2017 as agricultural land was transformed into swampland. Accordingly, MS-3 to MS-7 demonstrated a sharp decrease of agricultural land from 2011 to 2017, with some fluctuation among years occurring for MS-5 to MS-7. Within the sub-catchment of MS-8, agricultural land increased in 2011 and remained steady for the following years to become the only area with a high percentage of agriculture over time. The second sub-catchment with a steady state of agricultural land was MS-9.

The sub-catchments of water quality monitoring sites do not have primary forest land cover (undisturbed tropical forest). Rather, only secondary forest and plantation forest were present, and these were combined into one land use type to represent contemporary forest land. Forest land covered more than 10% and up to 40% at sub-catchments of MS-1 MS-6 and MS-7 on different dates, while smaller percentages were scattered in MS-2 to MS-5 (Figure 3.2). The two sub-catchments in the lower section (MS-8 and MS-9) did not have forest land over the period assessed.

In the upper section (MS-1), forest land almost doubled from 1996 to 2017 when it accounted for 257 km^2 (22% of sub-catchment area). The same pattern also occurred in MS-5 (see Appendix 1 for the total area of each land use). In contrast, MS-3, MS-4 and MS-7 experienced a steep decrease, with MS-7 alone losing more than 300 km^2 of forest land from 1996. In addition, MS-6 also showed a decreasing trend even though in 2017 it started to recover. It is clearly shown that the decreasing percentage of forest land is followed by increasing percentages of swamp, estate cropland, and or agricultural land (Figure 3.2).

Estate cropland, comprising predominantly oil palm, rubber and coconut plantations, is mainly located in the MS-2 to MS-5 sub-catchment, with recent small developments in sub-catchments of MS-1, MS-6 and MS-7 (Figure 3.2). Estate plantation in MS-3 and MS-4 comprised the second largest area after swampland from 2011 (>20%). Of the three types of plantation crop in the Mahakam River catchment, palm oil plantation often has the largest area (Kota Bangun BPS, 2017; Muara Muntai BPS, 2017; Muara Pahu BPS, 2017; East Kalimantan BPS, 2017).

Only small areas of settlement can be found within MS-1 to MS-7 sub-catchments over the time assessed (Figure 3.2). The exception is for MS-2 where no settlement was identified, even though observation during the survey indicated there were villages within this sub-catchment. These differences may be caused by the variation of satellite imagery analyses due to changes in atmospheric conditions and difficulties distinguishing villages from vegetation and agricultural land (Horning et al., 2010). The lower river section, represented by MS-8 and MS-9, is highly developed with an urban settlement which makes from 25% up to 60% of land use. The MS-9 sub-catchment has the capital of the East Kalimantan province (Samarinda), which accounts for the high percentage of urban land.

Another land use that was identified within the sub-catchment of some monitoring sites was mining (Figure 3.2). A small percentage of mining land existed in MS-1 to MS-6 and in MS-8, which showed an increasing trend over the time period assessed (<6% of the total area for each sub-catchment). The MS-7 sub-catchment had the highest percentage of mining land with minor changes over time (between 11% and 16% of area). MS-9 was the only sub-catchment that had no mining land use.

Other waterbodies (mainly other rivers and lakes) and barren land were categorised as one land use called “other”. Waterbody area was constant over time, so temporal changes were due to barren land caused by land conversion activities (Figure 3.2). MS-2 had a large area of barren land in 1996 and 2011 which then declined over time. In contrast, MS-9 had no barren land, with the land use category “other” consisting only of water.

3.3.2 General water quality in the Mahakam River

The current state of water quality in the Mahakam River was defined by twelve land-use related parameters from nine monitoring sites in the upper, middle and lower sections of the river. These parameters are water temperature, pH, EC, TDS, DO, COD, BOD, NO_2-N, NO_3-N, NH_3-N, TP and SO_4 (Table 3.6). Each parameter had more than 300 sampling times for the period 2010-2017 included in the analysis.

During this recent period, the average water temperature measured for all monitoring sites was 27.9 ^{0}C, pH averaged 6.7, TDS was 40.8 mg/L, and EC was 41.9 µS/cm. Overall, the upper, middle and lower sections of the river had average DO of 5.2 mg/L, COD at 20.8 mg/L and BOD was 6.5 mg/L. In addition, NO_3-N, NO_2-N and NH_3-N were 0.6 mg/L, 0.01 mg/L and 0.15 mg/L, respectively, on average. The concentrations of TP and SO_4 in the Mahakam River during this period was 0.03 mg/L and 2.6 mg/L, respectively (Table 3.6).

The 1993-1998 and 2010-2017 data were used to determine differences between historical and current conditions. However, the comparison was only applied for eight parameters and excluded TDS, NO_2-N, TP and SO_4 because data were not available for the 1993-1998 period. The Mann-Whitney test showed there were significant differences between past and current datasets for pH, EC, BOD, DO, NO_3-N and NH_3-N (Table 3.6 in red). pH showed high values for current data compared to historical data, while conductivity was lower. DO concentration and BOD were higher in 2010-2017, while NO_3-N and NH_3-N showed lower concentrations compared to historical data.

Table 3.6. Summary statistics of water quality parameters in the Mahakam River during 1993-1998 and 2010-2017 with a comparison of the Indonesian Government Regulations (PP.82/2001) and ANZECC (2000) 95th percentile trigger values. 80, 90 and 95%-ile values calculated using Excel are for water quality parameters measured over 2010-2017 (i.e., exceedances by 20, 10 or 5%, respectively, of measured values). Exceedances of the government limit are shown in **bold** and for ANZECC limit with an underline. - = no limit provided. ND=no data

Variable	**1993-1998**			**2010-2017**			Mann-Whitney (U) statistic	P value	**Indonesian PP.82/2001**	**ANZECC 2000**	**2010-2017**		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median			Limit value	Triger value (95%)	80th %-ile	90th %-ile	95th %-ile
Temperature (°C)	28.11	1.30	28.10	27.93	1.58	28.00	35025	0.112	±3*	-	29.18	30.1	30.67
pH	6.49	0.53	6.50	6.66	0.69	6.76	29520	<0.001	6 - 9	6 - 8	7.08	7.4	7.67
EC (µS/cm)	46.26	19.27	41.00	41.85	26.37	40.90	31029	0.012	-	20 - 250	53.3	62	73.84
TDS (mg/L)	ND	ND	ND	40.75	44.46	24.67			1000	<3000	60.77	116	173.18
DO (mg/L)	4.81	1.28	4.90	5.23	1.52	5.21	32307	0.003	6**	>5	6.60	7.19	7.70
BOD (mg/L)	4.31	3.16	3.00	6.53	5.91	4.84	28357	<0.001	2	<15	**9.75**	**14.52**	**21.0**
COD (mg/L)	20.12	8.97	19.50	20.80	16.56	16.00	31142	0.058	10	<40	**37.54**	**46.57**	**53.9**
NO_2-N (mg/L)	ND	ND	ND	0.01	0.005	0.004			0.06	-	0.01	0.01	0.01
NO_3-N (mg/L)	1.78	1.53	1.60	0.61	0.48	0.55	19958	<0.001	10	0.7	1.03	1.34	1.74
NH_3-N (mg/L)	0.43	0.42	0.29	0.15	0.32	0.07	11694	<0.001	0.5	0.9	0.15	0.26	**0.61**
Total P (mg/L)	ND	ND	ND	0.03	0.07	0.01			0.2	0.01	0.03	0.06	0.09
SO_4 (mg/L)	ND	ND	ND	2.56	3.68	0.87			400	-	4.48	10.26	13.25

*±3 from annual value ** DO value is a minimum requirement; all other values in PP.82/2001 are maximum concentration allowed for river water quality

A comparison of river water quality with the Indonesian government limits (PP.82/2001) and ANZECC (2000) 95th percentile trigger values during the periods 1993-1998 and 2010-2017 is presented in Table 3.6. The table shows that 20% of measured values for COD and BOD in the river exceeded the Indonesian government thresholds, while 10% and 5% of these values exceeded ANZECC trigger values for COD and 5% exceeded BOD trigger values. Furthermore, 20% of NO_3-N and TP values exceeded ANZECC trigger values; however, these values were within the range of the Indonesian government limits. Meanwhile, 5% of NH_3-N values exceeded the Indonesian government limit.

The inter-correlation matrix for water quality parameters showed that water temperature had positive correlations with EC, pH, SO_4 and TDS, and a strong positive correlation with EC (see Table 3.7). EC also indicated strong positive correlations with TDS, followed by BOD, TP, NO_3-N and SO_4. Furthermore, BOD had a strong correlation with COD; however, it had negative correlations with DO and TDS. pH had positive correlations with SO_4, TDS, DO, water temperature and COD, while DO had negative correlations with EC, BOD, NO_3-N, SO_4 and water temperature.

3.3.3 Pre- versus post-fire changes in water quality

Historical comparisons of water quality aimed to identify long-term differences that might be related to a major fire event in 1997-1998 by comparing recent (2010-2011; the closest date available after the event) water quality measurements with data from before the fire (1996-1997). The fire event in 1997-1998 burned a wide area of middle Mahakam River floodplain (Dennis 1999; Chokkalingam et al., 2005); thus, data used for Before-After analysis from monitoring sites MS-5 and MS-6 located within the area impacted by the fire event were compared with changes in unimpacted MS-1.

Table 3.7 Intercorrelation matrix of water quality parameters. Spearman r_s values with **bold** show significant correlations at P<0.05. Values with **bold** show highly significant correlations (P<0.001).

Variable	Temperature (°C)	pH	EC (uS/cm)	TDS (mg/L)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	TP (mg/L)
pH	**0.18**	-									
EC (uS/cm)	**0.48**	**0.15**	-								
TDS (mg/L)	**0.18**	**0.30**	**0.50**	-							
DO (mg/L)	**-0.23**	-0.03	**-0.24**	-0.07	-						
BOD (mg/L)	0.02	-0.08	**0.11**	**-0.27**	**-0.12**	-					
COD (mg/L)	0.02	**-0.25**	0.01	**-0.42**	-0.08	**0.49**	-				
NO_2-N (mg/L)	**-0.21**	-0.08	**-0.12**	**-0.13**	0.11	0.05	0.07	-			
NO_3-N (mg/L)	0.07	**-0.19**	**0.12**	**-0.19**	**-0.11**	0.05	**0.18**	**0.24**	-		
NH_3-N (mg/L)	0.08	-0.07	0.08	-0.07	-0.07	**0.11**	**0.15**	**-0.19**	-0.08	-	
TP (mg/L)	-0.01	**-0.21**	**0.12**	-0.05	-0.03	**0.21**	**0.15**	0.01	0.08	0.06	-
SO_4 (mg/L)	**0.20**	**0.39**	**0.16**	**0.32**	**-0.28**	**-0.27**	**-0.39**	-0.03	**-0.18**	**-0.27**	**-0.20**

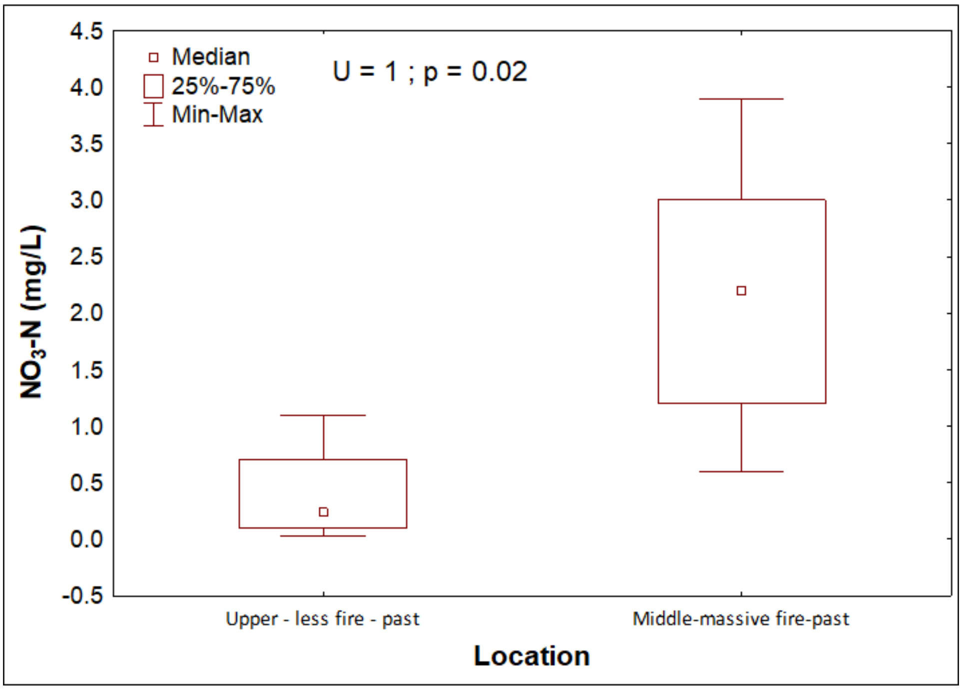

Figure 3-3: Box plot showing nitrate concentration for the upper (Unimpacted) location compared to the middle (Impacted) location using pre-fire data (past) which showed a significant difference.

The Unimpacted–Impacted site analysis found that NO_3-N was the only variable to show a significant difference between two locations before the fire event (1995 – 1997) with the middle reach having higher concentrations compared to upper reach (Figure 3.3). Meanwhile, the analysis between locations for current data indicated no significant differences (MS-1 vs MS-5 and MS-6) after fire event (2010-2011) (Table 3.8).

Table 3.8 Mann-Whitney test for Unimpacted–Impacted location comparison using current (2010 - 2011) data.

Variable	**U**	**p-value**
Temperature (^{0}C)	8.0	0.20
pH	9.0	0.26
EC (µS/cm)	16.0	0.93
DO (mg/L)	11.0	0.44
BOD (mg/L)	8.5	0.73
COD (mg/L)	10.0	0.35
NO_3-N (mg/L)	6.0	0.11
NH_3 -N (mg/L)	15.0	0.93

The Before-After analysis in the middle reach (Impacted location) showed four parameters (pH, BOD, COD and NO_3-N) had a significant difference between the past and present period (Figure 3.4 – only parameters with significant value are shown). pH was higher in the monitoring period after the fire event with a median of 6.7 compared to the value before fire event 6.1 with the same pattern also shown by COD and BOD. In contrast, the NO_3-N concentration was lower during 2010 - 2011 compared to 1996 -1997. NH_3 -N was not used in this comparison due to small number of data in 1996-1997 period (N=3), while 2010-2011 had 8 data values.

3.3.4 Trends in water quality

Historical (1993-1998) trends

For the 6-year period of 1993–1998, only eight parameters could be included in the statistical analysis, namely water temperature, pH, DO, EC, BOD, COD, NO_3-N and NH_3-N. These parameters were sampled from five monitoring sites: MS-1, MS-5, MS-6, MS-7 and MS-9. Trends over this period are presented in Table 3.8 below, and those with significant trends are described in more detail.

Water temperature showed a significant increasing trend over 1993–1998 in sites MS-6, MS-7 and MS-9 in the downstream middle and lower reaches of this river (Table 3.9; Figure 3.5). The trends for these sites showed increases between 0.4% and 0.9% per year, but these rates of change were not great enough to be considered “important”. In addition, statistically significant increasing trends of NO_3-N were observed in the three most downstream sites, as also found for water temperature (Table 3.9; Figure 3.6). These rates of change were between 3.4% and 35.6% per year, which can be categorised as an “important” deterioration over time, with MS-7 having the lowest rate of increase. Sites experiencing increasing concentrations are located in the downstream end of the monitoring reaches, suggesting this trend may be related to land use activity within the catchment prior to 1998.

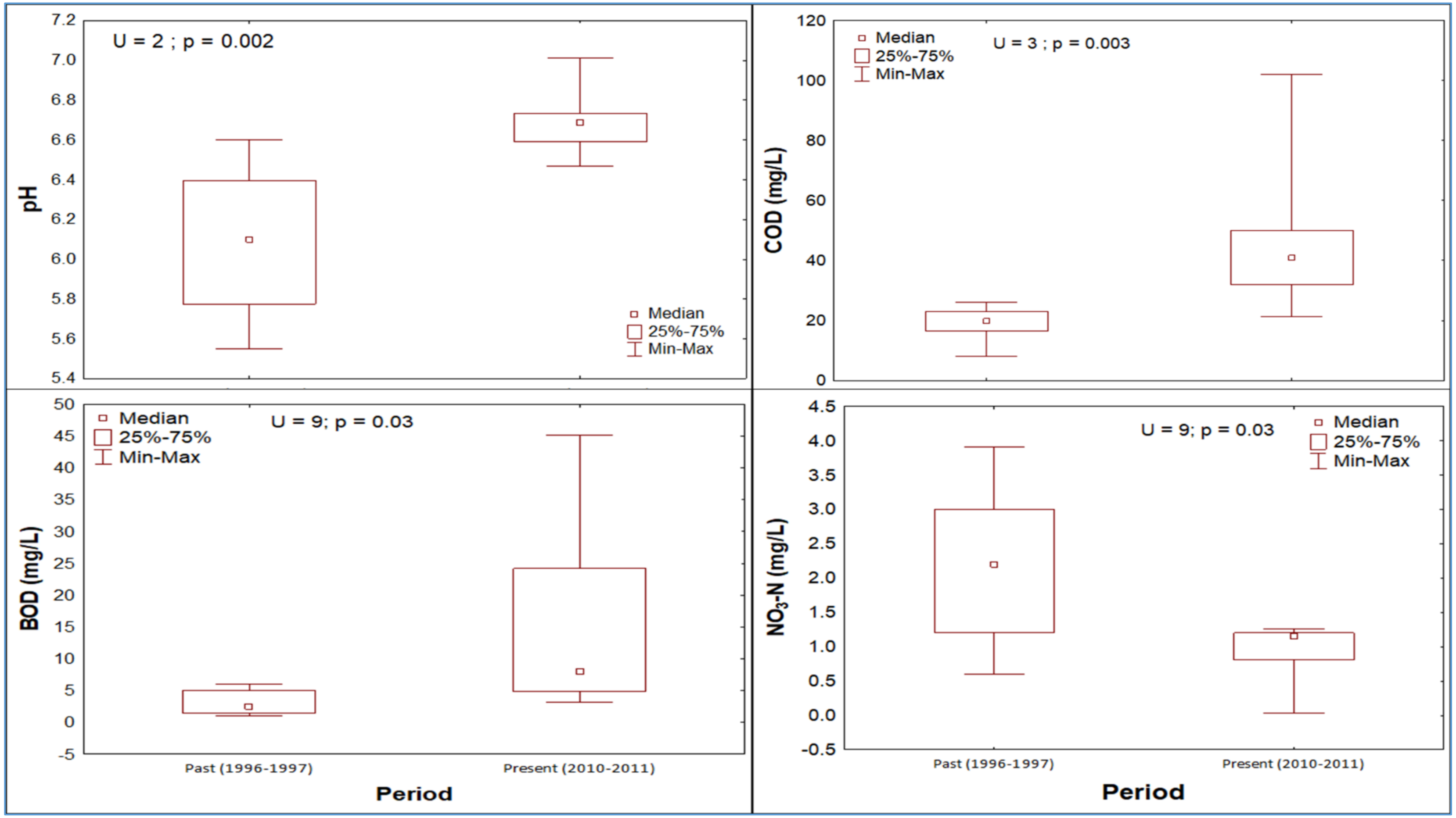

Figure 3-4: Box plots showing the water quality parameters in the middle of the Mahakam River (MS-5 and MS-6) that had significant differences before (past: 1996 - 1997) and after (present: 2010 - 2011) the fire event

Three monitoring sites indicated significant trends ($Z>1.96$; $p<0.05$) of increasing conductivity (EC), with rates of deterioration >1% per year (Table 3.9; Figure 3.7). MS-5 had the highest rate of change compared to other sites displaying trends. EC in the Mahakam River during 1993-998 had a wide range of between 2 µS/cm to 110 µS/cm. Some EC values showed an outlier in the 1996 data, which may indicate a localised event. These data were from monthly monitoring at the downstream site, and were included because it was considered unlikely to be due to an error.

Table 3.9 Seasonal Kendall test statistics (Z) (upper value) and slope (% per year) (parentheses) of statistically significant ($p<0.05$) trends at five monitoring sites (MS-1, MS-5, MS-6, MS-7, MS-9) in the Mahakam River during 1993-1998 (see Appendix 2 for further details). Values with a bold underline show an "important" improvement while "important" (>1% per year) deterioration is shown in bold with no underline; ns = not significant. (refer to Table 3.3 for variable abbreviations).

Variable	MS-1	MS-5	MS-6	MS-7	MS-9
Temperature	ns	ns	1.99 (0.47)	2.23 (0.53)	3.00 (0.90)
pH	ns	ns	ns	ns	ns
EC	ns	**1.974 (8.31)**	**2.10 (5.55)**	**2.02 (3.44)**	ns
DO	ns	ns	ns	ns	ns
COD	<u>**-2.75 (-22.63)**</u>	ns	ns	ns	ns
BOD	ns	ns	ns	ns	ns
NO_3-N	ns	ns	**2.14 (21.72)**	**4.28 (3.44)**	**5.59 (35.62)**
NH_3-N	ns	ns	ns	ns	ns

COD in MS-1 showed a decreasing trend during the period 1993-1998 with the rate of change around 22.6% per year, representing an "important" improvement (Table 3.9). The decreasing trend of COD may indicate there was a change in organic contaminants that entered the river. The slope of the COD trend can be seen in Figure 3.8. In contrast, there was no statistically significant trend in BOD at any monitoring site during 1993-1998.

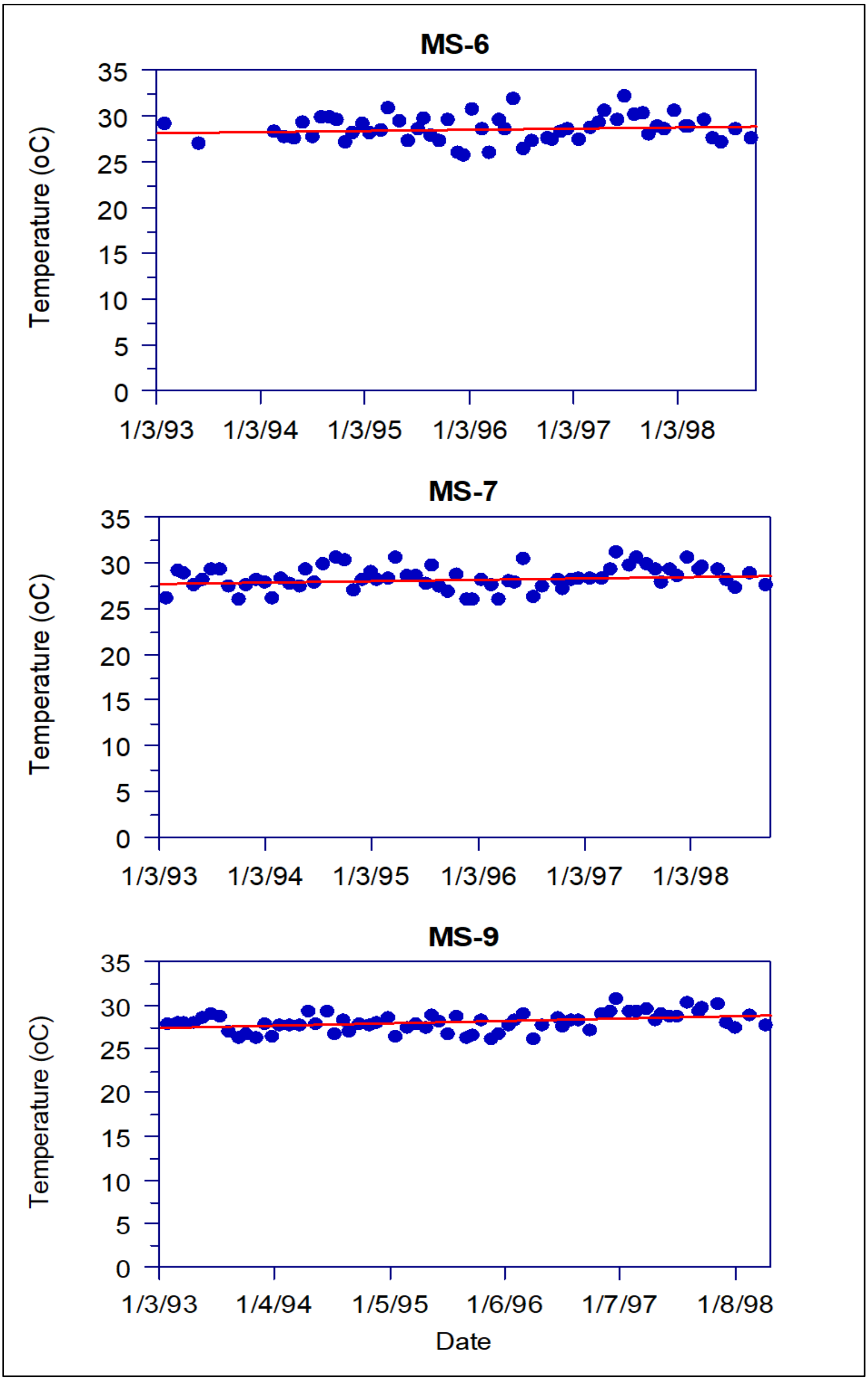

Figure 3-5: Water temperature trends in the Mahakam River for the period 1993-1998. The red line represents the overall trend (median slope) for the site

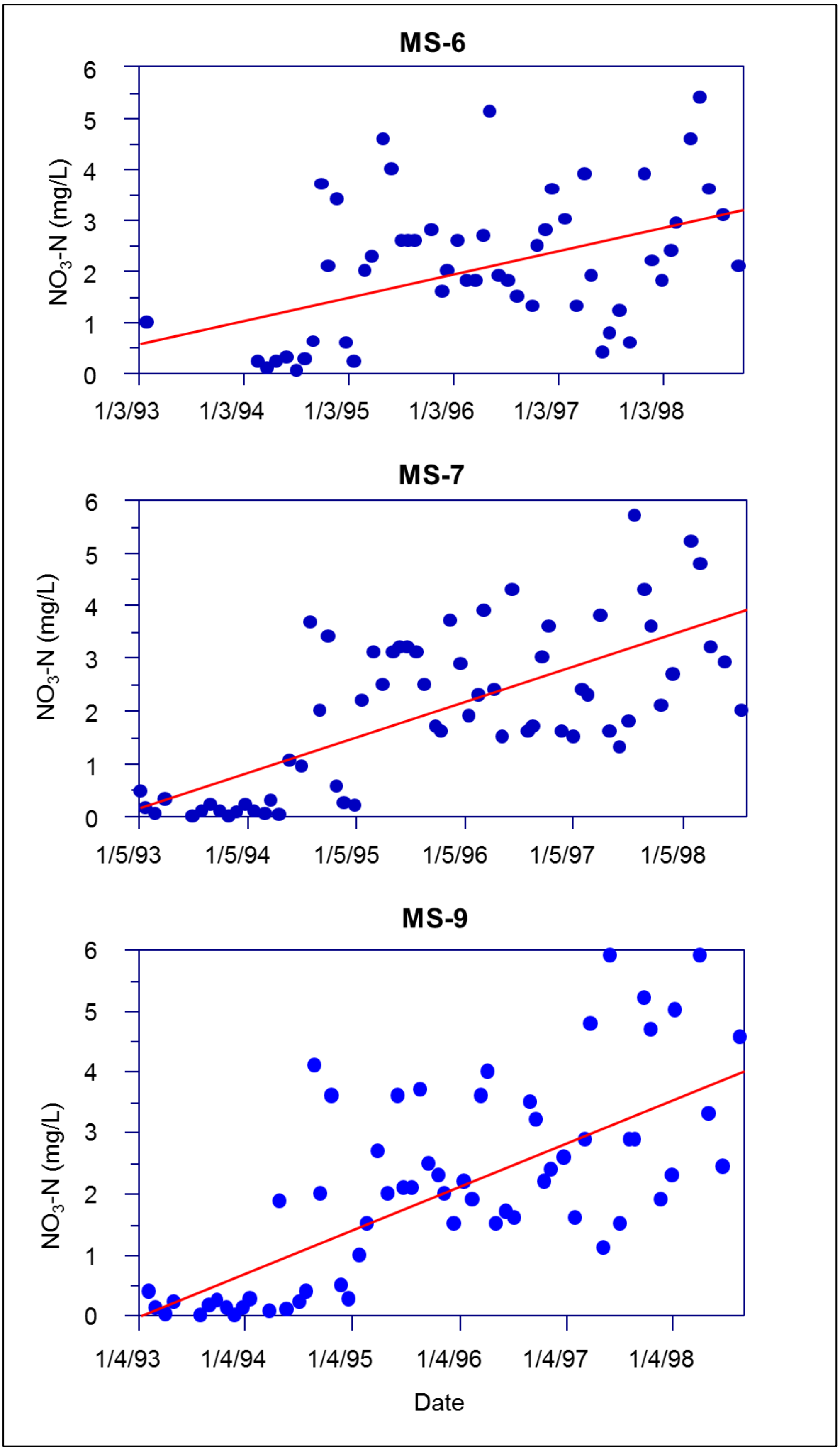

Figure 3-6: Nitrate trends in the Mahakam River for the period of 1993-1998. The red line represents the overall trend (median slope) for the site

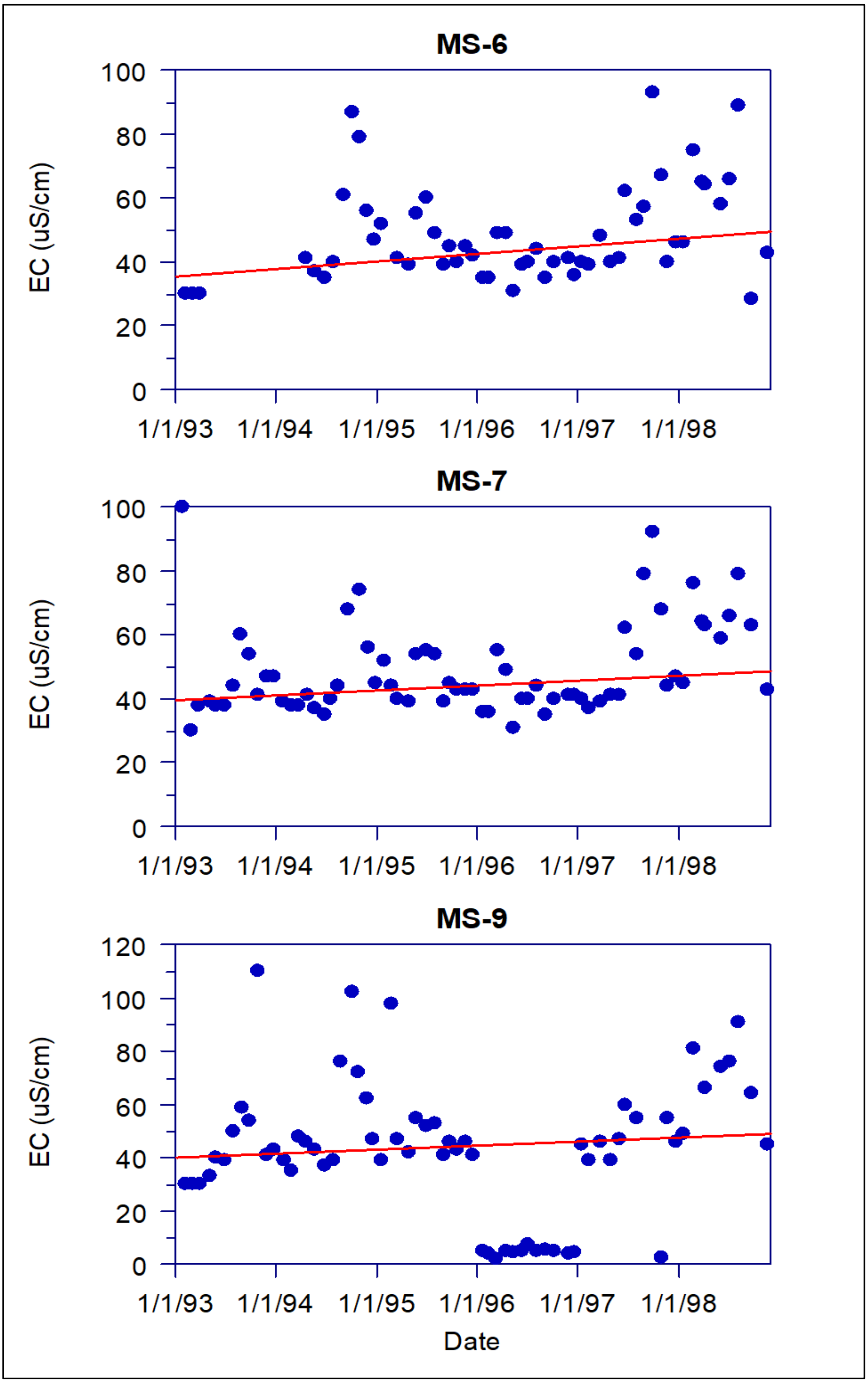

Figure 3-7: Electrical conductivity trends in the Mahakam River for the period of 1993-1998. The red line represents the overall trend (median slope) for the site

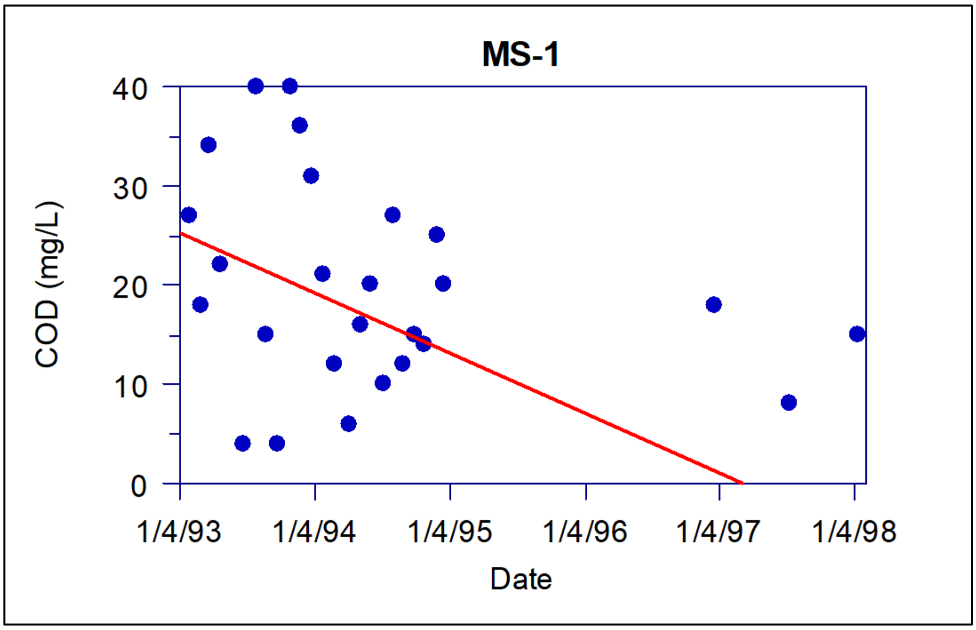

Figure 3-8: Chemical oxygen demand trend in the Mahakam River for the period of 1993-1998. The red line represents the overall trend (median slope) for the site

Current trends (2010-2017)

Twelve parameters from nine monitoring sites in the Mahakam River were used for trend analysis for the period of 2010-2017 (8 years). The results for Seasonal Kendall and Sen slope estimator statistics are presented in Table 3.10 below, and those with significant trends are described in more detail. No sites displayed significant recent trends for water temperature, pH, EC or NO_3-N.

Statistically significant increasing trends in TDS were observed for five sites (MS-1, MS-2, MS-3, MS-5 and MS-6), with a magnitude of change between 4.8% and 39.6% per year (Table 3.10; Figure 3.9). In addition, significant trends of SO_4 were observed at five monitoring sites in the Mahakam River: MS-1 to MS-5 located in the upper and middle reaches of the river (Table 3.10; Figure 3.10). All these sites showed increasing trends with the rates of change between 49.9% and 62.9% per year; thus, all these sites indicated important deterioration. The pattern in SO_4 values over 2015 to 2017 followed another more localised fire event along a tributary of the middle section of the Mahakam River (KLHK, 2017).

Table 3.10 Seasonal Kendall test statistics (Z) (upper value) and slope (% per year) (parentheses) of statistically significant ($p<0.05$) trends at nine monitoring sites (MS-1 to MS-9) in the Mahakam River during 2010-2017 (see Appendix 3 for further details). Values with a **bold** show an "important" (>1% per year) improvement while "important" deterioration is shown in **bold**; ns = not significant. (refer to Table 3.3 for variable abbreviations).

Variable	MS-1	MS-2	MS-3	MS-4	MS-5	MS-6	MS-7	MS-8	MS-9
Temperature	ns	ns	ns	ns	ns	ns	ns	ns	ns
pH	ns	ns	ns	ns	ns	ns	ns	ns	ns
EC	ns	ns	ns	ns	ns	ns	ns	ns	ns
TDS	**2.65 (7.56)**	**2.39 (4.82)**	**1.96 (6.61)**	ns	**2.88 (9.53)**	**2.39 (39.59)**	ns	ns	ns
DO	ns	ns	ns	ns	ns	ns	**-2.10 (-11.32)**	ns	ns
BOD	**-3.19 (-23.41)**	**-4.05 (-30.74)**	**-3.167 (-24.64)**	**-3.06 (-23.37)**	**-3.60 (-18.46)**	ns	ns	ns	ns
COD	**-2.58 (-21.95)**	**-4.25 (-30.59)**	**-3.41 (-38.98)**	**-3.41 (-30.44)**	**-4.11 (-41.12)**	ns	ns	ns	ns
NO_2-N	ns	ns	ns	ns	ns	ns	ns	ns	ns
NO_3-N	ns	ns	ns	ns	**-2.30 (-16.91)**	ns	ns	ns	ns
NH_3-N	ns	ns	**-2.76 (-17.33)**	ns	ns	ns	ns	ns	ns
TP	ns	**-2.10 (-53.76)**	ns	ns	**-2.47 (-12.30)**	ns	ns	ns	ns
SO_4	**2.99 (54.49)**	**3.85 (51.17)**	**3.16 (62.99)**	**3.44 (50.82)**	**2.95 (49.86)**	ns	ns	ns	ns

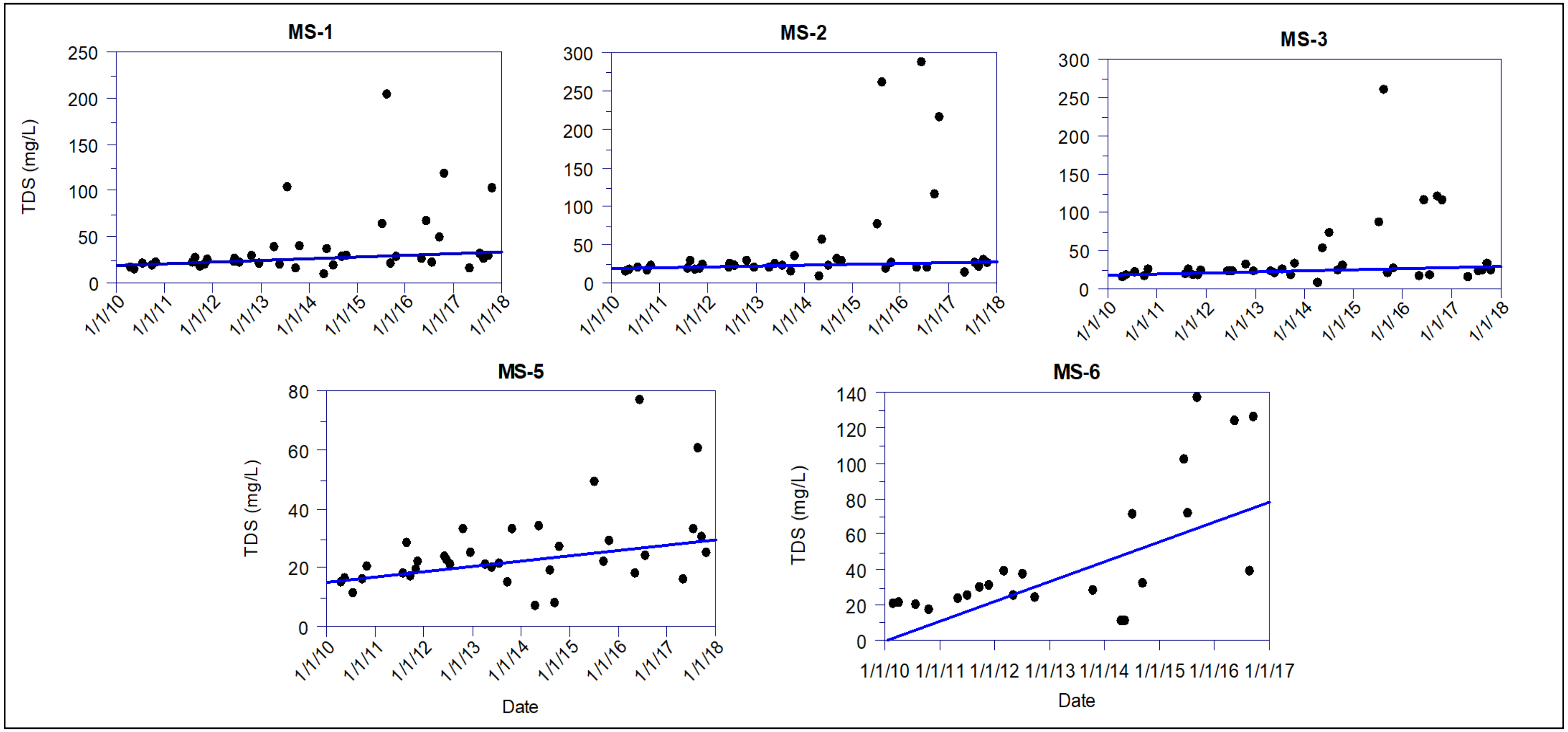

Figure 3-9: Total dissolved solids trends in the Mahakam River for the period of 2010-2017. The blue line represents the overall trend (median slope) for the sites

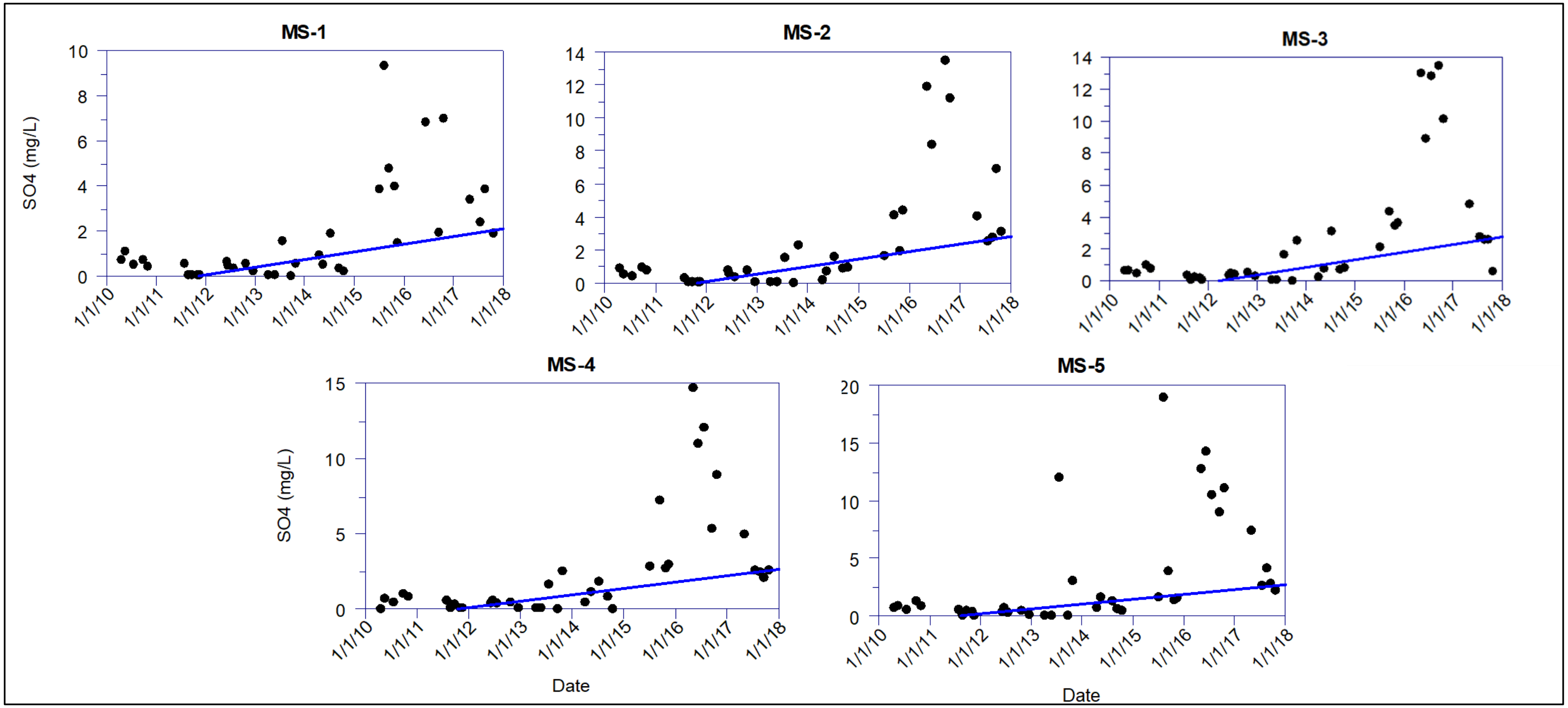

Figure 3-10: Sulphate trends in the Mahakam River for the period of 2010-2017. The blue line represents the overall trend (median slope) for the sites

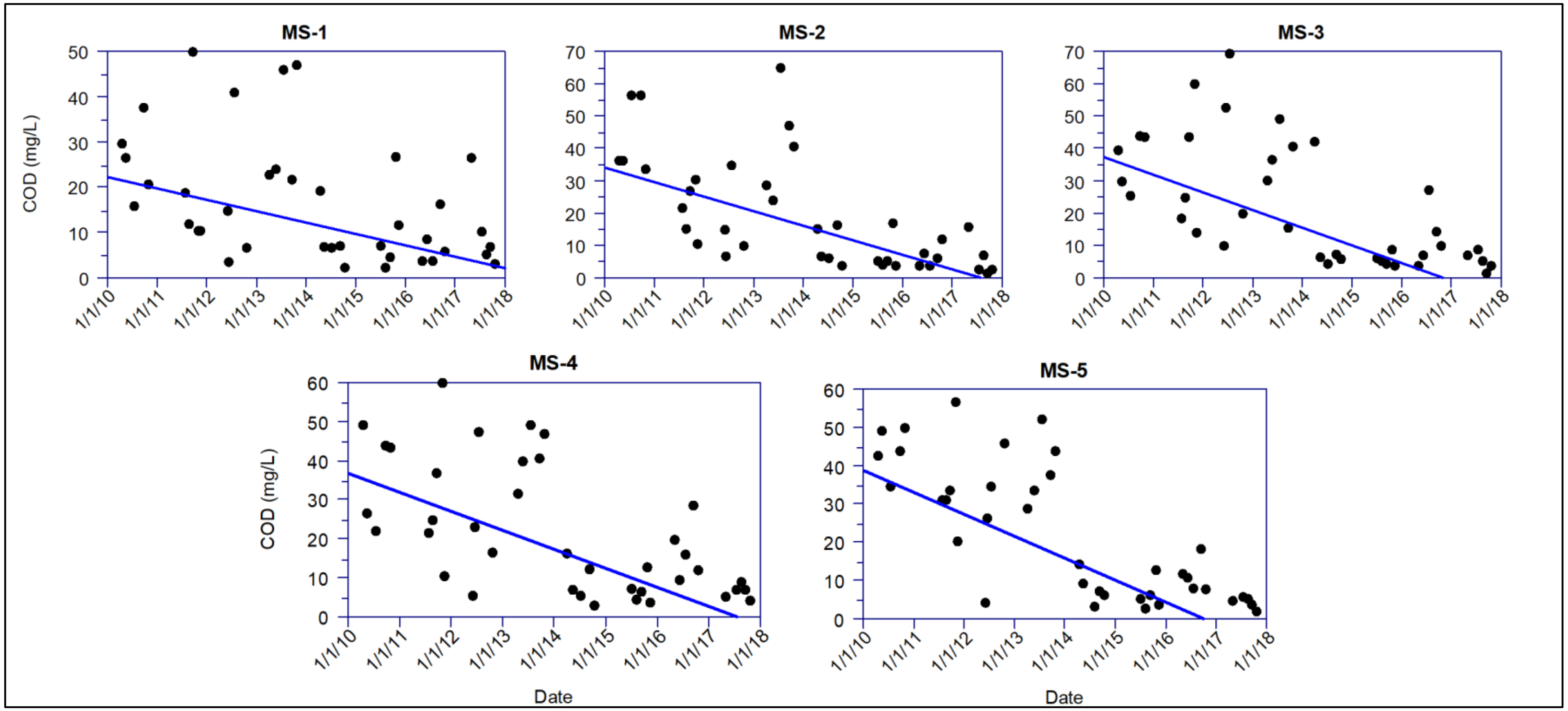

Figure 3-11: COD trends in the Mahakam River for the period of 2010-2017. The blue line represents the overall trend (median slope) for the sites.

Five upstream monitoring sites exhibited significant decreasing trends in COD while another four downstream sites indicated no significant trends (Table 3.10). Rates of change were high at between -21.9% to -41.1% per year (Figure 3.11). The decreasing trend during this period continued the decreasing trend from 1993–1998 (see Table 3.9 and Figure 3.8) for MS-1 and indicated a recent trend for MS-5. Meanwhile, BOD showed the same trend as COD during this period, at the same monitoring sites (MS-1 to MS-5) (Table 3.10). The rate of decline BOD was also high at -18.5% to -30.7% per year (Figure 3.12).

Meanwhile, only one site (MS-7) showed a significant trend in dissolved oxygen which decreased over time with the rate of change considered “important” at -11.3% per year (Table 3.10; Figure 3.13). Furthermore, MS-3 showed a significant decreasing trend for ammonia (Table 3.10), while other monitoring sites did not show any significant trend suggesting a localised influence. The rate of change was -17.3% per year, which indicated “important” improvement (Figure 3.13). Nitrate showed a decreasing trend in MS-5 and no significant trends for other sites. The rate of change at MS-5 was high at -16.9% (Table 3.10; Figure 3.13). The same decreasing trend was also exhibited by TP in two monitoring sites: MS-2 and MS-5 with the magnitude between -12.3% to -53.8% indicating an “important” improvement (Figure 3.13).

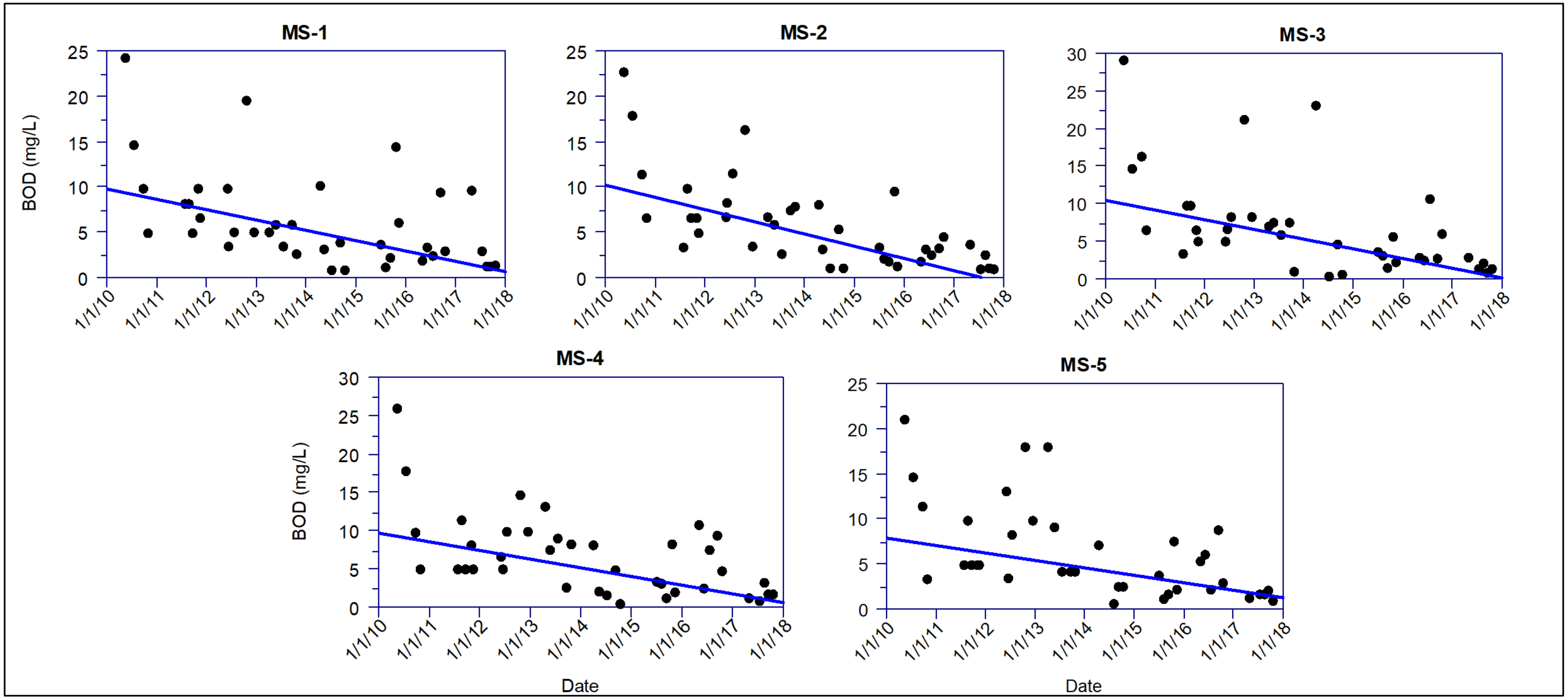

Figure 3-12: BOD trends in the Mahakam River for the period of 2010-2017. The blue line represents the overall trend (median slope) for the sites

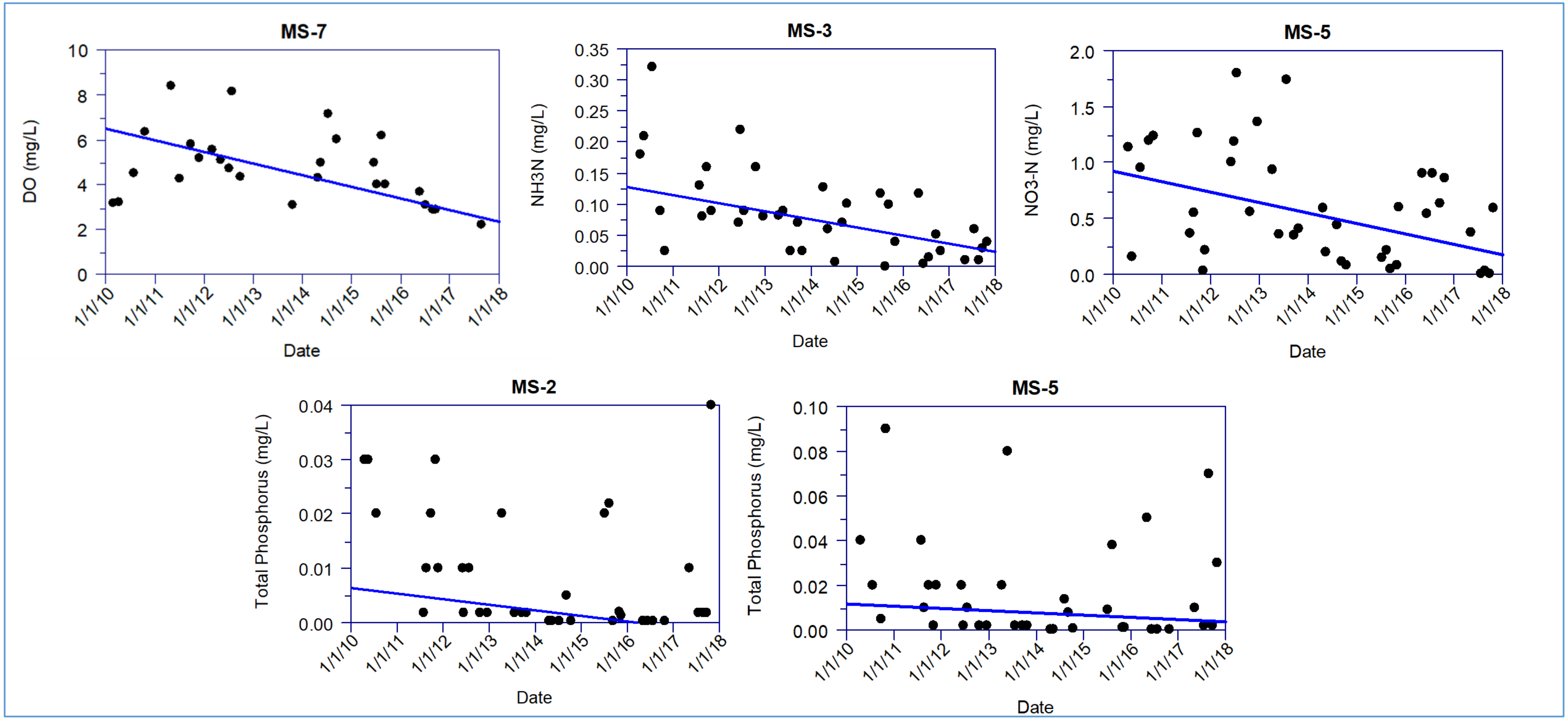

Figure 3-13: Dissolved oxygen, ammonia, nitrate and total phosphorus trends for the period of 2010-2017. The blue line represents the overall trend (median slope) for the sites

3.3.5 Spatial patterns in water quality

Historical (1993-1998) spatial patterns

The spatial pattern for historical data was analysed using Kruskal-Wallis test and illustrated in box-whisker plots (see Figure 3.14; only parameters with significant differences are shown). There were no significant differences between monitoring sites for NH_3-N, COD, BOD or pH. However, there were significant site differences for water temperature, EC, DO and NO_3-N.

Pairwise post-hoc comparisons indicated the water temperature effect was attributable to differences between MS-1, MS-6 and MS-7 over 1993-1998 (Figure 3.14). This result indicates that the upper river reach represented by MS-1 had lower median temperature compared to the lower river reach over 1993-1998. In addition, the post-hoc test showed that four sites had a significantly different median concentration for dissolved oxygen in the Mahakam River: MS-1, MS-6, MS-7 and Ms-9 (Figure 3.14). These sites represent the upper (MS-1) and the lower (MS-6, MS-7 and MS-9) reaches of the Mahakam River. MS-1 had a higher concentration of DO, while MS-6 to MS-9 had lower DO concentrations and a much higher range.

Differences between monitoring sites for EC values revealed that MS-5 was significantly different to MS-6 and MS-7 due to higher EC at the downstream end of the middle reach than the upstream end of the lower reach (Figure 3.14). The spatial pattern of NO_3-N in the Mahakam River over 1993-1998 showed increasing concentration from the upper reach to lower reach of the river, with a significant difference between MS-1 and MS-5 compared to downstream sites (Figure 3.14). This result followed the pattern of DO with the highest median value of NO_3-N found in MS-6, and the lowest median value is in MS-1.

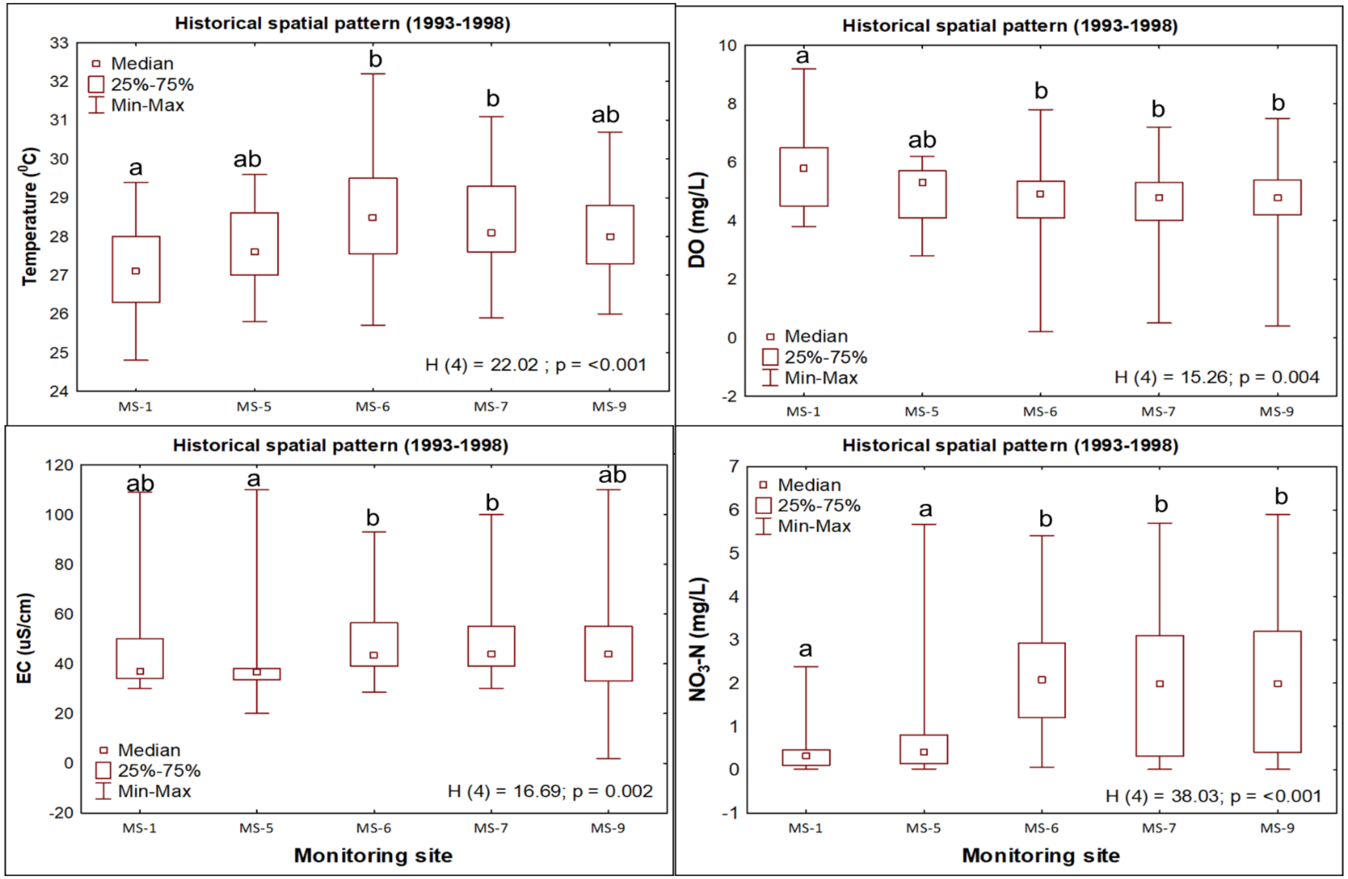

Figure 3-14: Box-whisker plots showing water quality parameters displaying significant spatial patterns during 1993-1998. Only the parameters with significantly different values are shown. Boxes with the same letter above are not significantly different following the multiple post-hoc comparison

Current (2010-2017) spatial patterns

There was no significant difference for COD, BOD, NO_2-N, NO_3-N, TP, SO_4, and NH_3-N between monitoring sites in the Mahakam River, indicating those parameters did not vary spatially along the river over the recent time period. However, significant spatial differences were evident for water temperature, TDS, pH and EC, although post-hoc tests indicated no pairwise differences between monitoring sites for pH (Figure 3.15).

The post-hoc test showed significantly lower temperature at the upper sites MS-1 and MS-2 than sites downstream from MS-5 (Figure 3.15). Significant differences in EC values between sites were observed at MS-2 and MS-8 where median conductivity was higher (Figure 3.15). Variation in EC was markedly lower from MS-6 downstream compared to most upstream sites during 2010-2017. TDS was significantly lower at MS-4 and MS-5 compared to MS-8, while other sites were not different from those three sites (Figure 3.15).

3.3.6 Land use and water quality correlation

The Spearman correlations showed that each land use type was correlated with at least one water quality parameter, with the exception of mining which was not correlated with any measured water quality parameter (Table 3.11). Forest land was negatively correlated with TP, while agricultural land correlated positively with water temperature, COD, NO_3-N and NH_3-N. In contrast, swampland showed a negative correlation with water temperature, COD, NO_3-N, NH_3-N and TP, while estate cropland also had a negative correlation with water temperature, COD and NH_3-N (Table 3.11). Furthermore, settlement was only correlated with two water quality parameters, namely NO_2-N and TP which both showed positive associations. This result indicates that land use types within the catchment could have different influences on the water quality in the river.

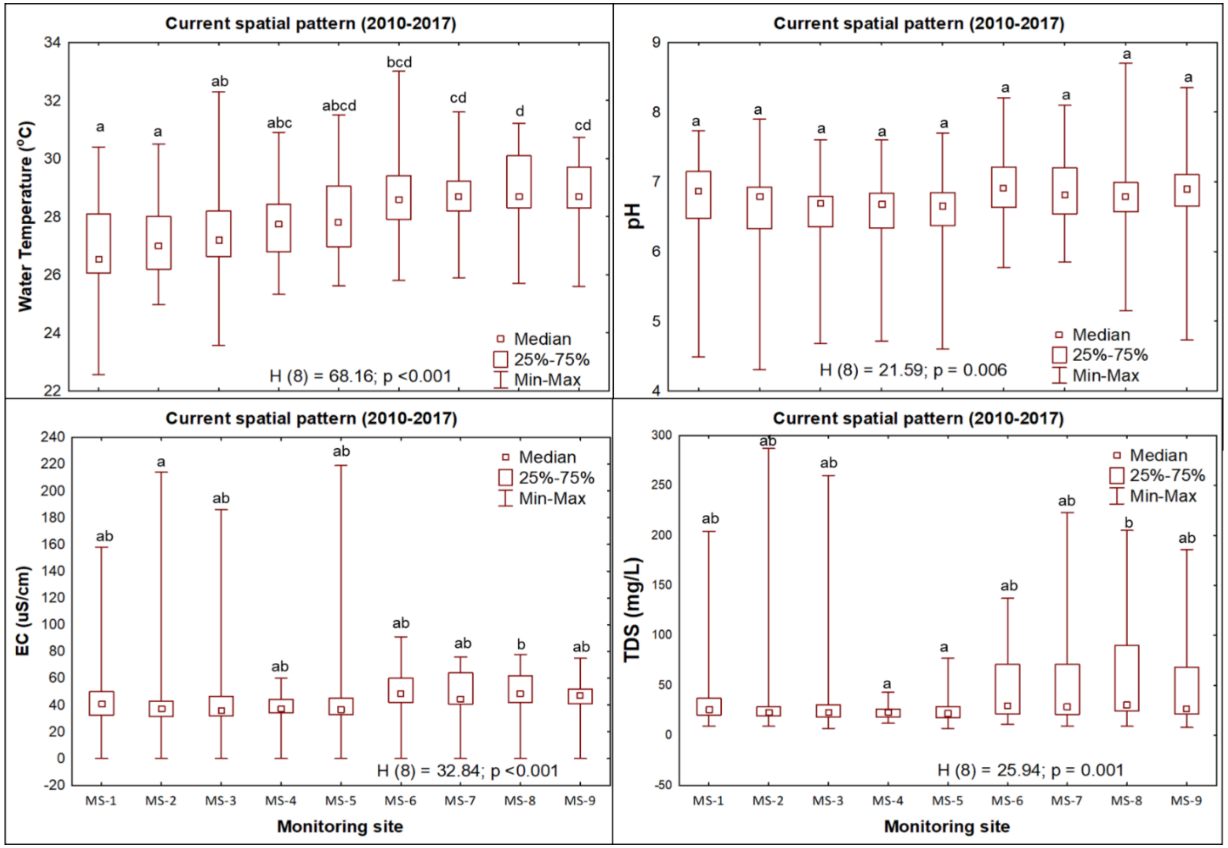

Figure 3-15: Box-whisker plots showing water quality parameters displaying significant spatial pattern during 2010-2107. Only the parameters with significantly different values are shown. Boxes with the same letter above are not significantly different following the multiple post-hoc comparison

Table 3.11 Spearman (r_s) correlation coefficients between land use type (% area) with water quality parameters. The significant results ($p<0.05$) are shown in **bold** and highly significant results ($p<0.01$) are shown in **bold.**

Variable	Land use type					
	FOREST	AGRICULTURE	SWAMP	ESTATE CROP	SETTLEMENT	MINING
Temperature	-0.07	**0.52**	**-0.57**	**-0.51**	0.34	0.24
pH	0.25	0.18	0.15	-0.26	0.18	0.18
EC	0.14	0.33	-0.17	-0.10	0.15	0.18
TDS	-0.08	-0.28	0.25	-0.24	0.31	0.27
DO	-0.14	-0.33	0.07	0.03	-0.08	-0.20
BOD	-0.10	0.26	-0.21	-0.17	-0.16	0.17
COD	-0.17	**0.43**	**-0.56**	**-0.40**	-0.06	-0.03
NO_2-N	-0.10	-0.17	0.10	-0.38	**0.43**	0.12
NO_3-N	-0.21	**0.43**	**-0.55**	-0.33	0.03	-0.11
NH_3-N	0.14	**0.42**	**-0.42**	**-0.55**	0.21	0.16
TP	**-0.46**	0.23	**-0.60**	-0.37	**0.53**	-0.17
SO_4	0.05	-0.38	0.38	0.13	0.15	-0.05

3.4 Discussion

This chapter focuses on the relationship between land use change and the water quality in the Mahakam River. Two different time periods (historical and current) were assessed and compared in terms of water quality patterns in response to land use change. The analysis was divided into two-time periods due to a large gap in water quality monitoring data over 12 years. The current period (2010-2017) was the most complete as a consistent water quality monitoring regime was in place, which enabled the exploration of inter-relationships among water quality variables and with land use. The results illustrated that physicochemical parameters of the river were related to land use change in the river catchment. This relationship could be used to determine the extent of river degradation caused by human activities and potential impacts on organisms living in the Mahakam River.

Tropical rivers in Southeast Asia have higher concentrations of the nutrients nitrogen and phosphorus during inundation periods due to erosion and inputs from floodplain areas, while pH and nutrients tend to be low when not flooding (Dudgeon, 1992). The current state of the Mahakam River may be typical of tropical Asian rivers with the warmer temperature (>25^{0}C), slightly acid pH (<6.5) and high concentration of nutrients compared to ANZECC trigger values, although seasonal changes attributable to monsoonal fluctuations were not explicitly analysed.

3.4.1 The effect of fire on water quality

The fire event effects on the Mahakam River were explored using water quality data from pre- and post-fire event monitoring. However, due to a gap in data monitoring, only the long-term impact could be explored for one large scale fire event. De Jong et al. (2015) found the water quality in the Middle Mahakam Lake in 1998 was in poor condition reflecting high nutrient concentrations, low pH, high TDS and high COD that may have been caused by the high amount of organic substances that entered the river system as the result of a recent fire event. My water quality comparison between pre- and post-fire event indicated increased levels of COD, BOD and pH, and decreasing NO_3-N concentration in the location exposed to massive fire in 1997-1998 twelve years after the event. However, the change over this period could also be attributable to a range of other factors factors with no evidence of enduring impacts from fire-related contaminants on the river. Indeed, Hope et al. (2005) indicated that by 2005 the burned area in the middle Mahakam had already recovered from the last fire event, with successional vegetation having already re-established. The increased concentrations of SO_4 after a localised tributary fire in 2015 also occurred in unaffected upstream areas, suggesting this was not a result of burning (discussed further below). Collectively, these results of historical and current data at locations impacted and unimpacted by a large fire event 12 years ago do not suggest any long-term impact on water quality in the Mahakam River.

3.4.2 Spatial patterns of land use and water quality

Generally, the land use within sub-catchments of the nine monitoring sites in the Mahakam River was dominated by swampland, estate cropland and agriculture, with increasing percentages of agriculture and urban land in downstream sections reflecting the intensification of human development (Wang et al., 2014). Land use in the upper section (MS-1) had less urban development and was dominated by contemporary forest land (secondary forest + plantation forest) as the major land use type after swampland, but further downstream towards MS-9 land use was dominated by settlement and agricultural land. Variations in land use type in catchments may influence the loadings of sediment, nutrients and organic matter into the river through disturbances to surface runoff and groundwater discharge (Allan et al., 2004; Thorp et al., 2006; Lee et al., 2009; Tu, 2011).

In relation to the land use spatial pattern, this study found that some water quality parameters in the Mahakam River varied downstream in both historical and current periods. The historical data illustrated the spatial variation for water temperature, DO, EC and NO_3-N, while in the current period the same pattern was also exhibited by water temperature and EC with the addition TDS. Water temperature, EC, TDS and NO_3-N increased from upper to lower reaches, while DO showed a decreasing pattern in a downstream direction. For some parameters, such spatial variability can reflect changing land use type within the catchment, as well as flow regime and river geomorphology (Edwards, 1995; Poole & Berman, 2001; Zhao et al., 2015). The variation from upstream to downstream could be in response to different pollution sources in the catchment, whereby forested land has low levels of pollution while urban settlements add more pollution through discharges to the river (Zhou et al., 2016).

The increasing water temperature downstream in the Mahakam River may be partly explained as a response to the river morphology. Downstream sections of the Mahakam River are wider with open water and less vegetation, allowing light to penetrate the water and increase the temperature (Brown & Krygier, 1970; Poole & Berman, 2001; Thorp et al., 2006). Such morphological effects may be exacerbated by land use influences, with agriculture and settlements dominating downstream sections. These land uses are associated with reduced the vegetation cover and soil stability resulting in increased deposition of sediment into the river. This process would change the river structure and influence the heat exchange in the river (Poole & Berman, 2001; Zhao et al., 2015). Although water temperature showed only a slight increase in the lower reach (upper reach mean temperature for historical and current period was 27.2 ^{0}C and 26.9 ^{0}C, respectively), such increases can impact on species and life stages sensitive to temperature variations as well as affecting instream processes such as microbial activity (Kaushal et al., 2010).

My study suggested a range of interacting factors affecting overall water quality. For example, DO showed a negative correlation with temperature, partly due to warmer water having lower capacity to hold DO than cooler water, which in turns may also affect aquatic organisms (Horne & Goldman, 1994). DO concentration in the water can also be influenced by the process of respiration, the input of organic matter to the river, and the organic compound loads into the river (Horne & Goldman, 1994). Anthropogenic contributions to the organic load can be attributed to agricultural and settlement land uses, primarily in the river downstream, while the upstream may be influenced by oxygen demand in the swamp forest. Since the Mahakam River is surrounded by peat swamp forest, particularly in the upper and middle reaches, detritus and dissolved organic matter from the swamp may enter the mainstem of the river and influence DO concentration due to accelerated biological processes.

EC showed a positive correlation with NO_3-N and had the same spatial pattern, suggesting that both parameters were influenced by the same factor(s), although the current period did not show a spatial pattern for NO_3-N. The differences of EC and NO_3-N values in the upper reach compared with the lower reach presumably reflect human activities in the catchment such as agriculture and urban development (Wang et al., 2014; Morrison et al., 2001; Daniel et al., 2002). The most highly developed settlement area was located downstream with no sewerage treatment plant and direct discharges of raw sewage to the river, which in turns would be expected to influence EC values due to the increase dissolved ions. This process may explain the spatial variation of EC between upper and lower reaches, as found in other studies (e.g. Morrison et al., 2001; Daniel et al., 2002).

Spatial variation of NO_3-N along the river course could also partly be in response to the increasing percentage of agricultural land in the downstream section of the river. Agricultural land in the catchment was mainly in rice paddy fields, secondary crops (legumes, corns and sweet potatoes) and vegetables, which may need additional fertiliser for productivity, which in turn leads to increased nutrient runoff to the river (Par & Mason, 2003; Larned et al., 2016). In the Mahakam River, estate cropland may also contribute to the increasing concentration of NO_3-N due to fertiliser used to increase productivity, particularly in the oil palm plantation. In addition, human settlement along the Mahakam River is mainly on the riverbank with sewage from domestic activities discharged directly to the river, leading to increases of NO_3-N (Simeonov et al., 2003), which may trigger high productivity of algae that decrease DO concentration and affect river biota.

Tributaries entering the middle and lower reaches may add to these nutrients in the mainstem of the river, which were indicated by lower nitrogen concentrations in the monitoring site above tributaries (MS-5) compared to the concentrations in the monitoring site (MS-6) below tributaries. However, the magnitude of such influences could not be quantified because the study did not measure tributary inflow discharges.

TDS concentration also increased downstream and was positively related water temperature, EC, and NO_3-N, suggesting it may be influenced by similar factors (i.e. agricultural and settlement land use, with the possible addition a small area of mining and cropland). Yu et al. (2016) concluded that high concentrations of TDS indicate soil erosion problems in the catchment.

From all variables that showed a longitudinal spatial pattern in the historical period, DO and NO_3-N might have caused some problems for aquatic biota due to marked differences between upper and lower reaches where levels exceeded values that may compromise species survival. Mean NO_3-N in the lower reach exceeded the ANZECC trigger value for 95% species protection for NO_3-N (0.7 mg/L) and was below the suggested value for DO (>5 mg/L), while the upper reach was within the acceptable range. Such spatial variability of water quality may have significant impacts on the distribution and abundance of species sensitive to water quality gradients (Horne & Goldman, 1994; MacKinnon et al., 2013).

3.4.3 Temporal patterns of land use and water quality

The land use within the catchment of the monitoring sites showed a changing pattern over time, most evident in swampland which occupied a vast area of the catchment. From 1996 to 2017, the swampland percentage of land cover decreased up to 3%. According to MacKinnon et al. (2013), in 1981 East Kalimantan was dominated by freshwater swamps and peat swamps with a total area 7,890 km^2, which had decreased from an original area of 11,700 km^2. MacKinnon et al. (2013) suggested that the cause of decreasing swampland was due to extensive human influences such as the development of agriculture, settlements, estate plantations, aquaculture activities and mining. The current result suggests the same pattern whereby the changing swampland area was followed by the changing areas of estate cropland, agricultural land, settlement and mining.

In 2017, the estate cropland increased up to 10% from total area in 1996, which resulted from the conversion of swampland and forestland. The increasing estate cropland in the catchments of monitoring sites may relate to the growing palm oil industry in Indonesia (Lee et al., 2014) since the majority of estate cropland is oil palm plantation, followed by rubber and coconuts. The forest land conversion to estate cropland particularly happened after logging and fire events (Fitzherbert et al., 2008; Lee et al., 2014). To convert the swampland into agricultural land (including fish ponds) or estate cropland, local people used slash and burn methods for clearing (Chokkalingam et al., 2005) which may generate runoff of sediment and combustion by-products.

The increased settlement, agricultural and estate cropland development over time may have resulted from a government program in 2007 to increase agriculture and cropland production, and the designation of East Kalimantan province as part of a transmigration program since 2007 (DJPKTL, 2016). The land use changes in the catchment over time likely contributed to the observed temporal trends of some water quality parameters in the Mahakam River.

In contrast, COD concentrations continued to improve from the historical to current period, particularly in the upper reach where the high percentage of forest land may reduce the inputs of nutrients to the river (Mainali & Chang, 2018). The vegetation in the forest would be able uptake nutrients from the soil and water, which coupled with soil denitrification processes, would reduce the nutrient release to the water (Peterjohn & Correll, 1984). The increasing percentage of forest land in places may be due the new establishment of plantation forest, mainly of wattle – *Acacia*, silk trees – *Albizia chinensis*, beechwood – *Gmelina arborea,* and gum trees – *Eucalyptus*, on barren land and swamp land. The improvement of BOD at the same location for the current period could be attributable to the same factors described above.

The improving trend of COD and BOD over time can also be partly attributed to the implementation of water quality standard regulations in 2001, with subsequent close monitoring of river water quality. Nevertheless, COD and BOD for the period of 2010-2017 still exceeded the Indonesian government threshold (2001) and ANZECC (2000) trigger values (refer to Table 3.6), whereas other measured parameters were within acceptable ranges. High COD and BOD can also reflect high organic load discharged to the river caused by high human activities within the catchment and the decomposition processes from surrounding swampland. For example, some studies have shown that mining, industry, urban and agricultural land uses can be responsible for increasing COD and BOD (e.g. Par & Mason, 2003; Chang, 2008; Xu et al., 2012; Shi et al., 2017). The high COD and BOD values for the current period suggest that current river management needs to improve to reduce oxygen demand below the regulation thresholds.

Meanwhile, in the current period, TDS concentrations over time exhibited an increasing trend. Soil erosion has been reported by a government agency (BPDAS) as one of the problems in the Mahakam River catchment, which may be related to the conversion of land use along the river (BPDAS, 2014). The increasing area of estate cropland over time, mainly oil palm plantation, may explain the increasing trend of TDS, which is consistent with the findings of Carlson et al. (2014) who indicated high yield sediment transported into the river by oil palm plantations. In contrast, the improvement of NO_3-N, NH_3-N, TP and DO at some monitoring sites but not others over recent years may indicate localised changes, however, the reasons for improvements only occurring in particular areas remain unclear.

Yu et al. (2016) asserted that soil condition in the catchment and input from industry and domestic sewage might affect the concentration of SO_4 in the river. In the Mahakam River, the concentration of SO_4 was more likely related to the vast area of swampland and agricultural runoff. The fertiliser used for agriculture to increase productivity can contain SO_4 that may increase SO_4 concentration in the river due to excess amount on the soil transported to the river from runoff. The area of swampland may also be related to decreasing of SO_4 through decomposition of organic material, which in return reduces the SO_4 through conversion into sulphur (Horne & Goldman, 1994).

3.4.4 Relationship between land use and water quality

Generally, as previously discussed, changes in land use types may correlate with spatial patterns and temporal trends of water quality. In the Mahakam River, current patterns (2010-2017) in water temperature, COD, NO_2-N, NO_3-N, NH_3-N and TP at monitoring sites were significantly correlated with the extent of forest, agricultural, estate crop, swamp or settlement land uses within monitoring site sub-catchments. Each land use type was related to more than one parameter, except for forest land which was only correlated with TP, as also found by Yu et al. (2016) in the Wei River Basin, China. TP mostly enters the river system through soil erosion (Horne & Goldman, 1994; Moss, 2010), and the negative correlation between TP and forest land use suggests that forest can control phosphorus discharged to the river through this process.

Swampland had a negative correlation with five water quality parameters (water temperature, COD, NO_2-N, NO_3-N, NH_3-N and TP), suggesting it may play an important role in reducing inputs of both nitrogen and phosphorus in the water. The possible reason may due to the ability of swampland to remove nitrate through submerged plant growth and denitrification processes, as well as filtering sediment and other nutrients (Moss, 2010). Denitrification in swamplands is mediated by bacteria under anaerobic conditions that convert NO_3-N into NO_2-N and also produces N_2 gas (Horne & Goldman, 1994).

In contrast to swampland, the extent of agricultural land showed a positive correlation with water temperature and COD, as well as NO_3-N and NH_3-N, which may implicate agriculture as the source of river pollution. The increasing agricultural land would also increase the water temperature due to less vegetation cover in the catchment, and increase COD due to high nutrients inputs, while lower percentages of agriculture would reduce the concentration. Settlement land also had a positive correlation with water temperature, NO_2N and TP. Positive correlations between agriculture and water quality parameters is in accordance with several studies examining the relationship of land use and water quality (e.g. Par & Mason, 2003; Simeonov et al., 2003; Huang et al., 2013; Bu et al., 2014; Wang et al., 2014; Yu et al., 2016; Mainali & Chang, 2018). Estate cropland had a negative correlation with water temperature, COD and NH_3-N, which may suggest that this land use type was not the source of these pollutants.

3.4.5 Summary

Land use in the sub-catchments of monitoring sites demonstrated changes over time and space that reflected changing patterns of human development. The upper reach remains dominated by the forest land, while the lower reach shows extensive agricultural land and settlement. Within 20 years, the forest land percentage area decreased from 14% in 1996 to only 8% in 2017. Estate cropland increased due to development for oil palm plantation along with small increases of agricultural land, mining and settlement over time. Although these changes in agricultural and settlement land extent were relatively small, they appeared to have significant implications for water quality in the Mahakam River.

The first hypothesis that water quality reflects the intensification of land use in the catchment was supported by the trend of water quality in both the historical and current periods. Both periods showed relationships with land use change through increasing or decreasing concentrations of water quality parameters in response to changing land use type. The increase in estate cropland over time was associated with increasing TDS, while agricultural intensification in the downstream monitoring sites was related to increasing SO_4 over time. Decreasing COD and BOD may relate to swampland areas buffering for oxygen demand process. Spatial patterns of water quality demonstrated the influence of estate cropland, agriculture and settlement as the main sources of pollutants in the Mahakam River.

The second hypothesis that water quality would decline along the river was also supported. Six out of twelve parameters showed increasing concentrations from upstream to downstream reflecting deterioration in water quality in the lower reach. As stated in the third hypothesis, this condition was primarily due to land use changes involving estate cropland, agricultural land and settlements causing declines in river water quality due to sediment yield, nutrient runoff and sewage discharge. Additionally, lack of sewerage treatment in settlement areas likely resulted in high loads of organic matter into the river from domestic waste.

Part of the third hypothesis was that a large-scale fire event would lead to long-term mobilisation of organic substances. This was not supported due to many confounding factors related to land use changes over the extended period between the fire and the subsequent recommencement of monitoring data collection. Accordingly, water quality along the Mahakam River was closely correlated with the prevailing land use types within monitoring site sub-catchments and intensification of key land use types over time. In these respects, the Mahakam River appears typical of other tropical rivers that are undergoing rapid change.

Chapter 4

The relationship of Irrawaddy dolphin distribution with water quality and fishing pressure in the Mahakam River

4.1 Introduction

In recent years, freshwater populations of the Irrawaddy dolphin have shown a decreasing trend of distribution and abundance across all three major areas of occurrence, leading to their IUCN (International Union for Conservation of Nature) Red List status being changed from Data Deficient to Critically Endangered (Kreb & Smith, 2000; Smith & Beasley, 2004; Jefferson et al., 2008; Reeves et al., 2008; Kreb et al., 2016). Riverine dolphin populations are facing numerous problems, not only through modifications to flow regimes and river connectivity but also from rural development leading to land-use changes and increased fishing pressure. It is widely known that land-use change causes water quality deterioration that leads to degradation and loss of habitat for many species (Horne & Goldman, 1994; Dudgeon, 2000b).

These factors may have direct and indirect interacting effects on riverine dolphin populations, particularly water quality which is essential for population health (Bashir et al., 2010) and for food supply (Henley et al., 2010; Miserendino et al., 2011). The impact on dolphin food supply mainly relates to decreasing prey abundance or distribution or altered prey species community composition. For instance, the conversion of floodplain land into agriculture, settlements and industrial land use can increase sedimentation and water turbidity that may affect the primary production and influence fish populations through food-web effects (Dudgeon, 2000b). Similarly, deforestation leading to the loss of forest cover could affect the food sources of some fish species that depend on allochthonous food-web pathways.

Aquatic mammal movements are mostly influenced by resource availability, the abundance of conspecifics and changes in habitat space, for example due to changes in water level (Stern, 2009; Braulik et al., 2014). These factors can lead to seasonal variability in spatial distribution patterns of dolphins which might be an adaptation to changing environmental conditions. In relation to seasonal patterns, some studies have shown that dolphin movement is more likely influenced by prey availability than other factors. For example, during the wet season, Irrawaddy dolphins in the Mekong River moved downstream to follow the prey migration (Smith, 2008; Beasley et al., 2013). Meanwhile, the Irrawaddy dolphin in the Mahakam River, also referred to locally as *Pesut*, apparently moves to deep water during the dry season to follow prey movement (Kreb & Budiono, 2005). These findings show that prey distribution can have a significant influence on dolphin distribution, and therefore suitable habitat for prey becomes a critical factor for dolphin survival.

The Mahakam River is one of the most important inland fisheries areas in Indonesia due to its high productivity (Christensen, 1993). In addition to water quality degradation, high fisheries pressure may therefore also pose a threat to Irrawaddy dolphin due to possible overexploitation of fish species, which are important dolphin prey, or mortality in bycatch (Beasley & Davidson, 2007). Bycatch accounted for 73% of all dead Mahakam River dolphin between 1995–2001 (Kreb & Budiono, 2005). Also, studies in other areas such as in Paloh, West Kalimantan, showed that finless porpoises (*Neophocaena phocaenoides*) and Indo-Pacific humpback dolphin (*Sousa chinensis*) were often caught unintentionally in gillnets causing mortality (Mustika et al., 2014), as also occurred for the Vaquita dolphin (*Phocoena sinus*) in Mexico (D'agrosa et al., 2000). In addition, use of electrofishing poses an added threat for Irrawaddy dolphin in the Ayeyarwady River, as well as in the Mahakam River (Kreb, 2004; Smith et al., 2009).

Rapid development in rural areas has changed the land cover and land use in the Mahakam River catchment, with ensuing impacts on the state of water quality. In Chapter 3, I saw increasing trends of dissolved solids and sulphate in the Mahakam River with a high rate of change per year. There is potential for these factors to directly influence river dolphins or their prey fish distribution and abundance. However, little is known about direct or indirect effects of river habitat degradation and habitat loss associated with land use/cover change or other environmental factors such as fishing pressure, and their interaction with water quality deterioration. These issues are particularly pertinent for the Irrawaddy dolphin in the Mahakam River where, over the last 20 years, there has been significant catchment deforestation and establishment of oil palm plantation, development for mining, and the associated growth in rural communities along this river.

This chapter aims to investigate key environmental factors that may affect the Irrawaddy dolphin distribution and abundance of the Mahakam River, focusing on the middle section where most dolphins occur. To understand the relative importance of water quality, habitat and fishing pressure, it is necessary to (i) quantify drivers of degradation in relation to biological and ecological factors affecting Irrawaddy dolphin distribution, and (ii) examine the implications of changes over time for dolphin population distribution. To address this aim, the specific objectives of this chapter are to:

- Identify Irrawaddy dolphin temporal and spatial distribution patterns during 1997-2017.
- Explore associations between spatial and temporal patterns of dolphin distribution, water quality and fishing pressure to identify which environmental factors can explain dolphin occurrence in the middle river section.
- Identify Irrawaddy dolphin habitat associations during a population survey carried out in 2017.

Based on findings from previous studies in the area (Kreb, 2002; 2004; 2005), the hypotheses of this chapter are: (i) water level will influence dolphin distribution due to decreasing or increasing connectivity between available habitat, (ii) the river section with extensive fisheries activities will have less frequent dolphin sightings, and (iii) dolphin distribution will be related to the state of water quality along the river course. Testing these hypotheses will help provide insight into the conservation and management of Irrawaddy dolphin in the Mahakam River.

4.2 Methods

4.2.1 Study area

The main channel and some large associated tributaries comprise the area of study for Irrawaddy dolphin distribution in the Mahakam River. The survey area traversed Samarinda Kota downstream to Laham upstream, covering 20 subdistricts (see Figure 2.1). Most dolphin sightings occur in the middle reach of the river (see Figure 4.1), where three major lakes and four major tributaries are connected to the river. For this study, the river was divided into three reaches (i.e. upper, middle and lower; see Figure 2.1), with the upper and middle reaches divided into two areas (i.e. Upper Reach: UR1 and UR2; Middle Reach: MR1 and MR2). Collectively, these reaches cover 504 km of mainstem river channel (see Table 4.2 for individual reach lengths). The average width of the Mahakam River in the upper, middle and lower reaches is 160 m, 200 m and 360 m respectively, and mean depth is 10 m, 15 m, 12 m (Kreb, 2002). Further details about the study area can be found in Chapter 2.

4.2.2 Data collation and survey method

4.2.2.1 Dolphin data

Dolphin data used in this study covered the period 1997 to 2017, and were acquired from monitoring conducted by RASI (Rare Aquatic Species Indonesia). These extensive monitoring surveys were conducted one to three times per year at either low- or high-water levels, or both. The dataset for December 2017 was obtained directly from the field survey by the author, along with associated habitat measurements. For the purposes of this study, the number of dolphins sighted and their locations (i.e. the GPS coordinates) on each date were used for the analysis.

During the field surveys, a medium-sized, motorised, wooden boat (c. 12 m length) travelled at a constant speed of c. 12 to 14 km $hour^{-1}$ in the middle part of the river. However, for safety reasons, the boat sometimes travelled near to the shoreline, for example when a tugboat and coal barge passed through where the river was narrow (typically < 100 m).

The monitoring team consisted of four observers each with a different task during the survey. The first observer was positioned in the front centre of the boat as the main observer who continuously scanned the river on the horizon using 7x50 binoculars. The second observer facing the rear recorded search efforts, weather conditions and other relevant information from the GPS every 15 minutes. The third and fourth observers facing to the front searched the left and right side of the boat (left and right strip transect). A position rotation applied (i) every 15 minutes to ensure the main observer in the front had time to rest their eyes and keep concentration high, or (ii) every time a dolphin was encountered.

Dolphin encounters were recorded as the location (coordinate) at the dolphin's position and number of dolphins (direct counted method). Number of new-borns (< 3 months old), calves and juveniles were identified directly. For the December 2017 survey, photographs were also taken from each individual's dorsal fin and matched to the existing photo-identification catalogue from RASI (1999-2017) to confirm the estimation number of group size.

As the focus of this chapter is associations between mainstem water quality and fisheries productivity, only dolphins sighted in the main river reach (LR1, MR1, MR2, UR1 and UR2) were included in the analysis of seasonal distribution and spatial distribution. Dolphin sighting data in tributaries were not used for the analysis because there was no analysis for water quality and other environmental factors that could correlate with counts from tributaries. However, the tributaries data are used for the general overview of dolphin distribution patterns in the Mahakam River.

4.2.2.2 Fisheries data

Fisheries data were acquired from Fisheries Agency of East Kalimantan province and Kutai Kertanegera district, with additional information obtained from Statistic Indonesia (https://www.bps.go.id/). Fishing gear type and number of units reported during 2010-2017 were used for the analysis, along with the reported productivity (number of fish per net per unit time) of key fish species which represent dolphin diet (D. Kreb, RASI – *personal* *communication,* 23 Sept 2018). The fishing pressure analysis focused in the middle section of the Mahakam River since (i) it is known as the main inland fisheries area, (ii) it is the preferred habitat for *Pesut* (Christensen, 1993; Kreb, 2002; Kreb and Budiono, 2005), and (iii) it has well-recorded fisheries data because most of the middle section (five subdistricts) is in the same administrative area (Kutai Kertanegara district). The remaining middle section subdistrict, Muara Pahu under Kutai Barat district, had no available fisheries information.

To support data on fishing gear type and number of units, dolphin mortality information in the Mahakam River was also gathered from RASI and Whale Stranding Indonesia (WSI - http://www.whalestrandingindonesia.com/). This information was used to identify any reported mortality events caused by fishing gear to understand the extent of bycatch in primary dolphin habitat.

4.2.2.3 Water quality data

As part of the analysis of environmental factors potentially affecting Irrawaddy dolphin distribution, five land-use related water quality parameters for the period of 2010-2017 were used (see Section 3.2 for methods): water temperature, pH, TDS (total dissolved solids), EC (electrical conductivity) and DO (dissolved oxygen). Data were from the middle section sites that matched with the dolphin area, using annual means to compare with dolphin data from the same period. In addition, measurements of water temperature, pH, DO, EC, TDS, river width and depth, current and clarity were obtained from a field survey in December 2017 at sites where dolphins were encountered and at regularly spaced-sites along the river where dolphins were not seen. For these measurements, DO was measured in-situ using a portable DO meter model HI 98193, while pH, EC, TDS and water temperature were measured with a Gro line hydroponic portable HI 9814 (Hanna Instruments, Bedfordshire, UK). River width was calculated with a Nikon Laser finder, river depth was estimated using an Echotest II depth sounder (Plastimo, Lorient, France), and water clarity was measured using a Secchi disk.

4.2.2.4 Catchment disturbance information

Habitat or catchment disturbance information was obtained by the author during the field survey on 5–12 December 2017, carried out simultaneously with the dolphin monitoring survey. Six human activities (settlement, transportation, road system, fisheries, crop plantation and mining) were recognised within the river and the adjacent catchment during the survey (Table 4.9). Different disturbances were recorded as absent (0), or low (1), medium (2) or high (3) intensity at the same location as dolphin sightings and periodically along the survey route where dolphins were not seen. The land use classification (see Chapter 3) was also assessed visually during the survey. This disturbance information gave insight into habitat conditions and the possible threat from activities along the river. Data were matched as closely as possible for dolphin sighting locations and water quality sampling locations where dolphins were not seen.

4.2.3 Statistical analysis

All statistical tests were done using STATISTICA v.13, including descriptive statistics (mean, median, minimum, maximum and standard deviation) unless otherwise stated. Time-series data from 1997 to 2017 for dolphin counts and environmental factors were assessed for normal distribution using the Shapiro-Wilk statistic, and were found to be non-normally distributed. Therefore, non-parametric tests were typically used for analysing dolphin distribution data in relation to environmental factors such as river water level, water quality parameters related to land use, fishing gear number and fish productivity.

Temporal patterns in dolphin sightings during 1997–2017 were measured by regression analysis for two seasonal periods: low- and high-water level using data from the mainstem river only. Differences in the median number of sightings between the two water levels over 1997–2017 were determined using the Mann-Whitney U test. Kruskal-Wallis test was used to assess the significance of differences between river reaches. If there was an effect of river reach (LR1, MR1, MR2, UR1, UR2), then a post-hoc multiple comparisons of mean-ranks was used to determine which sections were significantly different (Field et al., 2012). Similar analyses of dolphin temporal and spatial patterns were also applied to the water quality parameters, fish production and fishing gear. The lower river reach was included as a control since dolphins were never seen there.

More detailed collection of environmental variables associated with dolphin sightings was undertaken by the author during a field survey on December 2017, so data from this year were analysed separately. Differences in the number of dolphin sightings, estimated group size and environmental parameters among river mainstem, confluence and tributary habitats were determined using the Kruskal-Wallis test as described above. Due to missing data for river width at confluence areas, values were substituted using the mean of neighbouring areas to include width in the analysis.

To identify any environmental factors that could explain dolphin distribution patterns in the Mahakam River, Principle Component Analysis (PCA) was used, following normalisation of variables by substracting the mean and dividing by standard deviation. The PCA was calculated using PRIMER 7 (v.7.0.11) sofware. Factor loadings for the first three Principal Component axes were explored, using a cut-off on 0.4 to identify variables strongly associated with each axis. A two-dimensional PCA plot was used to visualise the relationships between sites and (i) a vector overlay of environmental variables distinguished using a correlation cut-off of 0.3, and (ii) bubble plots of dolphin group size.

4.3 Results

4.3.1 Dolphin sightings

The proportions of dolphin sightings in the main river stem and major tributaries were calculated to present a general overview of dolphin occurrence and distribution over 1997–2017 within different reaches of the Mahakam River (Table 4.1). During this period, 17 river surveys were conducted during low and high water levels, with 254 Irrawaddy dolphin sightings recorded in the main river channel and seven tributaries. 63.8% of sightings were recorded from the mainstem and 36.2% from the tributaries (Figure 4.1).

During 1997–2017, a total of 77 dolphin mortalities were reported, with 23.4%, 68.8% and 7.8% of these occurring in the upper, middle and lower river reaches, respectively. Of the deaths reported, the great majority (55.9%) were from gillnets. Other reported mortality was due to electrofishing (3.9%) and unknown causes (40.3%). Calf mortality accounted for 20.8% of all cases. MR1 and its tributaries were the location with high mortality caused by gillnets compared to other locations (Table 4.1).

4.3.1.1 Spatial patterns

Dolphins were distributed from the downstream part of the upper reach to the middle reach, but were never found in the lower reach or the upper part of the upstream section during the 1997–2017 surveys (Figure 4.1; Table 4.2). The middle reach of the river accounted 57.9% of total sightings (mean = 4.9 and 8.5 dolphins per year in MR1 and MR2, respectively). One 4.2 km-long tributary section in the middle section (MR1.5 – area within the square on Figure 4.1) had frequent sightings during the period (9.5%; mean = 2.2) compared to other tributaries (see Table 4.2).

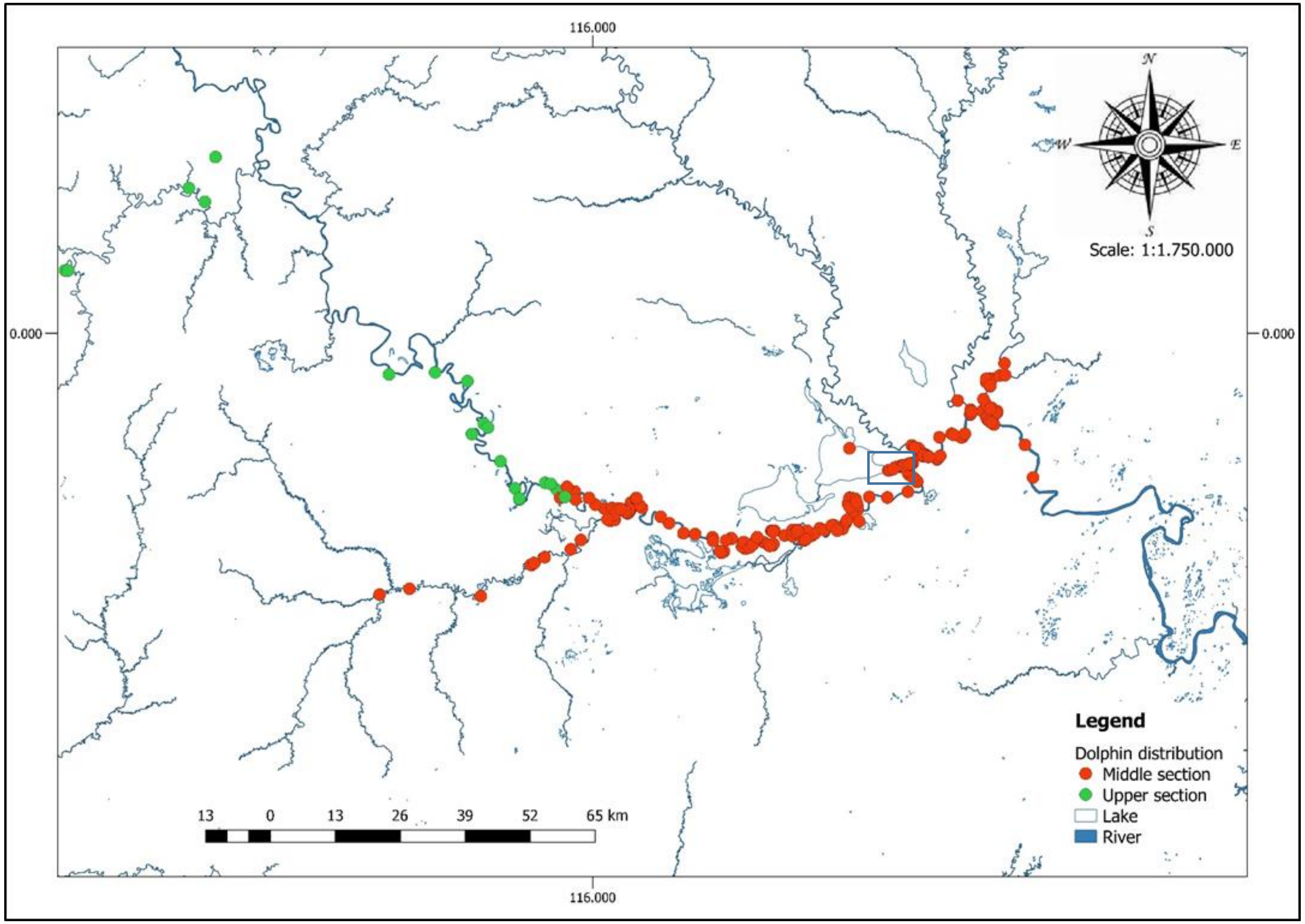

Figure 4-1: Map showing dolphin sightings in the Mahakam River over 1997–2017. Square on the map shows the tributary area with 9.5% of sightings over 4.2 km (MR1.5)

Table 4.1 Rate of dolphin mortality caused by gillnets in all reaches of the Mahakam River during 1997–2017. LR = lower river; MR = middle river; UR= upper river; codes with the decimal place are on tributaries.

River reaches	**Mortality cases**		**Mortality due to gillnets**	
	No. of dolphin	**Percentage**	**No. of dolphin**	**Percentage**
LR1	6	7.8	2	2.6
MR1	13	16.9	9	11.7
MR1.2	4	5.2	4	5.2
MR1.5	10	13.0	6	7.8
MR2	23	29.9	11	14.3
MR2.1	2	2.6	1	1.3
MR2.2	1	1.3	0	0.0
UR1	10	13.0	9	11.7
UR2	6	7.8	1	1.3
UR2.1	2	2.6	0	0.0
TOTAL	**77**		**43**	55.9

Kruskal-Wallis test for dolphin sightings on the river mainstem sections showed that there were significant differences over 1997-2017 ($H=43.59$; $p<0.001$), although this result largely reflected the absence of dolphins from LR1 and UR2 (Figure 4.2). Meanwhile, MR1 was not significantly different from MR2 and UR1. This result indicates that, over time in the Mahakam River, dolphin sightings occurred with similar frequency in mainstem sections where dolphins were observed, although there was high variability in MR2. Dolphin occurrence during low and high-water level within the river mainstem can be seen from Figure 4.3. The patterns showed that MR2 had more dolphin sightings during low-water level, while occurrences during high-water levels were almost the same between MR1 and MR2.

Table 4.2 Dolphin survey reach lengths and number of dolphin sightings for the period 1997–2017 on the Mahakam River. For site codes, LR = lower river; MR = middle river; UR = upper river; codes with the decimal place are on tributaries.

River reach	Site code	River reach length (km)	Total no. sightings	% of sightings	Mean	Std.Dev.	Median
Lower Reach Samarinda - Sebulu	LR1	105.08	0	0.00	0.00	0.00	0.00
Middle Reach Muara Kaman - Muara Wis	MR1	96.02	54	21.26	4.91	3.86	5.00
Middle Reach-tributary Sabintulung – Sungai Kedang Rantau	MR1.1	34.87	2	0.79	0.18	0.40	0.00
Middle Reach-tributary Sungai Kedang Rantau	MR1.2	48.18	19	7.48	1.73	1.95	1.00
Middle Reach-tributary Sungai Kedang Kepala	MR1.3	47.58	12	4.72	1.09	1.22	1.00
Middle Reach-tributary Sungai Belayan	MR1.4	20.22	16	6.30	1.45	2.62	1.00
Middle Reach-lake-tributary Sungai Pela – Lake Semayang	MR1.5	4.18	24	9.45	2.18	1.72	2.00
Middle Reach Muara Muntai - Muara Pahu	MR2	97.90	93	36.61	8.45	6.27	8.00
Middle Reach-tributary Sungai Kedang Pahu - Muara Lawa	MR2.1	82.09	5	1.97	0.45	0.82	0.00
Middle Reach-tributary Sungai Kedang Pahu - Damai	MR2.2	110.94	8	3.15	0.73	1.62	0.00
Upper Reach Melak - Tering	UR1	107.04	15	5.91	1.36	1.63	1.00
Upper Reach Long Iram - Laham	UR2	97.53	0	0.00	0.00	0.00	0.00
Upper Reach-tributary Sungai Ratah	UR2.1	107.24	6	2.36	0.55	0.69	0.00
Total		**958.87**	**254**				

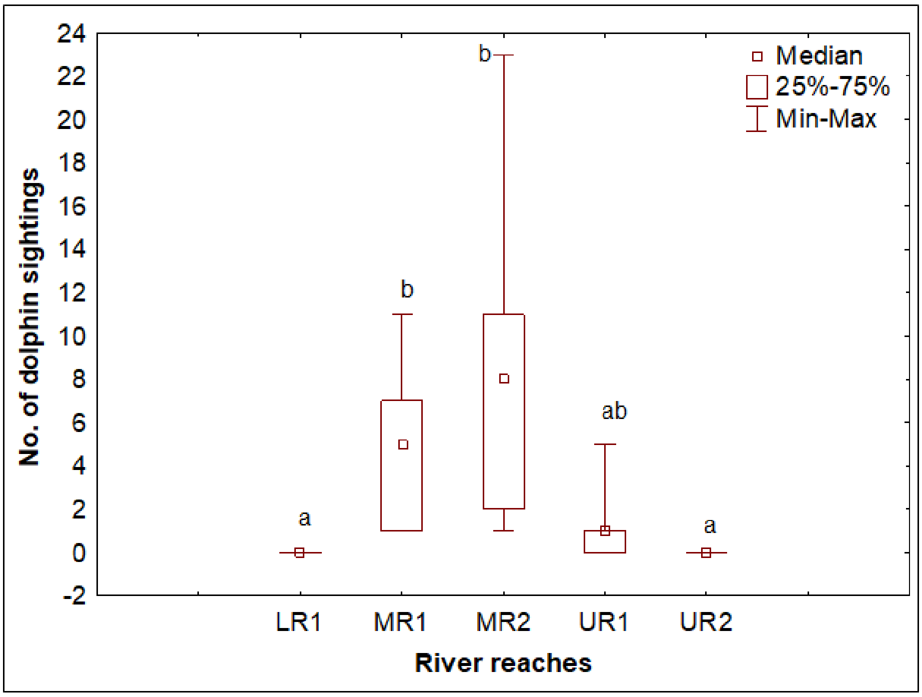

Figure 4-2: Box-whisker plot showing the differences in number of dolphins sighted between Mahakam River sections for 1997-2017. Boxes with the same letter above are not significantly different following the multiple post-hoc comparison (see text for detail)

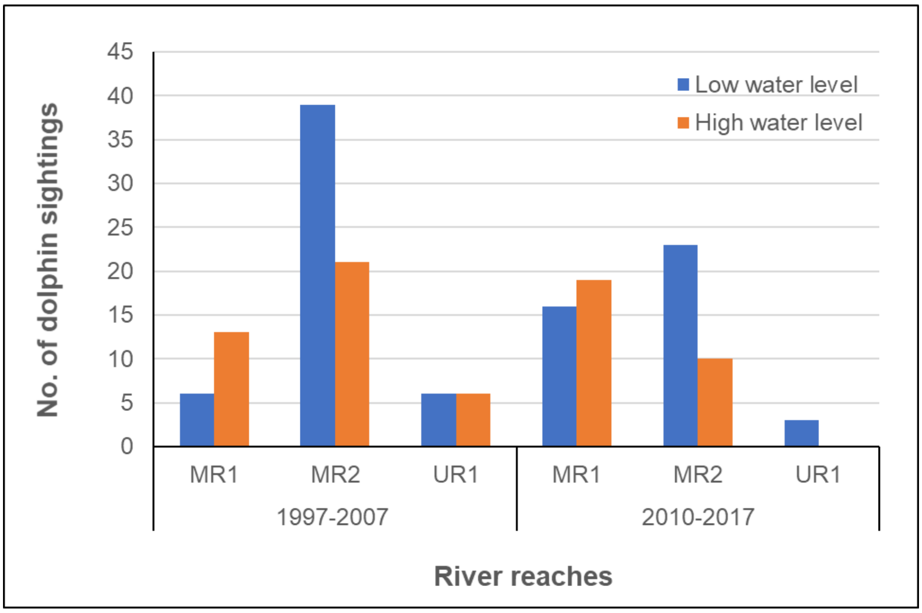

Figure 4-3: Bar chart shows the distribution of dolphin sightings within Mahakam River sections based on the water level for two-time periods. MR = middle river; UR=upper river

4.3.1.2 Temporal patterns

Dolphin sightings recorded at different water levels (high and low) were analysed using linear regression to assess temporal patterns. Figure 4.4 suggests that dolphin sightings at low-water levels increased slightly over the monitoring period, although the regression was not statistically significant. Dolphin sightings at high-water levels showed the opposite pattern which also was not statistically significant. Furthermore, there were no significant differences in numbers of dolphins sighted over the 11 years between two water levels based on Mann-Whitney test (U=42.5; p=0.25, Figure 4.5).

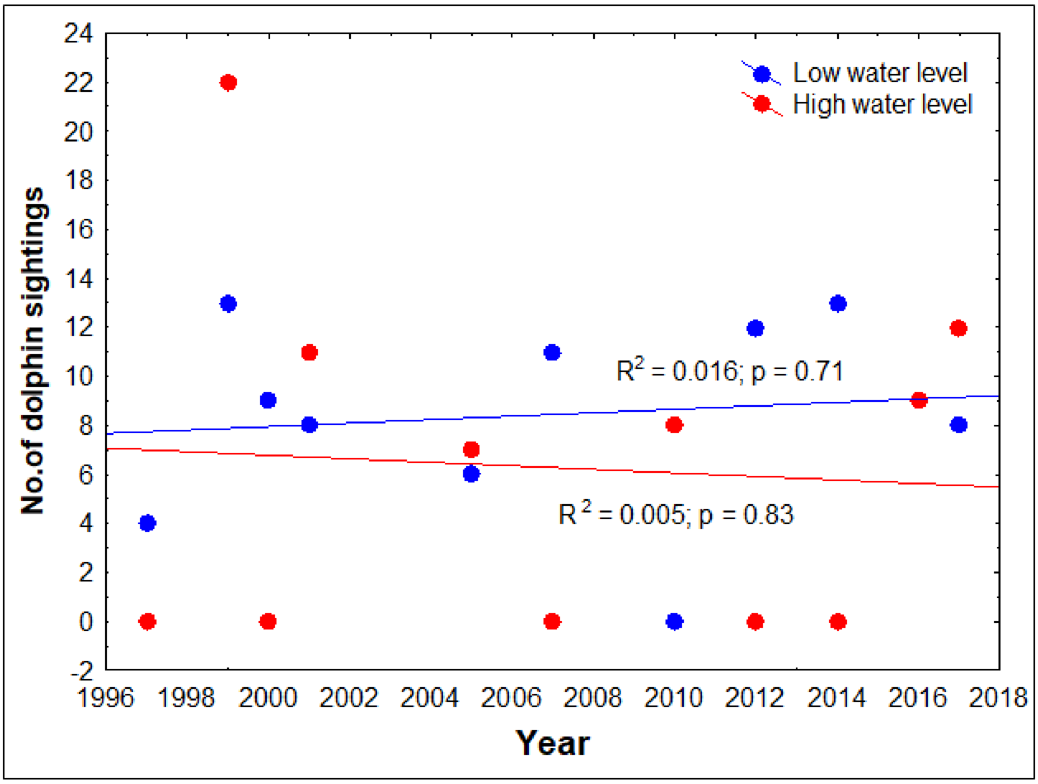

Figure 4-4: Temporal patterns of dolphin sightings over 1997-2017 during low and high-water levels for the Mahakam River mainstem

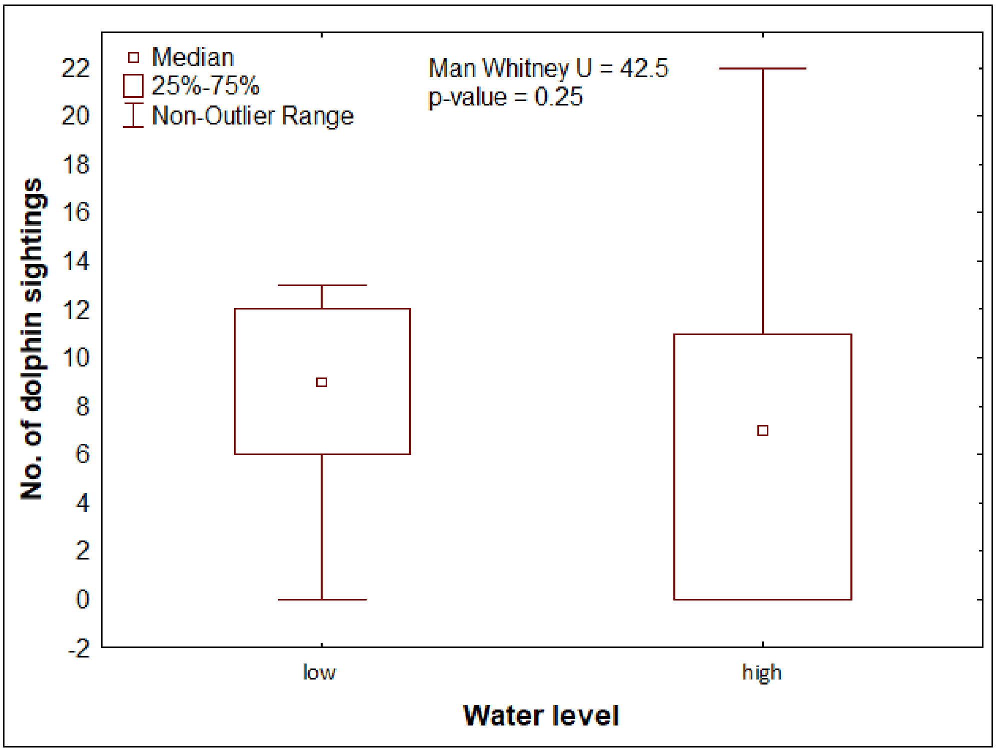

Figure 4-5: Box-whisker plot showing differences in dolphin sightings at two water levels over 11 years in the Mahakam River mainstem

4.3.2 Temporal and spatial patterns in environmental factors

The middle reach was specifically chosen for this analysis because, as well as being the main dolphin habitat (Kreb, 2004), it has consistent monitoring for water quality and comprehensive fisheries records. This analysis used combined dolphin sighting data from low- and high-water level sightings. The environmental factors used in analyses were (i) production of important fish prey species for dolphin; (ii) number of gillnets; and (iii) water quality parameters related to land use (for the list of fish species and water quality parameters see Table 4.3). Environmental data collected over 2010-2017 in the middle reach were used to determine the temporal patterns, while to identify spatial patterns data from the lower and middle sections were used for the same period, as data for several parameters were unavailable for upper river sections. The lower reach functioned as a control site representing conditions where dolphins were absent.

Table 4.3 Summary statistics for dolphin sightings and each environmental factor in the middle and lower reaches of Mahakam River for the period 2010-2017 (2010, 2012, 2014, 2016, and 2017). - = no data

Variable	Middle reach			Lower reach		
	Mean	**Std.Dev**	**Median**	**Mean**	**Std.Dev**	**Median**
Dolphin sightings						
Combined low and high-water level sightings	13.4	4.5	12.0	0.0	0.0	0.0
Fishing gear						
No. of gillnets	9257.0	1271.6	9727.0	241.0	134.1	191.0
Prey species productivity (ton/year)						
Lais (*Cryptoprerus micronema* - Siluridae)	699.5	429.6	767.2	-	-	-
Patin jambal (*Pangasius djambal* - Pangasiidae)	1242.5	747.2	1578.0	24.6	21.3	18.9
Baung (*Hemibagrus nemurus* - Bagridae)	1374.2	931.9	1466.4	85.3	72.3	85.9
Kendia (*Thynnichthys vaillanti* - Cyprinidae)	1565.1	1048.3	1837.8	39.7	22.9	51.8
Repang (*Osteochilus repang* - Cyprinidae)	808.2	847.7	855.0	15.7	-	15.7
Water quality (annual mean value)						
Water temperature (^{0}C)	27.5	0.5	27.6	28.6	0.6	28.6
pH	6.6	0.1	6.6	6.9	0.4	7.0
Total dissolved solids (TDS) (mg/L)	39.5	22.5	37.7	44.2	27.5	46.8
Electrical conductivity (EC) (µS/cm)	35.6	25.2	26.8	56.5	40.8	34.3
Dissolved oxygen (DO) (mg/L)	5.2	1.2	5.8	4.3	1.6	3.9

4.3.2.1 Temporal patterns

The temporal pattern for water quality parameters and dolphin sighting data are presented in Figure 4.6. Number of dolphin sightings during combined low- and high-water surveys showed a significantly increasing trend over 2010-2017. Although TDS concentration and EC gradually increased over time, no temporal patterns in annual mean water quality parameters were statistically significant. The temporal patterns of prey fish productivity showed that three of the key species had decreased production over time while two species showed an increasing trend. Apparent increases in catches occurred for Baung (*Hemibagrus nemurus* – Bagridae) and Lais (*Cryptoprerus micronema* – Siluridae), while Patin jambal (*Pangasius djambal* – Pangasiidae), Kendia (*Thynnichthys vaillanti* - Cyprinidae), and Repang (*Osteochilus repang* – Cyprinidae) decreased. However, all these patterns were not statistically significant (Figure 4.7). In contrast, the number of gillnets showed a significant increase over the period (Figure 4.7; R^2 = 0.86; p = 0.02). The increasing number of gillnets over time in the middle section may indicate a greater intensity of fisheries activities.

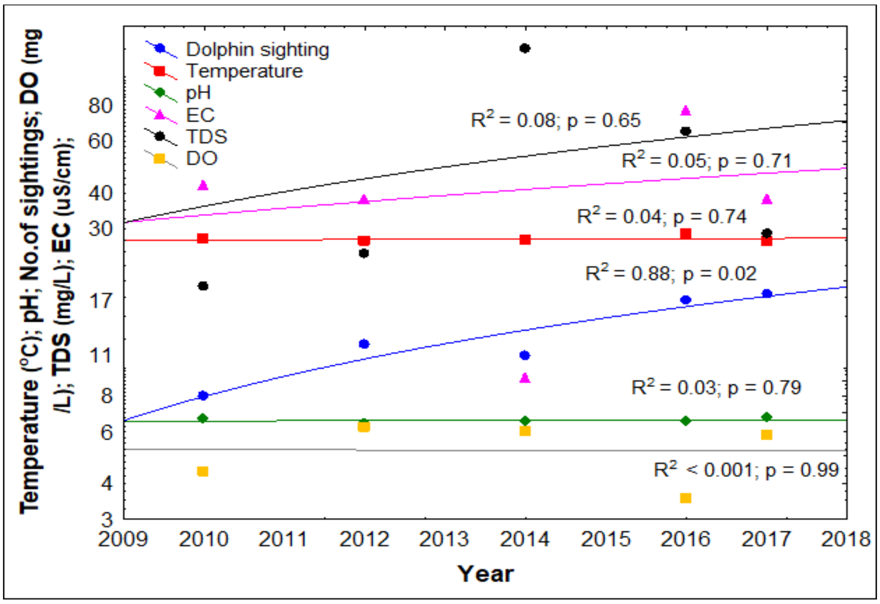

Figure 4-6: Temporal pattern of water quality parameters in relation to dolphin sightings during the period 2010-2017 in the middle section of the Mahakam River

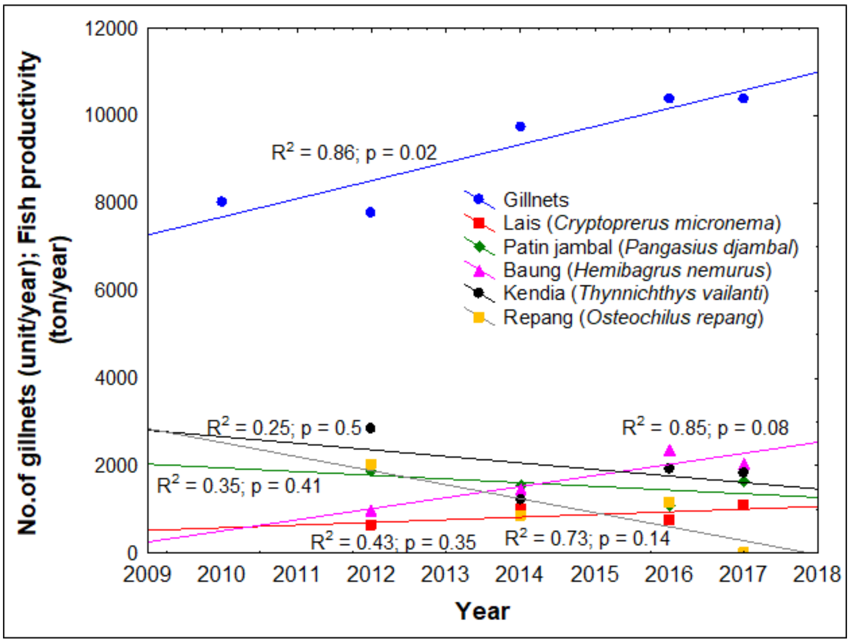

Figure 4-7: Temporal patterns of fishing gear (gillnets) use and the productivity (ton/year) of important fish prey for dolphin during the period 2010-2017 in the middle section of the Mahakam River

4.3.2.2 Spatial patterns

Spatial variation in environmental parameters was evident between river reaches, including the lower river, based on the Kruskal-Wallis test and the multiple post-hoc comparisons. MR2 had significantly lower water temperature compared to the lower river (Figure 4.8). On the other hand, MR1 has the highest number of gillnets reflecting high intensity of fishing in this river reach, even though it was not significantly different from MR2 (Figure 4.8). Along with the high number of gillnets, the highest productivity of Baung (*Hemibagrus nemurus*), Patin jambal (*Pangasius djambal*), and Kendia (*Thynnichthys vailanti*) occurred in MR1, which was significantly different to LR1 but not compared to MR2 (Figure 4.8). LR1 was the river section with the lowest reported fish productivity, and in combination with high temperature this may contribute to the absence of dolphins in the lower reach.

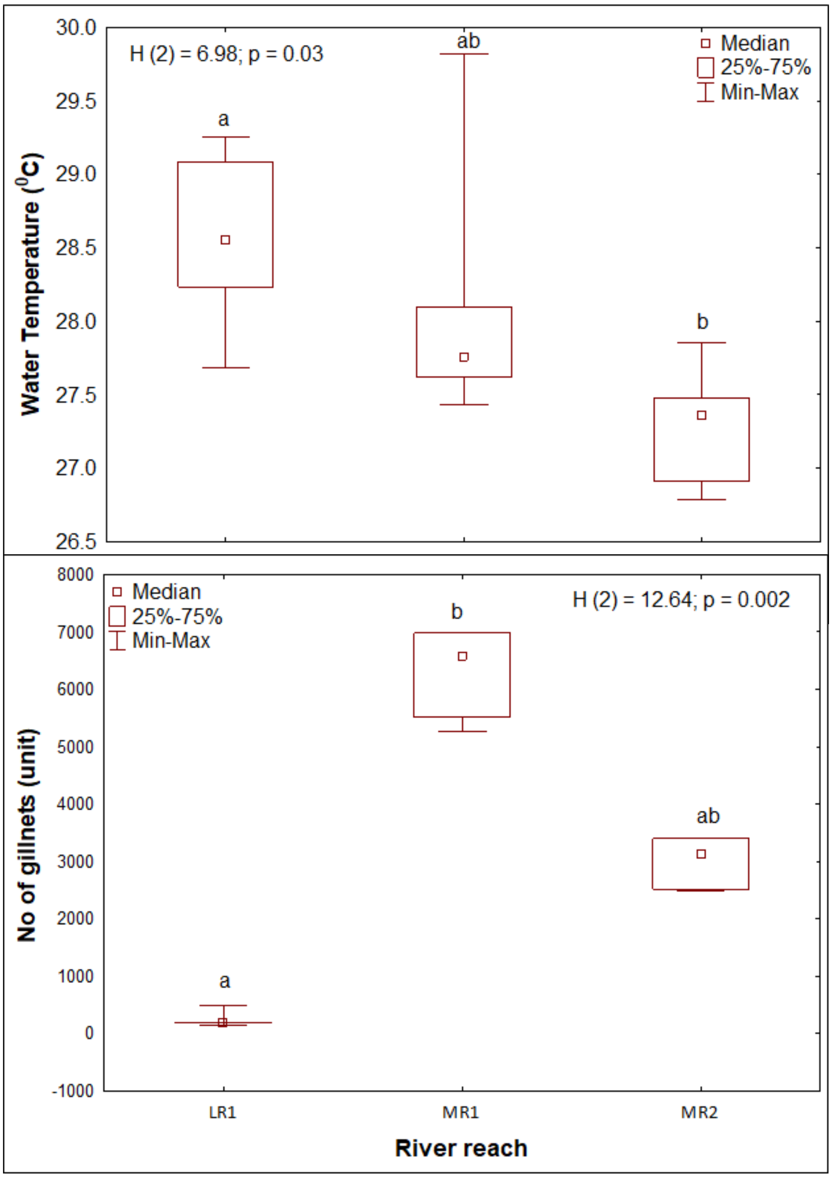

Figure 4-8: Box-whisker plots showing the spatial pattern of water temperature and number of gillnets within the middle and lower Mahakam River. Boxes with the same letter above are not significantly different based on the multiple post-hoc comparisons

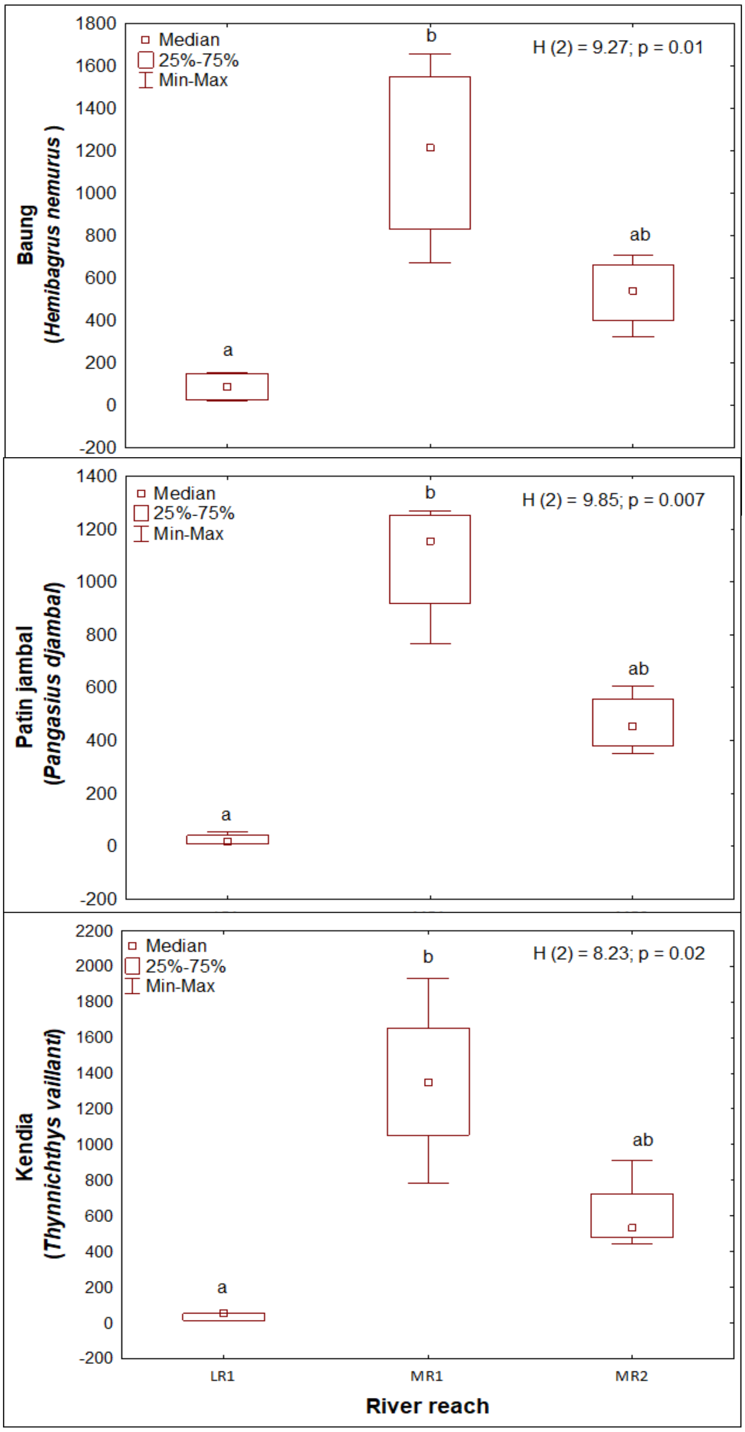

Figure 4-9: Box-whisker plots showing the spatial pattern of selected dolphin prey species within the middle and lower Mahakam River. Boxes with the same letter above are not significantly different based on the pairwise post-hoc comparison

4.3.3 Environmental factors associated with dolphin distribution (2010-2017)

A Principal Component Analysis (PCA) was carried out to understand which environmental factors may have affected the variation of dolphin sightings in the Mahakam River during 2010-2017. The first two axes had eigenvalues >1 and explained 75.7% of the variation, with 98.3% total variation explained by five principle components (Table 4.4).

The relationships between environmental variables with presence/absence of dolphins in river sections were demonstrated by the factor loading values for PC axes. The first axis (PC1) appeared to reflect water quality parameters related to land use with factor loadings >0.4 for DO (positive), EC, TDS and water temperature (all negative) (Table 4.5). Axis 2 factor loadings were strongest for number of gillnets followed by pH and EC. The third axis (PC3) was strongly represented by gillnet number and pH of the water (Table 4.5).

The two-dimensional plot with the vector overlay of environmental factors indicated that the majority of dolphin sightings was associated with sites that had higher DO concentration and lower EC and temperature along axis 1, although a small number of dolphin sightings occurred at sites with high water temperature and EC (Figure 4.10). Additionally, the absence of dolphins was characterised by higher TDS and pH and lower numbers of gillnets.

Table 4.4 Eigenvalues and percent variation explained by each principal component (PC) axis for sites with dolphin presence/absence in the Mahakam River during 2010-2017.

PC	Eigenvalues	%Variation	Cumulative %variation
1	3.15	52.5	52.5
2	1.39	23.2	75.7
3	0.596	9.9	85.6
4	0.571	9.5	95.1
5	0.191	3.2	98.3

Table 4.5 Factor loadings for the first three principal component (PC) axes for each environmental variable measured in the Mahakam River during 2010-2017. The stronger the factor, the closer to +1 or -1. Values > 0.4 are shown in bold.

Variable	PC1	PC2	PC3
Gillnet (unit)	0.219	**-0.601**	**0.759**
Water temperature (^{0}C)	**-0.419**	-0.269	-0.16
pH	-0.301	**0.565**	**0.589**
EC (µS/cm)	**-0.426**	**-0.455**	-0.129
TDS (mg/L)	**-0.469**	0.153	0.180
DO (mg/L)	**0.533**	0.125	-0.049

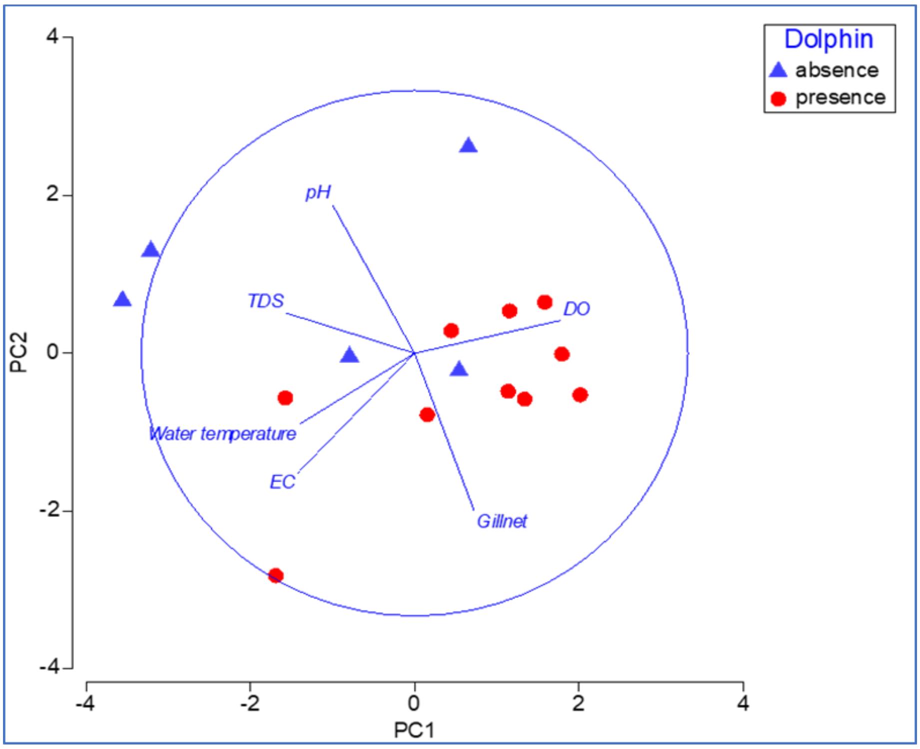

Figure 4-10: Plot of dolphin presence-absence on principle component axes 1 and 2 showing correlated environmental factors in the Mahakam River during 2010-2017

4.3.4 Intensive survey (2017)

4.3.4.1 Current dolphin distribution and demographics

In December 2017, an eight-day survey was conducted during the high-water level season when the riverbank and floodplain were inundated. At this time, 15 dolphin sightings were recorded, and 110 individual dolphins counted. All dolphins were in the middle reach with 33% of sightings from three major tributaries (MR1.2, MR1.4, and MR1.5), 27% in tributary confluence areas and 40% in river mainstem areas not associated with tributaries (see Appendix 4). In terms of group size and age composition, the majority of dolphins recorded were adults (82.7%), followed by a juveniles (10%), then calves (5.5%) and newborns (1.8%). From the 15 groups, only three were not found with either juveniles, calves or new-borns. Groups with <10 dolphins accounted for 80% of the sightings, while sightings of larger groups (>10 dolphins) were less frequent (20%) (Figure 4.11).

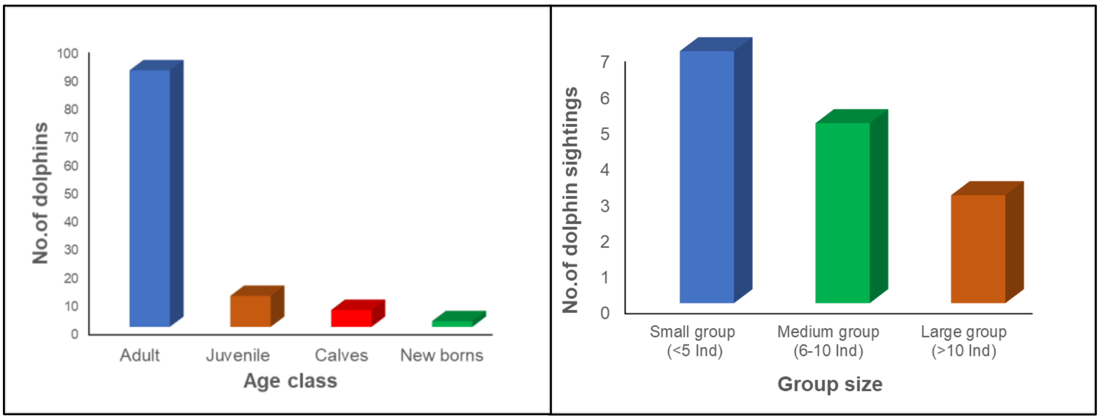

Figure 4-11: Age composition and group size of dolphins sighted on the Mahakam River in December 2017

Summary statistics of dolphin size and physical and chemical parameters at the three different types of river section (mainstem, tributary and confluence area) are presented in Table 4.6. The Kruskal-Wallis test indicated that river current ($H=6.5$; $p=0.038$), and width ($H=6.1$; $p=0.045$) were significantly different between the mainstem, tributary and confluence sites, whereas other parameters were not significantly different. Pairwise comparisons indicated the river mainstem and tributaries had different river widths, while the river current was higher in the mainstem than in confluence areas (Table 4.6).

Table 4.6 Mean (± SD) dolphin group size and physicochemical measurements in mainstem, tributary and confluence areas of the Mahakam River in 2017. N=6, 5 and 4, respectively.

Variable	Middle Mainstem	Tributary	Confluence
Dolphin			
Group size (#individuals)	9 ± 5.0	8.2 ± 7.4	3.5 ± 2.6
Physicochemical parameters			
Current (m/s)	3.1 ± 0.9	1.8 ± 1.1	1.1 ± 0.9
Depth (m)	16.4 ± 5.7	18.8 ± 4.3	16.3 ± 6.3
Width (m)	228.5 ± 54.4	140.4 ± 22.4	185.3 ± 52.9
Water temperature (^{0}C)	28.6 ± 0.6	28.3 ± 0.7	29.1 ± 0.9
pH	6.1 ± 0.3	6.2 ± 0.3	6.2 ± 0.2
DO (mg/L)	3.9 ± 0.7	3.3 ± 1.9	3.3 ± 1.6
Clarity (cm)	36.7 ± 8.9	41.4 ± 6.9	43 ± 12.3
TDS (mg/L)	30.0 ± 24.5	26.0 ± 8.9	22.5 ± 5.0
EC (µS/cm)	60.0 ± 48.9	48.0 ± 13.0	47.5 ± 9.6

4.3.4.2 Environmental factors associated with dolphin presence

Dolphins were recorded more often at mainstem locations with DO concentration between 3–4.5 mg/L (Figure 4.12). A high number of sightings (40%) occurred where the water temperature was between 28-29^{o}C, which was mostly in the mainstem. Dolphins were also frequently sighted in mainstem river sections with depth between 11–20 m (53%) or in tributaries with width <150 m (40%) (Figure 4.12). Parts of the river that had higher water velocity (between 1 and 3 m/s) and less turbid water (>40 cm clarity) had a higher frequency of dolphin sightings (53% and 67%, respectively). Furthermore, dolphins were recorded more often at locations with pH >6. These results indicated the range of physical parameter values associated with a higher chance of dolphin sightings.

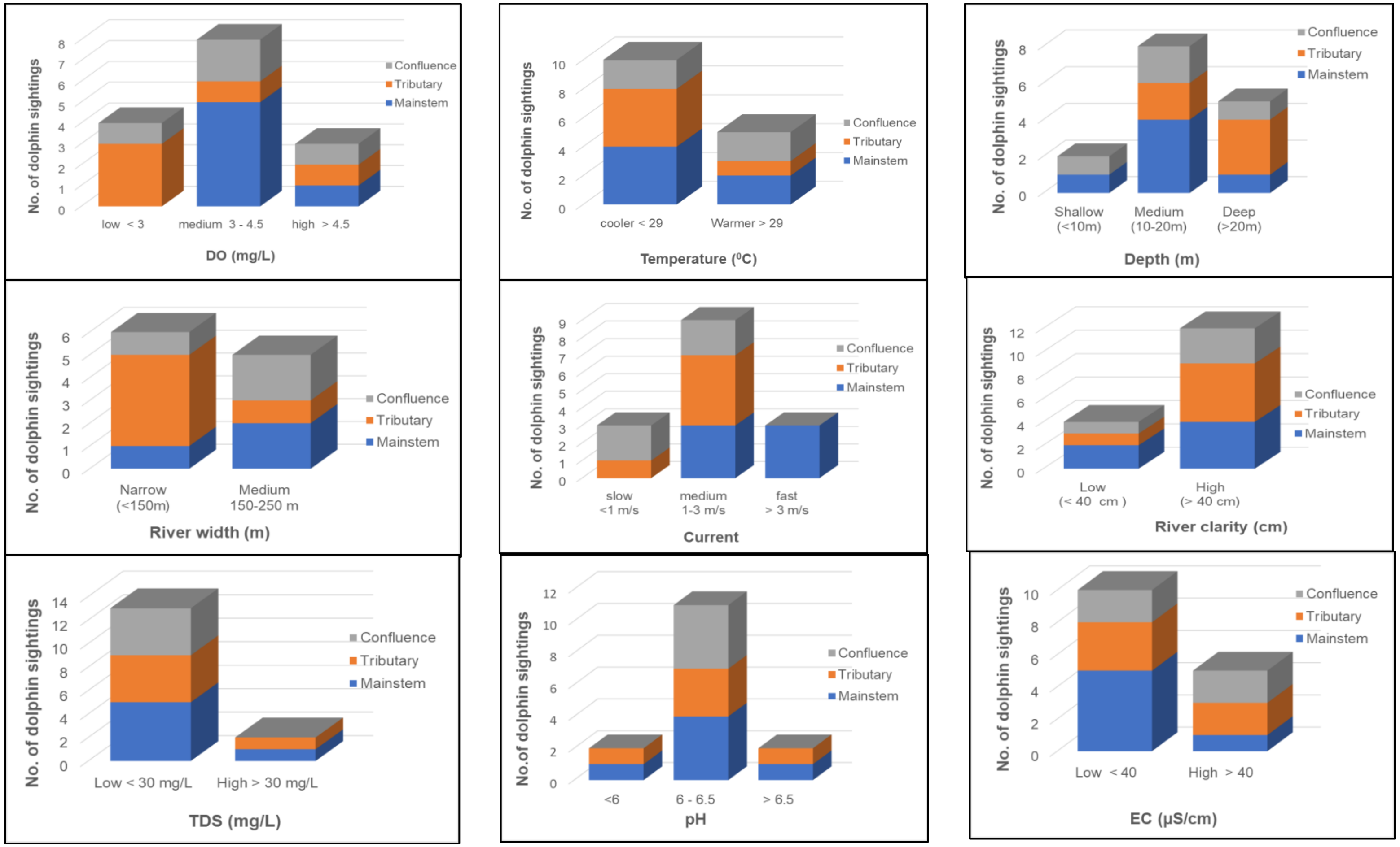

Figure 4-12: Physical and water quality conditions at sites where dolphins were seen in December 2017

4.3.4.3 Environmental factors explaining dolphin distribution

PCA was conducted on environmental variables measured during the 2017 survey where dolphins were sighted. The eigenvalues showed that the first three axes accounted for 77.1% of variation with 94.8% of total variation accounted for by five PCs (Table 4.7). The relationship of each environmental variable with dolphin group size can be seen from factor loading values of three principle components (PC). Factor loadings for the first axis were >0.4 for TDS, clarity, pH and EC (all negative), while the second axis showed a positive association with river depth and a negative association with DO (Table 4.8). Axis 3 indicated a relationship with river width and current. The two-dimensional plot showing an overlay of environmental variables in relation to dolphin group size indicated that larger groups occurred to the right along axis1 and were associated with lower TDS, pH, clarity, and EC (Figure 4.13). The vectors suggested high TDS and clarity corresponded but this was due to an extreme outlier.

Table 4.7 Eigenvalues and percent variation explained for each principal component (PC) axis representing environmental variables measured in the Mahakam River during the intensive survey in 2017.

PC	Eigenvalues	%Variation	Cumulative %variation
1	3.18	35.4	35.4
2	2.06	22.9	58.3
3	1.69	18.8	77.1
4	1.29	14.3	91.4
5	0.31	3.4	94.8

Table 4.8 Factor loadings for the first three principal component (PC) axes for each environmental variable measured in the Mahakam River during the intensive survey in 2017. The stronger the factor, the closer to +1 or -1. Values > 0.4 are shown in bold.

Variable	PC1	PC2	PC3
Current (m/s)	0.223	-0.347	**0.512**
Depth (m)	-0.065	**0.565**	0.145
Width (m)	-0.010	0.176	**0.579**
Water temperature (^{0}C)	-0.139	0.217	-0.268
pH	**-0.413**	-0.341	-0.06
DO (mg/L)	-0.270	**-0.555**	0.143
Clarity (cm)	**-0.447**	-0.045	-0.351
TDS (mg/L)	**-0.499**	0.167	0.259
EC (µS/cm)	**-0.485**	0.168	0.309

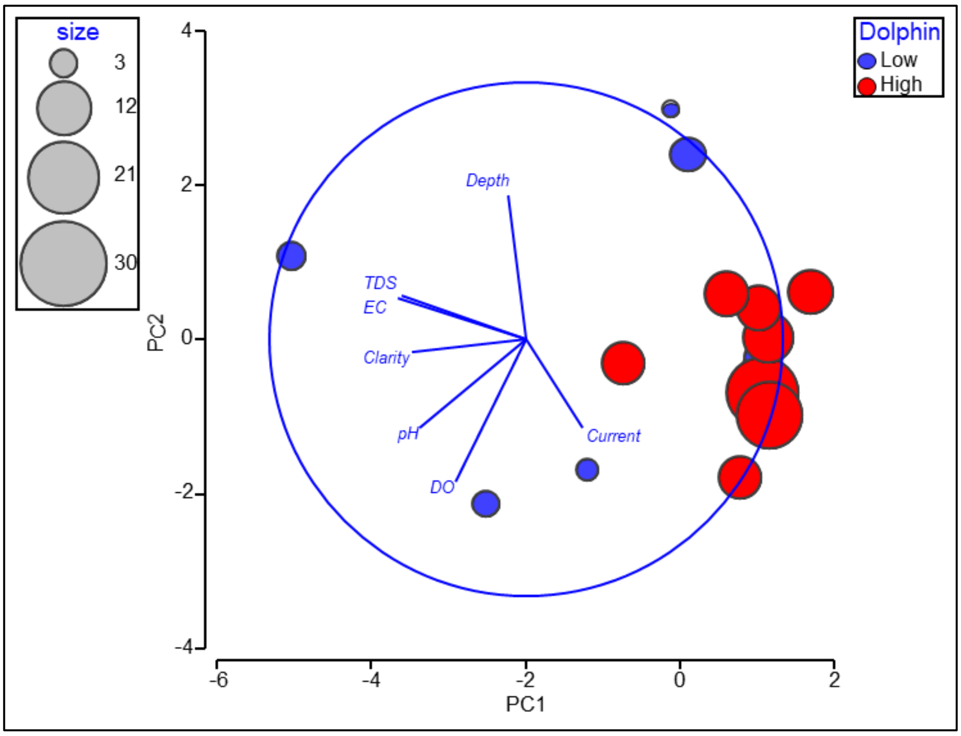

Figure 4-13: Plot of dolphin group size on principal component axes 1 and 2 showing correlated environmental factors in the Mahakam River during the intensive survey in 2017

4.3.5 Habitat disturbance

During the survey, a visual assessment of habitat disturbance within the river and on the riverbank was also carried out to characterise the human influences associated with dolphin habitat. These data were compiled based on river reaches in the mainstem (MR1, MR2), tributaries (MR1.2, MR1.3 and MR1.5) and at tributary confluences.

Table 4.9 shows the mainstem of the river had more intense boating, roading, fisheries and cropping at locations where dolphins were present, while settlement and mining was more prevalent albeit at low intensity in areas where dolphins were absent. In the tributaries, MR1.5 had the most intense human activity where dolphins were recorded, with two of four main activities occurring at high intensity (settlement and boat traffic; Table 4.10). MR2.1 was the only tributary where dolphins were not seen with a low intensity of disturbance comprising oil palm plantation on the riverbank. The confluence area was exposed to human activities in low to medium intensity, primarily from boating, although there was no pattern with dolphin presence or absence (Table 4.11). Fisheries activities and boat traffic were two types of human activities that potentially have a direct interaction with dolphin (Figure 4.14).

Table 4.9 Intensity of human disturbances observed in the mainstem of the Mahakam River (middle reach) where dolphins were present or absent during intensive survey in 2017. 0 = absent; 1 = low; 2 = medium; 3 = high intensity

Disturbance	MR1		MR2	
	Present	Absent	Present	Absent
Settlement	0	1	0	1
Boats	3	1	2	1
Road system	2	0	0	0
Fisheries	0	0	1	0
Cropland	2	0	1	0
Mining	0	1	0	0

Table 4.10 Intensity of human disturbances observed in the tributaries of the Mahakam River (middle reach) where dolphins were present or absent during intensive survey in 2017. 0 = absent; 1 = low; 2 = medium; 3 = high intensity

Disturbance	MR1.2		MR1.3		MR1.5		MR2.1
	Present	Absent	Present	Absent	Present	Absent	Absent
Settlement	0	2	0	1	3	0	0
Boats	1	2	0	1	3	0	1
Road system	0	1	0	0	1	0	0
Fisheries	0	1	0	1	1	0	1
Cropland	0	0	0	0	0	0	1
Mining	0	0	0	0	0	0	0

Table 4.11 Intensity of human disturbances observed in the confluence of the river (middle reach) during intensive survey in 2017. 0 = absent; 1 = low; 2 = medium; 3 = high intensity

Disturbance	Confluence	
	Present	Absent
Settlement	1	1
Boats	2	2
Road system	0	1
Fisheries	0	1
Cropland	1	1
Mining	0	0

Figure 4-14: Two types of disturbances with potential for direct interaction with Irrawaddy dolphin in the Mahakam River (middle reach). A and B show fisheries activities and C photo shows commercial boat traffic (note dolphins in foreground). Photo A and C courtesy of RASI. Photo B by author.

4.4 Discussion

As one of the rivers inhabited by the Critically endangered Irrawaddy dolphin, the Mahakam River and its catchment have an important role in supporting the existence of this dolphin species in Indonesia. However, some disturbances caused by human activities such as deforestation, settlement development, industry and mining have been suggested as factors causing deterioration of the river ecosystem and threatening the species. Degradation of river water quality due to human activities described earlier, and the intensity of fishing have been proposed as the main threats to Irrawaddy dolphin (Kreb & Budiono, 2005). However, to what extent these disturbances would affect distribution in the Mahakam River have not been investigated. The focus of this chapter is to examine the environmental factors that may have an influence on the river ecosystem and threaten the Irrawaddy dolphin population in the Mahakam River.

4.4.1 Dolphin distribution

This study supports the previous observations of Irrawaddy dolphin distribution occurring mainly in the middle reach of the Mahakam River (Kreb & Budiono, 2005). The mainstem of the middle reach, from Muara Muntai to Muara Pahu (MR2) and Muara Kaman to Muara Wis (MR1), had a high frequency of dolphin sightings over time, with MR2 having more sightings compared to MR1. A possible reason for this was that MR2 received less human disturbance in terms of settlement development, boat traffic and fisheries activities (further explained below), whereas MR1 is more populated with substantial fisheries activity. Irrawaddy dolphin were consistently sighted along these two river reaches indicating that these areas are the important habitat.

The occurrence of Irrawaddy dolphin in the mainstem of the middle reach could be due to many factors, which can directly or indirectly affect dolphin distribution. Shelford (1931) emphasised that the presence or absence of an organism in one location may be a response to certain environmental factors that influence the tolerance level of each animal to specific biotic and abiotic factors. The biotic factors may relate to predator existence and food availability, which in combination with physical environmental factors often control animal movement. Irrawaddy dolphin is on the top level of trophic interactions in the Mahakam River, suggesting that prey distribution could be more important in explaining high dolphin occurrence in the middle reach rather than physical environmental factors such as flow water regime.

Many studies have indicated that river discharge, low-water flow or seasonal flooding can influence fish distribution and dolphin occurrence within rivers (e.g. Smith et al., 2006; Beasley, 2007; Reeves & Martin, 2008). In rivers like the Mahakam River, where the vast floodplain area would be exposed to seasonal inundation, the river width will be wider, and the connectivity between river and floodplain land increased during high-water flow (Khan, 2017). Such flooding would increase the foraging area of dolphin enabling it disperse into the floodplain or move further upstream in tributaries (Baird & Mounsouphom, 1994; Kreb, 2004; Kreb & Budiono, 2005; Baird & Beasley, 2005). Thus, the probability of dolphins being sighted in a specific location would be expected to decrease. Most fish in tropical rivers would spawn during the flood season and enter inundated floodplains for breeding and feeding (Dudgeon, 1992; Baird & Mounsouphom, 1994), so it seems likely that dolphins would also disperse into inundated floodplain for feeding rather than concentrate in the mainstem of the river during the flood season.

During the last recent survey, 15 sightings were recorded at all river sections in the middle reach (mainstem, tributary and confluence) with estimated total group size of 110 individuals. Dolphins mostly occurred in water between 10–20 m deep, which is similar to patterns also observed for Irrawaddy dolphin in the Mekong River (Baird & Mounsouphom, 1994; Beasley, 2007). Kreb (2004) indicated that Irrawaddy dolphins prefer river sections with deep pools and medium velocity, which corresponds with most dolphin records in the recent survey. At low water level, the habitat would be restricted due to decreased connectivity between river sections, meaning dolphins may be more likely to congregate in deep pools within the mainstem. Thus, in low water discharge, dolphins may be more likely to move to deeper areas to avoid being trapped in shallow water, which likely corresponds with fish movements for the same reason (Beasley, 2007). In support of this, Leatherwood et al. (2000) suggested that deep water areas may directly or indirectly be affecting dolphins by providing refuge from counter-current or being the location of fish aggregation that related to the food supply.

Although flow regime may influence prey distribution, which in turn would be expected to affect dolphin movement, my study found that the number of sightings at both water levels in the Mahakam River were not significantly different. Water depth, current and channel width of the river were of secondary importance for dolphin numbers in the middle reach. This finding may partly reflect the small population that inhabited a restricted area in the Mahakam River; although further study on dolphin home range and foraging area would be needed to have a better understanding of this. Thus, it is also important to examine other contributing factors, in addition to prey availability and flow regime, that may affect dolphin distribution in the Mahakam River, as described below.

4.4.2 Environmental characteristics and habitat disturbance

Based on environmental time series data over 2010-2017, this study identified several physicochemical factors that characterised the middle reach of the river and may be related to dolphin numbers. Water temperature in the middle reach was lower (mean 27.5 ^{0}C) than in the lower reach (28.5 ^{0}C), where the Irrawaddy dolphin has never been seen. Although the difference in these spot measurements was small, over time accumulated temperature may influence the biological and chemical processes in the river, as well as fish metabolism. For example, warm water can interfere with reproduction and growth mechanisms, which in turn could influence prey fish abundance and distribution (Horne & Goldman, 1994; Wood & McDonald, 1997). Though the warm temperature may not have had a direct impact on dolphin physiology, it may increase the susceptibility to disease.

From my study on the Mahakam River water quality (see Chapter 3), water temperature showed a negative correlation with dissolved oxygen (DO) in the water such that warmer water typically had lower DO concentration. From 2010 to 2107, DO concentration in the middle reach was higher than the lower reach. Although unlikely to directly affect respiration of air-breathing dolphins, low DO could affect fish and potentially restrict their productivity or accessibility as prey. Total dissolved solids (TDS) and electrical conductivity (EC) in the lower reach were also high compared to the middle reach, which indicated that the lower reach might receive high-polluting discharges. TDS may not affect dolphin since they navigate and locate prey using echolocation, although sometimes dolphins use a downwelling light to capture fish in the surface (Tyack, 2008) suggesting turbid water might decrease ability to capture some prey.

Alternatively, TDS may have a direct effect on fish prey abundance (Wright, 2009). Dudgeon (1992) asserted that deforestation in tropical river catchments increases sedimentation and surface runoff, potentially affecting fish abundance due to lost habitat and less supply of food supported by allochthonous inputs. Erosion would increase TDS and EC in the river water (Yu et al., 2016), causing water turbidity which reduces light penetration into the water, limiting primary productivity and potentially leading to lower fish abundance through reduced basal resource supply. The combination of warm water, low DO, high TDS and high EC may contribute to low prey fish productivity in the lower reach, which might partly explain the absence of dolphins.

Dudgeon (2011) asserted that overfishing was also a potential threat for fish populations in tropical rivers. Irrawaddy dolphin’s main diet in the Mahakam River consists of five fish species dominated by cyprinids and catfish. Higher fish production in the Mahakam River correlated with increasing fishing intensity indicated by the number of gillnets, one of main fishing gears used in the Mahakam River. This finding may simply reflect the fact that most fishing occurs in areas of high fish abundance. The same reason may explain why the lower reach exhibited a low intensity of fisheries activities leading to low fish productivity estimates. The finding that dolphin numbers were highest in areas of high fish productivity may reflect overlap with fish migration corridors and areas of aggregation area, as found elsewhere for river dolphins (Smith et al., 2006; Beasley, 2007).

The middle reach located in the Middle Mahakam Area (MMA) is well-known as an area with high productivity of inland fisheries (Christensen, 1992), and therefore attracts intense fishing as evidenced by the higher number of gillnets. The high fish productivity in the middle reach may partly be due to the availability of vast floodplain areas and many swamp lakes and tributaries that provide suitable habitat for fish larvae and fry (Gorski et al. 2011), while in the lower reach, the swampland had changed into agriculture and urban areas which likely reduce the habitat suitability for fish. In addition, the middle reach has two designated areas for fish reserves that are Batu Bumbun and Loa Kalang. Both were located in the tributary of downstream end of MR2 and tributary of upstream end of MR1, respectively. These fish reserves are potentially explaining the high frequency of dolphin sightings in the middle reach. Spill-over from the fish reserve may play a role in sustaining the abundance of prey in the middle reach despite the high fishing pressure, raising an interesting avenue for future research.

The high number of gillnets in the middle reach would not only contribute to decreasing food supply but may also pose a direct threat to Irrawaddy dolphin through bycatch events. More than half of the reported dolphin mortality cases appeared to be caused by gillnets, most of which occurred in MR2 where dolphins were widely distributed. However, this inference should be treated with caution since the dolphin mortality data were obtained when dolphins were found floating or stranded in one location, and the origin of the dolphins was not always known. The high apparent mortality due to gillnets in MR2 contrasts with the lower number at MR1 where dolphins may avoid high disturbance from an urban area and high fishing pressure. Thus, dolphins may move to locations with less disturbance, represented by less fishing gear and human activity, to enhance the opportunity of catching fish (Khan, 2017).

From the catchment disturbance observations, boats and fisheries were the two activities that can have direct interaction with Irrawaddy dolphin in the Mahakam River, and potentially pose a threat for the dolphin population. Intense boat traffic would increase the chance of boat collision and noise disturbance to dolphins, which may alter their behaviour and damage dolphin sensory organs (Kreb & Rahadi, 2004).

4.4.3 Summary

The middle reach of the Mahakam River was confirmed as the most important habitat for Irrawaddy dolphin, as indicated by the consistent dolphin sightings throughout 1997–2017. Dolphin occurrence in this particular area was more likely related to environmental factors that influenced dolphin prey rather than direct impacts on individual dolphins. Number of gillnets, representing fishing pressure or a cause of direct mortality, was considered of secondary importance as a factor affecting dolphin distribution. The major contributing factors affecting prey abundance appeared to be related to land use impacts on water quality such as TDS, DO, EC and water temperature.

The first hypothesis that water level would influence dolphin distribution was not supported due to no significant difference in dolphin sightings between low and high water. Water level was more likey to have a direct influence on prey fish abundance and distribution which could indirectly affect dolphin distribution, but responses of dolphins to changing prey availability were not evident potentially due to the sparse population present in the Mahakam River.

The second hypothesis that river sections with extensive fisheries activities will have less frequent dolphin sightings was not supported. Dolphins were widely distributed in the middle reach despite intensive fisheries activities compared to the lower reach that had lower fisheries pressure. However, within the middle reach dolphins were more frequent in MR2 (Muara Muntai – Muara Pahu) which had less fishing pressure based on gillnet numbers than in MR1. This pattern may reflect a strategy of dolphins to avoid human disturbance and increase the chance of encountering more food, combined with the possible spill-over of prey from a fish reserve.

The third hypothesis that water quality would be related to dolphin distribution was supported, although these factors were likely to affect dolphins indirectly by influencing prey species productivity in the river. Dolphins were never found in the lower reach where agriculture and settlement development were intense and contributed to water quality deterioration (see Chapter 3), which likely interacts with other forms of human disturbance such as boating.

Chapter 5

General Discussion

The general aim of this study was to quantify the relationship between broad-scale catchment and river habitat degradation caused by human activities in relation to Irrawaddy dolphin distribution in the Mahakam River. While there are some studies in the Mahakam River and its floodplain on various aspects of hydrology, fisheries, lake ecology and dolphin population dynamics (e.g. Christensen, 1992; Kreb, 2004; Chokkalingam et al., 2005; Sassi et al., 2010; Hidayat et al., 2011; Hidayat, 2013; Vermeulen, 2014; de Jong et al., 2015), there are limited studies on the relationship of catchment disturbance with river water quality and to what extent water quality could affect dolphin distribution. Overseas studies on land use and water quality relationships have acknowledged that land use within the river catchment plays an important role in determining river health (e.g. Tu, 2011; Bu et al., 2014; Wang et al., 2014; Yu et al., 2016; Shi et al., 2017; Mainali & Chang, 2018).

Furthermore, studies of Irrawaddy dolphin in the Mekong River and Ayeyarwady River have highlighted that dolphin distribution may be related to environmental factors such as flow regime and water quality that would also influence dolphin food supply (Beasley, 2007; Bashir et al., 2010; Henley et al., 2010; Miserendino et al., 2011).This thesis aimed to determine (i) the relationship between land use change and water quality, and (ii) how this influenced dolphin distribution relative to other factors such as productivity of prey species and human disturbance. To address these aims, I quantified the spatial and temporal changes in water quality in the Mahakam River from government monitoring sites in relation to changing land use within sub-catchments. I used this information in conjunction with data on fisheries productivity and my own surveys of human disturbance factors to investigate the environmental factors associated with Irrawaddy dolphin distribution in the Mahakam River.

5.1 Dolphin habitat

Irrawaddy dolphins in the Mahakam River were frequently sighted in the middle reach of the river (mainstem areas MR1 and MR2) over 20 years. Based on this pattern and the occurrence of calves and juveniles during monitoring survey, this river reach provides important habitat for Irrawaddy dolphin within the river. The middle reach has a geomorphology characterised by many major lakes and tributaries, with vast peat swamp forests that form the immense floodplain area (Chokkalingam et al., 2005; van Gerven & Hoitink, 2009; MacKinnon et al., 2013; Hidayat et al., 2016). These off-channel areas are known as the main areas of freshwater fish productivity, as asserted by Christensen (1992; 1993a; 1993b). Two tributaries in the middle reach are designated as a fish reserve, and may contribute to the fish abundance in the middle reach. Along with higher water quality, prey availability supported in part by the fish reserve may attract dolphins to this part of the river.

Like other tropical rivers, the Mahakam River is also exposed to extensive human activities in the river catchment (Latrubesse et al., 2005; Dudgeon et al., 2006). In terms of land use, this is characterised by higher proportions of estate cropland and agricultural land than in the lower reach where dolphins were not observed. In my study, the land use data did not show the occurrence settlements in the middle reach, but this may be partly due to the variation of satellite imagery resulting from changing atmospheric conditions and difficulties distinguishing villages from vegetation and agricultural land (Horning et al., 2010). However, from observation during a recent survey, I found the middle reach to have high development of settlements, although it was less populated than the lower reach. Although differences in land use type and composition between river reaches reflect the intensity of human disturbance in river sub-catchments (Wang et al., 2014), dolphins were always found in the middle reach suggesting the land use type were not having a direct effect on dolphin distribution.

In my study, dolphins occurred in the river reach that was less turbid with higher dissolved oxygen and cooler water. These factors are more likely to influence habitat availability for fish prey rather than having direct effects on dolphins. These water quality parameters are important for fish metabolism and could affect fish prey productivity, although this was not specifically investigated in my study (see below). Furthermore, dolphins were likely to occur in parts of the river that had deep water areas, medium current and narrow width, similar to studies for other river dolphins (Smith et al., 2006; Beasley, 2007; Reeves et al., 2008), suggesting that these habitats may be correlated with prey distribution.

5.2 River health and food supply

Longitudinal variations in water quality affect the distribution and abundance of the species sensitive to water quality gradients (Horne & Goldman, 1994; MacKinnon et al., 2013). The Mahakam River catchment land cover and land use changed over time due to intensive development in rural areas, which in turn may be affecting dolphin health and fish prey abundance (Bashir et al., 2010; Henley et al., 2010; Miserendino et al., 2011). From my study, the current state of water quality in the Mahakam River indicated that some parameters, namely COD, BOD, NO_3-N, NH_3-N, and TP, exceeded the Indonesian government threshold and/or the ANZECC trigger value for species protection. The high concentration of these parameters indicates that the Mahakam River received many pollutants from the catchment, whereas normally tropical rivers would have low nitrogen and phosphorus concentrations and soft water (Dudgeon, 1992).

The water quality in the Mahakam River changed spatially and temporally during 1997–2017, reflecting changing patterns of land use in the catchment. For example, water temperature increased in a downstream direction which may reflect extensive agricultural land in the lower parts of the river reducing the vegetation cover shading tributaries in the river catchment. Warmer water can affect fish reproduction and growth, thereby influencing fish abundance (Dudgeon, 1992; Horne & Goldman, 1994; Wood & McDonald, 1997). The lower reach of the river also had poorer water quality compared to other reaches. This condition may be due to the co-occurrence of two major sources of pollution, agriculture and settlements which contribute fertiliser runoff and sewage to the river. NO_3-N was lower in the middle reach compared to the lower reach where it may increase the productivity of algae and decrease DO concentration. Lower DO concentration in the lower reach affecting fish prey may partly explain the absence of dolphin from this area.

The increasing percentage area of estate cropland in the catchment, notably in the middle reach, showed a positive relationship with TDS concentration in the river, presumably reflecting soil erosion due to land clearance (Fitzhebert et al., 2008). Although TDS may not directly affect dolphins, which use echolocation, it may influence fish prey movement and basal resources supporting river food webs (e.g., through effects on primary productivity). The increasing trend in TDS over time would increase these potential threats to dolphin prey. In addition, the agricultural land in the downstream cacthment showed a positive relationship with SO_4 that reflecting amount of fertiliser discharged into the river. Similar to TDS, SO_4 may not directly affect dolphins but may influence fish prey productivity. My study suggested that indirect effects on prey were likely to be the main pathway by which water quality parameters related to land use affected dolphins in the Mahakam River. Thus, habitat for dolphins should also support prey fish productivity, conditions that may not occur in the lower reach.

The role of fish prey in determining dolphin distribution has also been indicated by some studies overseas. For example, the Irrawaddy dolphin in the Mekong River would follow fish movement to deep water during low water flow (Beasley, 2007; Smith & Jefferson, 2002), while in the flooding season the fish prey would disperse into the floodplain area for spawning and feeding (Dudgeon, 1992). Dolphins would disperse into the inundated floodplain because many fish occur in this area. Thus, floodplain disturbance would not only impact on habitat loss but also adversely affect water quality needed for fish reproduction and growth.

The dominant fish species in the Mahakam River is from the Cyprinidae family (Christensen, 1992) which dominates the fish community in Asian tropical river generally (Winnemiller et al., 2008). Accordingly, it is a key dietary species for Irrawaddy dolphin and also a target fisheries species in the Mahakam River. Two species of cyprinids and one species catfish showed a decreasing catch rate over time while the number of gillnets increased. This observation may suggest pressure from overfishing in the river, although the main reason for fish species decline is unclear since this study did not assess causes of decreasing productivity. Another two catfish species showed increasing productivity; however, it was not clear whether this was due to increased fish stocks or due to increasing fishing effort represented by the number of gillnets.

5.3 Threats and mortality

Humans and dolphins must share habitat on the river, particularly in the middle reach. Extensive development in the Mahakam River catchment has increased the frequency of boat traffic in the river to support human activities and the demand for fish resources as a food supply. Up to 20 boats per hour would use the river waterways (Kreb & Rahadi, 2004), and this high number would increase the potential of collision. In addition, noise from the boat engines would change dolphin behaviour and potentially damage dolphin sensory organs (Kreb & Rahadi, 2004). Also, as noted earlier, floodplain disturbance due to swampland conversion into settlements, agricultural land and cropland would likely affect the fish prey abundance both through loss of habitat and deterioration in water quality influencing dolphin fish prey. Collectively, these activities showed the extent of human influence in the Mahakam River which may lead to a decreasing dolphin population and overall biodiversity loss.

From my observations and analysis of fisheries data, the increasingly high fishing pressure in the middle reach where the dolphins were present may make prey resources susceptible to overfishing. Additionally, the high number of gillnets deployed in the river would increase the bycatch threat to dolphins, with more than 50% of dolphin mortalities in the Mahakam River known to be caused by gillnets, although not all these reports can be confirmed. On the other hand, unsustainable fishing methods such as electrofishing could also cause fatalities, as has happened to Yangtze river dolphin (Zhang et al., 2003; Turvey et al., 2007).

5.4 Conservation efforts

Considering the decreasing number of Irrawaddy dolphin populations and changing distribution patterns, urgent conservation action is needed to overcome these problems. Some initiatives have been taken to reduce the threats and possible impacts on the dolphin population in the Mahakam River. Training of fisherman was conducted on how to release dolphins from gillnet without causing further injury or death, helping reduce the mortality caused by entanglement. Raising awareness has also been conducted for related stakeholders, youth and communities (Kreb et al., 2010).

In addition, protection areas for Irrawaddy dolphin have been proposed and included core river habitat and forest swamp areas (Kreb & Budiono, 2005). In 2009, Muara Pahu sub-district in the middle reach (MR2) was designated as a protected area for Irrawaddy dolphin (SEAMAM III, 2015). Recently, the area designated for Irrawaddy dolphin protection has gone to the provincial government for approval (Kreb, pers.comm, 2017). The conservation efforts from other areas where Irrawaddy dolphin occur could provide lessons to be learned in improving the conservation initiative in the Mahakam River. For example, the Ayeyarwady Dolphin Protected Area (ADPA) aims to reduce illegal fishing activities, promote human-dolphin cooperation, protect dolphin habitat through the elimination of gold mining and promote sustainable fishing practices (Lin, 2017). Moreover, in the Mekong River, an initiative started in 2005 through the Cambodian Mekong Dolphin Conservation Project is focussing on population studies, education, policy development and promoting transboundary collaboration with Lao PDR (Phan, 2017).

Conservation efforts to protect Irrawaddy dolphin should be followed by improvement of river management through regulation of catchment activities, industrial discharge evaluation, sewerage treatment plant development and improvement of agricultural practices. Policy that supports sustainable river management should be put in place to ensure the Irrawaddy dolphin habitat would not be further degraded due to uncontrolled human activities. Law enforcement is also important to ensure the policy is implemented. Evaluation and monitoring of river management and policy implementation are needed to provide comprehensive information that can be used to enhance the conservation effort and reduce the impacts of catchment activities. The establishment of the freshwater protected area in the Mahakam River may be important solution that can help to enhance dolphin habitat (Kreb & Budiono, 2005; Kreb et al., 2010) along with the improvement of fish reserve areas to help support prey fish species.

5.5 Future work

This study gives an insight into the relationship between land use change and water quality status in the Mahakam River, and other environmental factors that may influence Irrawaddy dolphin distribution. However, this study was limited to assessing the water quality parameters influenced by land use change, and effects of heavy metals in the river or on dolphin populations were not assessed due to limited availability of data. Further study should be carried out to determine patterns and sources of heavy metals in the river from mining activities, and the effects on dolphin population health to understand the overall impact of human activities in the river catchment. Additionally, a study on factors affecting the abundance and distribution of fish in the Mahakam River should be carried out to understand the importance of fish prey for Irrawaddy dolphin distribution and to quantify on the role of fish reserves in the middle reach.

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Appendices

Appendix 1: Total catchment area (ha) in each monitoring site. MS = monitoring site

Land use type	MS-1				MS-2				MS-3			
	1996	2011	2014	2017	1996	2011	2014	2017	1996	2011	2014	2017
FOREST	132.1	76.64	83.24	257.35	50.73	45.64	42.17	36.84	73.58	21.24	1.85	0
AGRICULTURAL	0	3.45	3.45	22.18	0	0.74	0	16.05	0	366.66	0	0
SWAMP	1002	1017.52	1037.25	824.44	774.21	654.7	878.72	883.78	759.23	267.59	634.61	601.99
ESTATE CROP	0	5.63	9.89	10.45	17.09	17.09	116.42	149.57	0	192.77	192.29	195.26
SETTLEMENT	2.76	0	0	3.53	0	0	0	0	0	0	0	6.15
MINING	0.67	5.09	5.82	8.67		4.41	0.79	1.20	0	5.40	5.40	1.06
OTHERS	16.43	45.66	14.35	27.38	285.32	404.77	89.24	39.91	76.54	55.69	75.20	104.89
Total area (ha)	1154	1153.99	1153.99	1153.99	1127.34	1127.3	1127.34	1127.34	909.35	909.35	909.35	909.35

Appendix 1 continued

Land use type	MS-4				MS-5				MS-6			
	1996	2011	2014	2017	1996	2011	2014	2017	1996	2011	2014	2017
FOREST	73.58	21.24	1.85	0.00	34.53	0.00	0.00	66.21	260.73	82.69	61.52	166.05
AGRICULTURAL	0.00	366.66	0.00	0.00	16.34	536.16	23.62	29.67	37.98	382.40	45.14	46.34
SWAMP	759.23	267.59	634.61	601.99	776.62	245.17	778.43	649.19	362.04	196.52	565.57	405.09
ESTATE CROP	0.00	192.77	192.29	195.26		41.61	44.96	81.30				32.60
SETTLEMENT	0.00	0.00	0.00	6.15	5.41	9.87	9.87	12.81	3.40	2.55	2.55	14.56
MINING	0.00	5.40	5.40	1.06	7.57	7.57	8.94	8.87	2.87	2.87	2.87	10.40
OTHERS	76.54	55.69	75.20	104.89	81.02	81.12	55.68	73.45	37.21	37.21	26.59	29.20
Total area (ha)	909.35	909.35	909.35	909.35	921.50	921.50	921.50	921.50	704.23	704.23	704.23	704.23

Appendix 1 continued

Land use type	MS-7				MS-8				MS-9			
	1996	2011	2014	2017	1996	2011	2014	2017	1996	2011	2014	2017
FOREST	316.28	16.91	3.18									
AGRICULTURAL	56.92	278.81	60.76	46.23	0.36	17.94	14.86	14.86	2.11	2.11	2.11	2.11
SWAMP	317.72	373.82	584.64	602.73	18.54	0.23	2.77	2.77				
ESTATE CROP			5.80	3.11								
SETTLEMENT	10.29	11.28	17.45	30.04	9.69	10.09	10.09	10.03	9.31	9.31	9.31	9.31
MINING	95.06	114.45	133.89	123.59	0.83	1.17	1.71	1.77				
OTHERS	21.73	22.74	12.30	12.32	1.96	1.96	1.96	1.96	3.29	3.29	3.29	3.29
Total area (ha)	818.00	818.00	818.00	818.00	31.39	31.39	31.39	31.39	14.70	14.70	14.70	14.70

Appendix 2: TimeTrend analysis results for water quality during the period 1993-1998

Site	Variable	Samples used	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-1	Temperature	27	27.204	29.4	24.8	27.1	8	20	1.565	0.118	0.366	1.35
MS-1	pH	27	6.628	7.97	5.4	6.6	-1	19	0	1	-0.05	-0.764
MS-1	EC	25	46.923	109	30	37	2	18	0.236	0.814	0.964	2.605
MS-1	DO	27	5.737	9.2	3.8	5.8	3	19	0.459	0.646	0.296	5.112
MS-1	BOD	26	5.038	12	1	4	-2	15.333	-0.255	0.798	-0.126	-3.157
MS-1	COD	25	19.615	40	4	18	-13	19	-2.753	0.006	-6.054	-33.633
MS-1	NO3-N	22	0.398	2.38	0.01	0.31	8	15.333	1.788	0.074	0.277	89.249
MS-1	NH3N	22	0.466	1.54	0.01	0.27	-1	11	0	1	-0.169	-62.492
MS-5	Temperature	29	27.755	29.6	25.8	27.6	7	27.667	1.141	0.254	0.17	0.617
MS-5	pH	29	6.28	7.2	5	6.4	-6	24.667	-1.007	0.314	-0.051	-0.799
MS-5	EC	27	42.214	110	20	36.5	11	25.667	1.974	0.048	3.032	8.307
MS-5	DO	29	4.866	6.2	2.8	5.3	-1	27.667	0	1	-0.101	-1.897
MS-5	BOD	29	4.621	13	1	3	-1	25.667	0	1	0	0
MS-5	COD	23	17.308	32	4	19	-2	24.667	-0.201	0.84	-1.339	-7.05
MS-5	NO3-N	20	0.856	5.67	0.02	0.4	7	14.333	1.585	0.113	0.29	72.47
MS-5	NH3N	23	0.512	1.66	0.03	0.5	1	13.667	0	1	0.02	3.927
MS-6	Temperature	56	28.587	32.2	25.7	28.5	27	169.667	1.996	0.046	0.133	0.466
MS-6	pH	59	6.496	7.8	5.1	6.5	-15	193.667	-1.006	0.314	-0.057	-0.884
MS-6	EC	56	48.475	93	28.6	43.5	28	166	2.096	0.036	2.412	5.545
MS-6	DO	56	4.734	7.8	0.2	4.9	-13	169.667	-0.921	0.357	-0.1	-2.038
MS-6	BOD	51	3.961	13	1	3	-20	126	-1.693	0.091	-0.498	-16.601
MS-6	COD	51	20.961	45	7	21	-16	130	-1.316	0.188	-1.47	-7.001
MS-6	NO3-N	53	2.159	5.4	0.05	2.09	27	147	2.144	0.032	0.454	21.722
MS-6	NH3N	22	0.336	1.23	0.01	0.15	-4	15.333	-0.766	0.444	-0.284	-189.233

Appendix 2: continued

Site	Variable	Samples used	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-7	Temperature	67	28.327	31.1	25.9	28.1	38	274.667	2.233	0.026	0.149	0.532
MS-7	pH	69	6.562	7.7	5.4	6.6	1	304.333	0	1	0	0
MS-7	EC	69	48.87	100	30	44	36	301.333	2.016	0.044	1.511	3.435
MS-7	DO	67	4.555	7.2	0.5	4.8	-4	282	-0.179	0.858	-0.02	-0.415
MS-7	BOD	67	4.239	14	1	3	-14	264.143	-0.8	0.424	0	0
MS-7	COD	64	20.172	40	3	20	-13	252.333	-0.755	0.45	-0.67	-3.351
MS-7	NO3-N	63	2.001	5.7	0.01	1.99	68	244.667	4.283	0	0.675	33.908
MS-7	NH3N	34	0.449	1.43	0.03	0.33	-11	42.333	-1.537	0.124	-0.251	-76.018
MS-9	Temperature	67	28.003	30.7	26	28	51	277.667	3.001	0.003	0.252	0.901
MS-9	pH	69	6.441	7.6	5.3	6.5	-14	304	-0.746	0.456	-0.051	-0.779
MS-9	EC	66	43.1	110	2	44	16	272.667	0.908	0.364	1.505	3.421
MS-9	DO	67	4.734	7.5	0.4	4.8	-6	276	-0.301	0.763	-0.034	-0.71
MS-9	BOD	65	4.231	13	1	3	-25	235	-1.566	0.117	-0.224	-7.472
MS-9	COD	65	20.723	54	3	19	-26	256	-1.563	0.118	-0.903	-4.752
MS-9	NO3-N	62	2.116	5.9	0.01	2	86	230.667	5.597	0	0.712	35.615
MS-9	NH3N	32	0.398	1.3	0.01	0.36	-6	40	-0.791	0.429	-0.035	-9.745

Appendix 3: TimeTrend analysis results for water quality during the period 2010-2017.

Site	Variable	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-1	Temperature	26.904	30.4	22.56	26.535	0	206	0	1	-0.006	-0.024
MS-1	pH	6.673	7.73	4.49	6.87	26	206	1.742	0.082	0.072	1.051
MS-1	EC	42.903	158	0.012	41	-6	162	-0.393	0.694	-0.332	-0.809
MS-1	TDS	37.685	204	9	25.67	39	205	2.654	0.008	1.94	7.558
MS-1	DO	5.57	8.94	2.6	5.745	-12	206	-0.766	0.443	-0.079	-1.373
MS-1	BOD	6.038	24.18	0.7	4.84	-46	198	-3.198	0.001	-1.133	-23.412
MS-1	COD	16.343	49.8	2	11.43	-38	206	-2.578	0.01	-2.509	-21.949
MS-1	NO2-N	0.004	0.012	0	0.004	-2	172.667	-0.076	0.939	0	0
MS-1	NO3-N	0.547	1.91	0	0.44	-25	172.333	-1.828	0.068	-0.059	-13.389
MS-1	NH3N	0.182	2	0.005	0.088	-18	206	-1.184	0.236	-0.01	-11.278
MS-1	TP	0.012	0.09	0	0.002	-16	164.667	-1.169	0.242	0	-17.59
MS-1	SO4	2.812	23.47	0.006	0.7	46	190	2.995	0.003	0.343	54.49
MS-2	Temperature	27.206	30.5	24.97	27	-2	204	-0.07	0.944	-0.025	-0.093
MS-2	pH	6.513	7.9	4.3	6.785	10	206	0.627	0.531	0.015	0.228
MS-2	EC	40.027	214	0.007	36.95	-14	201.333	-0.916	0.36	-1.105	-2.99
MS-2	TDS	44.643	287	9	22.67	35	203	2.386	0.017	1.093	4.819
MS-2	DO	5.471	7.83	2.7	5.6	4	206	0.209	0.834	0.016	0.287
MS-2	BOD	5.713	22.6	0.81	4.36	-58	198	-4.051	0	-1.34	-30.744
MS-2	COD	18.774	64.61	1.25	14.7	-62	206	-4.25	0	-4.497	-30.591
MS-2	NO2-N	0.006	0.023	0	0.004	6	197.333	0.356	0.722	0	0
MS-2	NO3-N	0.598	1.83	0.007	0.505	-15	205	-0.978	0.328	-0.046	-9.189
MS-2	NH3N	0.113	1.25	0.001	0.065	-26	206	-1.742	0.082	-0.005	-8.032
MS-2	TP	0.036	0.96	0	0.002	-28	175.333	-2.093	0.036	-0.001	-53.76
MS-2	SO4	3.139	18.15	0.006	0.915	58	206	3.851	0	0.45	51.156

Appendix 3: continued

Site	Variable	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-3	Temperature	27.516	32.3	23.57	27.35	-1	205	0	1	-0.003	-0.009
MS-3	pH	6.518	7.6	4.68	6.695	-3	205	-0.14	0.889	-0.003	-0.05
MS-3	EC	39.705	186	0.008	35.95	-25	200.333	-1.696	0.09	-1.522	-4.233
MS-3	TDS	39.008	260	7	23	29	205	1.956	0.051	1.52	6.608
MS-3	DO	5.338	9	2.4	5.47	-8	206	-0.488	0.626	-0.067	-1.222
MS-3	BOD	6.659	29.04	0.3	5.21	-45	193	-3.167	0.002	-1.284	-24.639
MS-3	COD	21.534	69.26	1.25	14	-50	206	-3.414	0.001	-5.457	-38.978
MS-3	NO2-N	0.005	0.014	0	0.004	-7	195.667	-0.429	0.668	0	0
MS-3	NO3-N	0.545	1.95	0.007	0.44	-19	205	-1.257	0.209	-0.043	-9.747
MS-3	NH3N	0.148	2	0.001	0.08	-41	200.333	-2.762	0.006	-0.013	-17.325
MS-3	TP	0.053	0.65	0	0.003	-24	188.667	-1.674	0.094	0	-9.108
MS-3	SO4	3.129	23.57	0.006	0.77	46	206	3.156	0.002	0.472	62.991
MS-4	Temperature	27.642	30.9	25.32	27.75	-6	206	-0.348	0.728	-0.035	-0.124
MS-4	pH	6.552	7.6	4.71	6.69	10	206	0.627	0.531	0.019	0.288
MS-4	EC	36.04	60	0.008	37	-14	185.333	-0.955	0.34	-1.061	-2.867
MS-4	TDS	36.106	199	12	23	28	188	1.394	0.163	0.847	3.734
MS-4	DO	5.375	8.78	2.4	5.325	-2	206	-0.07	0.944	-0.013	-0.241
MS-4	BOD	6.528	25.82	0.4	4.84	-44	198	-3.056	0.002	-1.131	-23.369
MS-4	COD	21.234	59.67	2.8	16	-50	206	-3.414	0.001	-4.871	-30.441
MS-4	NO2-N	0.005	0.021	0	0.004	5	201	0.282	0.778	0	0.258
MS-4	NO3-N	0.561	1.99	0	0.43	-23	185	-1.617	0.106	-0.072	-16.747
MS-4	NH3N	0.08	0.44	0.004	0.05	-21	200.333	-1.413	0.158	-0.005	-10.859
MS-4	TP	0.026	0.39	0	0.007	-14	194.667	-0.932	0.351	0	-3.196
MS-4	SO4	3	23.57	0.003	0.925	50	206	3.436	0.001	0.422	50.817

Appendix 3: continued.

Site	Variable	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-5	Temperature	28.057	31.5	25.62	27.8	1	205	0	1	0.025	0.09
MS-5	pH	6.531	7.7	4.6	6.645	20	204	1.33	0.183	0.036	0.535
MS-5	EC	41.948	219	0.009	36.43	-6	193.333	-0.36	0.719	-0.323	-0.887
MS-5	TDS	36.257	216	7	22.2	42	204	2.871	0.004	2.116	9.532
MS-5	DO	5.225	9.04	2.55	5.23	2	206	0.07	0.944	0.012	0.239
MS-5	BOD	6.063	20.96	0.5	4.48	-51	193	-3.599	0	-0.827	-18.458
MS-5	COD	21.564	56.38	1.8	14	-60	206	-4.111	0	-5.757	-41.12
MS-5	NO2-N	0.005	0.02	0	0.004	4	198	0.213	0.831	0	0
MS-5	NO3-N	0.606	1.8	0.007	0.545	-34	206	-2.299	0.021	-0.092	-16.912
MS-5	NH3N	0.108	1.25	0.001	0.06	-11	205	-0.698	0.485	-0.006	-9.451
MS-5	TP	0.058	0.84	0	0.009	-29	200.333	-2.471	0.013	-0.001	-12.301
MS-5	SO4	3.252	18.91	0.006	1.04	43	205	2.953	0.003	0.419	49.862
MS-6	Temperature	28.721	33	25.8	28.6	3	38.333	0.323	0.747	0.074	0.259
MS-6	pH	6.951	8.2	5.77	6.915	7	38.333	0.969	0.333	0.075	1.078
MS-6	EC	46.409	91	0.015	48.5	4	36.667	0.495	0.62	2.138	4.408
MS-6	TDS	62.593	255	11	31.585	16	39.333	2.392	0.017	12.506	39.595
MS-6	DO	4.924	8.4	2.7	4.525	-6	39.333	-0.797	0.425	-0.171	-3.787
MS-6	BOD	6.588	24.19	0.2	4.84	8	39.333	1.116	0.264	0.293	6.05
MS-6	COD	18.36	39.2	2.6	17.99	-2	25.333	-0.199	0.843	-0.408	-2.268
MS-6	NO2-N	0.006	0.024	0	0.005	-9	38.333	-1.292	0.196	-0.001	-13.896
MS-6	NO3-N	0.624	1.2	0	0.7	-4	39.333	-0.478	0.632	-0.039	-5.601
MS-6	NH3N	0.091	0.28	0.001	0.09	-1	28.333	0	1	0	0
MS-6	TP	0.027	0.28	0	0.008	-8	39.333	-1.116	0.264	-0.004	-45.814
MS-6	SO4	2.743	12.49	0.032	0.995	10	39.333	1.435	0.151	1.223	122.877

Appendix 3: continued

Site	Variable	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-7	Temperature	28.727	31.6	25.9	28.7	1	44.333	0	1	0.037	0.13
MS-7	pH	6.926	8.1	5.85	6.81	12	43.333	1.671	0.095	0.141	2.077
MS-7	EC	44.466	76.07	0.013	44.5	-3	41.667	-0.31	0.757	-0.349	-0.785
MS-7	TDS	55.675	223	9	29	11	44.333	1.502	0.133	9.98	34.413
MS-7	DO	4.758	8.4	2.2	4.53	-15	44.333	-2.103	0.035	-0.513	-11.324
MS-7	BOD	7.277	32.24	0.08	6	-1	44.333	0	1	-0.227	-3.784
MS-7	COD	22.698	61.7	1.7	20.65	-4	31.333	-0.536	0.592	-1.046	-5.066
MS-7	NO2-N	0.006	0.024	0	0.005	-5	40.333	-0.63	0.529	0	-9.925
MS-7	NO3-N	0.651	1.32	0	0.72	-2	39.333	-0.159	0.873	-0.032	-4.464
MS-7	NH3N	0.216	1.8	0.005	0.08	3	44.333	0.3	0.764	0.007	8.78
MS-7	TP	0.024	0.18	0	0.01	-8	43.333	-1.063	0.288	-0.003	-30.779
MS-7	SO4	2.88	14.25	0.032	0.883	9	44.333	1.202	0.23	0.235	26.592
MS-8	Temperature	28.997	31.2	25.7	28.7	13	41.667	1.859	0.063	0.265	0.924
MS-8	pH	6.808	8.7	5.15	6.78	7	41.667	0.93	0.353	0.08	1.181
MS-8	EC	46.051	77.9	0.018	48.86	-8	40.667	-1.098	0.272	-1.604	-3.282
MS-8	TDS	57.194	205	9	30.5	7	41.667	0.93	0.353	2.369	7.766
MS-8	DO	5.162	9.6	2.6	4.645	-9	41.667	-1.239	0.215	-0.644	-13.87
MS-8	BOD	6.392	22.58	0.8	4.2	-4	40.667	-0.47	0.638	-1.147	-27.311
MS-8	COD	21.536	58.82	1.4	16.685	-7	35.667	-1.005	0.315	-4.003	-23.99
MS-8	NO2-N	0.007	0.022	0	0.005	-7	37.667	-0.978	0.328	-0.001	-19.824
MS-8	NO3-N	0.733	1.93	0.01	0.74	1	41.667	0	1	0.01	1.352
MS-8	NH3N	0.242	2.5	0.001	0.1	-7	41.667	-0.93	0.353	-0.025	-25.069
MS-8	TP	0.032	0.31	0	0.013	-8	40.667	-1.098	0.272	-0.002	-12.432
MS-8	SO4	3.047	14.25	0.032	1.005	13	41.667	1.859	0.063	0.522	51.967

Appendix 3: continued

Site	Variable	Mean	Max	Min	Median	Kendall statistic	Variance	Z	P	Sen slope (annual)	Percent annual change
MS-9	Temperature	28.723	30.73	25.6	28.7	6	43.333	0.76	0.448	0.08	0.279
MS-9	pH	6.893	8.35	4.73	6.9	12	43.333	1.671	0.095	0.098	1.423
MS-9	EC	43.531	75	0.014	47	1	41.667	0	1	0.304	0.646
MS-9	TDS	49.593	186	8	27	13	44.333	1.802	0.072	10.056	37.244
MS-9	DO	4.802	8.74	2.05	4.45	-3	42.333	-0.307	0.759	-0.05	-1.114
MS-9	BOD	8.117	32.24	0.08	4.68	10	43.333	1.367	0.172	0.441	9.421
MS-9	COD	25.953	78.74	2.6	24.67	-3	44.333	-0.3	0.764	-1.868	-7.572
MS-9	NO2-N	0.007	0.02	0	0.007	-7	40.333	-0.945	0.345	-0.001	-20.146
MS-9	NO3-N	0.707	2.01	0	0.65	-3	44.333	-0.3	0.764	-0.089	-13.73
MS-9	NH3N	0.262	2.5	0.005	0.075	-5	44.333	-0.601	0.548	-0.005	-6.755
MS-9	TP	0.03	0.3	0	0.011	-11	42.333	-1.537	0.124	-0.003	-27.903
MS-9	SO4	2.93	14.69	0.032	1.13	7	44.333	0.901	0.368	0.317	28.019

Appendix 4: Dolphin sightings and group size during extensive monitoring survey December 2017.

River reach	River section	Dolphin group size
MR1	Mainstem	3
MR1.5	Tributary	3
MR1	Confluence	1
MR1.2	Tributary	5
MR2	Confluence	2
MR1.5	Confluence	4
MR1.4	Tributary	4
MR1.4	Tributary	21
MR1	Mainstem	11
MR2	Mainstem	8
MR2	Mainstem	18
MR2	Mainstem	8
MR1.5	Tributary	8
MR1	Mainstem	7
MR1.4	Confluence	7