THE UNIVERSITY OF HULL

Management of Watergate to Enhance Fisheries In the Nam Kam River System, Thailand

being a Thesis submitted for the Degree of

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by

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ACRONYMS

CPUE	Catch per unit effort
DoF	Department of Fisheries, Thailand
MRC	Mekong River Commission
MFD	Mekong Fish Database
ICOLD	International Commission on Large Dam
ICEM	International Center for Environmental Management
IHA	Indicator of Hydrologic Alteration
IUCN	International Union for Conservation of Nature
FAO	Food and Agriculture Organization of the United Nations
FAO/DVWK	Food and Agriculture Organization of the United Nations in arrangement with Deutscher Verband fur Wasserwirtschaft und Kulturbau e.V.
RID	the Royal Irrigation Department, Thailand
RVA	Range of Variability Approach
WCD	World Commission on Dams
WHO	World Health Organization
WQD	Water Quality Division, Thailand

DECLARATION OF AUTHORSHIP

I, Miss Apiradee Hanpongkittikul, declare that this thesis and the work present in it are my own and has been generated by me as the result of my own original research.

This study funded with support from the Fisheries Programme of the Mekong River Commission in 2013 and 2014 covering two components:

1. Distribution and migration patterns of two economic fish species in Nam Kam River conducted in 2013 and;
2. The impact assessment of weir operation on fish abundance in Nam Kam River and its tributary conducted in 2014

These are based on work done by myself jointly with other colleques from Department of Fisheries, Thailand. The secondary data about the migration of fish through fish passes (Thoranit Naruemit and Suraswadi watergates) used in Chapter 7 were provided by Ngoichansri *et al.* (inpress), my colleques who that got the funding from the same source and the research has been conducted in the same sampling period (2012-2013).

I confirm that:

1. This work has been done wholly or mainly while in the candidature for a research degree at this University;

2. Where I have cited or used secondary data from the work of others, the sources are always given;

3. I have acknowledged all main sources of help;

4. Where any part of this thesis has previously been published, presented and submitted as an anual report to funding agency before university submission, this has been clearly stated as below.

CONFERENCE PRESENTATIONS

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ABSTRACT

The impact of watergate operation on hydrology and habitat, and their effects on fish migration, fish diversity, population structure, and recruitment of fisheries resources were studied in the Nam Kam River system, a tributary of the Mekong in Thailand. The factors that influence the migration of fish were identified and the effectiveness of fish passage facilities installed at watergates in the river system were investigated.

The flow regime and flood cycle were modified by watergate operation, which is designed to control floods in the wet season and retain water for irrigation in the dry season. Fluctuations in flow and water level were created and varied along the river in the wet season. Timing, frequency and duration of floods in each habitat down the river were altered. Operations for irrigation removed low flows and created longer periods of no flow in the dry season. The river becomes stagnant and water levels in the floodplains above the watergates are higher than pre-construction. Many new nursery and feeding habitats were created after construction, but water abstraction also disconnected the floodplain below the watergate and the mainstem river. Flow modification driven by watergate operation for flood control is likely to delay water level rise at the onset of the flood in the downstream area that trigger upstream migration of fish into the Nam Kam River system, especially pangasids. The watergate operation limits the upstream migration of adult fish at the onset of the flood season and inhibits the upstream migration of late migrating species, the downstream migration of fish, and drifting of eggs, larval and juvenile fish since all sluice gates were closed at the end of the flood season. Longitudinal migrating species are more likely to be impacted than lateral migrating species and this will impact on the overall population structure of fishes.

Several longitudinal migratory white fish species, main channel residents and main channel spawners declined in abundance or were absent in the upstream area above Thoranit Naruemit Watergate and it most likely resulted from hydrological alteration driven by watergate operation. Fish larvae and juvenile fish in this river system were dominated by resident grey and black fish, while recruitment of white fish species was limited as watergate operation obstructs the upstream migration of adult fish during the spawning season. Diversity of fish in the river decreased from downstream to upstream area, it shows a negative relationship with number of barriers. The relative abundance of white fish was significantly different between the floodplain above and below Thoranit Naruemit watergate during the study period. Seasonal distribution of fish in the Nam Kam River system is different from the free-flowing Songkhram River. At the end of flood season, diversity of fish in the regulated river was high since larvae and juvenile fish and many white and grey fish species are stranded in the floodplain above the watergate after sluice gates were completely closed. These fish have subsequently adapted to feed and grow in the poor habitat conditions during the dry season. Genetic study of two target species, *Hemibagrus nemurus* and *Osteochilus hasselti*, indicates high genetic diversity and big population sizes maintained by gene flow from the downstream populations and nearby populations when the watergates are opened. Populations of the two target species in the most upstream lake, Nong Han, are contributed by migrating fish from Mekong River and resident populations with in the river system. Rate of migrations, small genetic distances and genetic differentiations between subpopulations of the target species support the occurrence of gene flow in this river; many subpopulations have little genetic differentiation between samples although there is the series of barriers in the river system. By chance, population size of the two migratory species migrating through the Thoranit Naruemit and Suraswadi fish passes were relatively big and bigger than populations along the river suggesting that upstream migration of target species is only partially limited by watergate operation. This is probably because the Nam Kam River is a rather short river and gene flow in the river system was supported by the operation schedule that fully open the watergates in flood season and the fish pass operation at the onset and the end of flood season. Thus, the most important things that need to be addressed to maintain fisheries resources in this river system are watergate and fish passage operations.

Fish passage facilities in the Nam Kam support migration of more than 135 fish species and mitigate the impact of delayed watergate opening on the recruitment of fish in this river system. However, the operational schedule needs to be adjusted since fish can only use the fish passes when the sluice gates are closed or partially opened dring high river discharge in the wet season. Upstream migration is only completely unobstructed when the watergates are open to maximum capacity. The watergate and fish passes management schemes in the river system are key important factors to mitigate the impact on hydrological changes and habitat changes, to enable free movement of fish through the river system and enhance the fisheries in the Nam Kam River system. Recommendations for watergate and fish pass operation based on the integrated knowledge gained from this study are provided.

DEFINITION:

The term “watergate” used throughout this thesis is not a generally recognized term in English but is currently used in the Mekong River Basin and especially in Thailand. The term “watergate” describes a small scale run-of-the-river project (Figure 1) constructed for irrigation and flood control. It comprises a number of main sluice gates but some spillways and fish passage facilities installed. In the flood season, running water from a river is guided down a channel through these sluice gate and there will be a large amount of wasted water during the peak flow period as the excess water flow through the sluice gate when it was opened to maximum capacity or the excess water drains through the fish pass or over the spillways. All watergates normally hold water for irrigation purposes in the dry season. All watergates in the Nam Kam River system in this study were fitted with the fish passage facilities (pool type fish passes).

a.  b. 

Figure 1 Typical, watergate and fish passage facilities in the Nam Kam River system. a. Main watergate with 4 sluice gates (Thoranit Naruemit watergate), b. pool type fish pass.

Chapter 1: Introduction

Background

Over the past three centuries, demand for water has steadily increased globally and the quantity of water needed has increased, but freshwater resources are limited and unequally distributed (ICOLD, 2014). Dam and watergate construction, artificial lakes and major impounding reservoirs on the mainstem of rivers have provided valuable services, such as storage and provision of water for irrigation (to satisfy domestic, industrial and agricultural requirements) hydropower generation, improved navigation, expanded recreational opportunities and flood control. While watergate construction offers an opportunity to improve supply for irrigation and control flooding and thus contribute significant benefits, their construction has many negative environmental impacts and may cause significant changes to the ecosystem. Watergate construction on mainstem river brings many changes to the river and fish habitats. It regulates flow and alters seasonal flooding cycles (Agostinho *et al.,* 2008; Halls & Kshatriya, 2009; Dudgeon, 2000) causing changes in downstream discharge (volume of water, timing and amplitude), reduces floodplain habitats, traps nutrients in the impoundments, and also results in deterioration of water quality (WCD, 2000). In particular, regulated flow regimes negatively affect the functioning of ecosystem by degrading feeding habitats, spawning grounds (Kwak, 1988; Trexler, 1995; Baras & Lucas, 2001; Grift *et al.*, 2001, 2003) and nursery areas along the river (Gehrke *et al.*, 1995, 1999; Modde *et al.*, 2001; Grift *et al.*, 2003), thus disturbing the fish recruitment processes (Kummu & Sarkkula, 2008). The physical barrier of the dam wall also blocks fish migration routes (Baran & Myschowoda, 2008; Barlow *et al.,* 2008; Larinier, 2012) and thus contributes to changes in fish species composition, abundance and diversity as well as size structure of the community (Starr, 2009). This will also genetically isolate and degrade upstream populations, since population fragmentation can reduce within-population genetic polymorphism and increase genetic differentiation within the area (Knaepkens *et al.,* 2004). Many of these changes occur gradually, and undesirable consequences may appear after a long period. These effects will usually take place either during construction, operational stage or directly after it, and in some cases several years afterwards. Detrimental events can occur immediately or in the long term, and the damage can be anything from insignificant to complete loss of species and ecosystem functioning (Francisco, 2004; Manouchehri & Mahmoodian, 2002; WCD 2000).

In the lower Mekong River basin which support the second most diverse freshwater fish fauna in the world (Baran, 2010), many hydropower dams have recently been proposed on the mainstem and tributaries, causing concerns over possible declines in fish species diversity and fisheries production (Ziv *et al.,* 2012). More than 124 existing, under construction and potential large dam projects and associated reservoirs have been built in almost all of the hydrographic basins and 70 hydropower dams projects are scheduled to be complete in tributaries by 2030 (MRC, 2011), while 11 are at various stages of consideration along the mainstem of the lower Mekong River (Baran & Myschowoda, 2009; MRC, 2010). Accordingly most research and public debate has focused on the mainstem dams (Barlow, 2008; Barlow *et al.,* 2008; Dugan, 2008; Baran & Myschowoda, 2009; Halls & Kshatriya, 2009; Baran, 2010; Dugan *et al.,* 2010; Ferguson *et al.,* 2011) while the impact of dams on the Mekong tributaries has received relatively little attention so far. A few studies have assessed the impact of dams in the Mekong tributaries in Thailand; for example Mun River (Amornsakchai *et al.,* 2000; Jutagate *et al.,* 2005; Jutagate *et al.,* 2007; Phomikong *et al.,* 2014) and Nam Kam River (Ngoichansri *et al.,* 2013, unpublished; Hanpongkittikul *et al.,* unpublished; Phomikong *et al.,* 2014) and others have explored the impact of large dams in tributaries in Laos (Phouthavong, 2015).

The Nam Kam River is the third largest of the Mekong tributaries in Thailand, connecting the Mekong to Nong Han, the biggest natural lake in northeast Thailand. This river functions as a migratory route for more than 121 fish species migrating between the Mekong and Nong Han (Ngoichansri *et al.,* unpublished). Between 1995 and 2009, a series of five watergates were constructed on the Nam Kam River and a further two watergates on its main tributary, the Nam Bang River, for the purposes of irrigation and flood control. To aid fish migration, all watergates were fitted with pool-type fish passage facilities. Several investigations have reported on the diversity, community structure and migration of fish through fish passages in Nam Kam River (Srisatit, 1981; Pongsri *et al.,* 2008; Ngoichansri *et al.,* 2013). Others have explored the impact of watergate operation and environmental factors on migration patterns (Ngoichansri *et al.,* unpublished; Hanpongkittikul *et al.,* unpublished) and community structure of fish (Phomikong *et al.,* 2014). All these previous studies were conducted in the mainstem of the Nam Kam River only, while the Nam Bang River was not studied. To my knowledge no studies have examined the population structure and distribution of fish in the whole Nam Kam River system, or any river in Thailand that has been blocked by a series of “run-of-the-river” watergates.

Although there are many barriers in this river, evidence from a previous study (Ngoichansri *et al.,* unpublished) showed that more than 103 species were able to pass from the Mekong River through the Nam Kam fish passes and most were mature and ready to spawn. It was also found that juveniles of several species migrated upstream through the fish pass at the last watergate into Nong Han Lake a few months after the onset of upstream migration of mature adults (Ngoichansri *et al*., unpublished). However, the whereabouts of the fish after passing through the fish passes has not been studied and little is known about the impact of watergate management on fish migration, which is known to affect diversity, abundance and distribution of fishes as well as recruitment and fish production in the river. Furthermore, the way to manage and mitigate the impacts of watergate operation on fisheries resources in the Nam Kam River and its tributary have not been studied. Gaps in current knowledge, and where they are addressed in this thesis, include:

1. Effects of flow modification due to watergate operation in the Nam Kam River and its tributary.
2. Little work has been done to quantify the influence of the flooding cycle on fish populations in this area.
3. Little is known about the spawning area and the distribution of fish larvae and juvenile fishes, which are important to help understand fish production and recruitment in Nam Kam and its tributary.
4. Information that discriminates whether the juveniles migrating through the Nong Han swamp are offspring of migratory fish from the Mekong River or resident populations in the river system. Also the importance of spawning migrations to each spawning/nursery area and how they contribute to fisheries resources production in this river system is unknown.
5. Information on the migration patterns and the impact of watergate management on fish migration, which affect genetic diversity and population structure of fishes in the area, are unknown.

Aims and objectives

As outlined above, there is a growing need to understand: 1) the hydrological and habitat changes caused by watergate operation, which may 2) affect population structure and distribution of fish in the area 3); the impact of the watergate operation on recruitment process, and spawning floodplain areas for larvae and juvenile fish as spawning and nursery grounds; 4) impact of the watergate operation on population structure and genetic structure of fish across the system and 5) impact of the watergate operation on the fish migration in the Nam Kam River system.

The objectives of this study are thus to:

1. investigate the impact of watergate operation and hydrological factors on fish assemblage structure and recruitment in the regulated Nam Kam River system.
2. investigate efficiency of watergate operation and fish passage facilities to support fish migration in the regulated Nam Kam River system.
3. determine migration patterns of economically important fish species through the Nam Kam River system.
4. identify solutions to mitigate the impact of watergate operation on the Nam Kam River system.

The thesis was divided into chapters which address the diverse knowledge gaps outlined above in determining the impact of watergate operation on fisheries resources in the study area and factors contributing towards and changes observed. The information from this study can be used to assist management of water resource schemes for the Nam Kam irrigation system to sustain fish production. It will also be transferrable to other water regulation schemes throughout the Mekong as this cumulative impact becomes increasingly important as the number of dam projects in the Mekong basin continues to increase in the foreseeable future.

Structure

The study was divided into key topics to fill some of the gaps in knowledge outlined above, each of which are addressed in Chapters 3 to 8. Specific objectives and hypothesis are provided at the start of each chapter. Fish species are referred to by scientific names throughout the thesis. The content of each chapter is summarized below.

Chapter 2: Literature Review

In this chapter, migration of freshwater fishes and hydrological flows in the Mekong River and Nam Kam River systems are reviewed. The impact of instream construction is reviewed, focusing on habitat changes, on fish populations, genetic diversity, and migration of fishes. Further, a description of the study area is provided.

Chapter 3: Hydrological and habitat change in the Nam Kam River system.

This chapter describes spatial and temporal changes in the hydrological profile and habitat characteristics of the Nam Kam River system. An analysis of hydrological characteristic and habitat variations over the study period was carried out.

Chapter 4: Population structure and distribution of fish in the Nam Kam River system.

In this chapter, the distribution, abundance and diversity of fishes and shifts in fish community structure throughout an annual cycle are investigated. The impact of hydrological changes on the fish populations in the Nam Kam River system are assessed.

Chapter 5: Spawning and nursery ground in the Nam Kam River system.

This chapter examines the larval and juvenile fish communities at multiple sites and explores shifts in community structure throughout the annual hydrological cycle. Spawning and nursery grounds are identified. The contribution of spawning migrations to fish production of the river system is estimated. Impacts of watergate operation on spawning and nursery habitats and recruitment of fish in the Nam Kam system are evaluated.

Chapter 6: Population structure and genetic diversity of fish in the Nam Kam River system.

This chapter assesses the population structure and genetic diversity of two economically important fish species (*Hemibagrus nemurus* (Valenciennes, 1840) and *Osteochilus hasselti* (Valenciennes, 1842) and evaluates likely impacts of watergate operation and eco-hydrology change on genetic diversity and population structure of these species in the Nam Kam River and its tributary.

Chapter 7: Patterns of fish migration in the Nam Kam River system

In this chapter, migration of fish through the most downstream fish passes is evaluated using seine netting. The migration patterns of two economically important fish species after migration through fish passes are determined using physical tagging and genetic tagging. The migration triggers of fish into the river system are evaluated. The impact of watergate operation and eco-hydrology changes on migration patterns of fish are investigated.

Chapter 8: Conclusions and recommendations

This chapter integrates the knowledge gained from Chapters 3 to 7, summarizes the impact of watergate operation on hydrological and habitat changes, fish population structure and distribution of fish, recruitment, species and genetic diversity and fish migration patterns in the river system, and provides recommendations for further study. Watergate management schemes are discussed in terms of how to regulate flows by the watergates and fish passes to provide benefit to fisheries resources and irrigation needs in the cascade system.

Chapter 2: Literature Review

2.1. Description of the system/ study area

2.1.1 The Nam Kam River system

This study was carried out on the third largest tributary of the Mekong River in Thailand. The Nam Kam River is 123 km long from its source, Nong Han Lake, the biggest natural lake in the northeast of Thailand to its confluence with the Mekong River (Figure 2.1). This river receives water from Nong Han Lake through Suraswadi Watergate, which is controlled by the Department of Fisheries, Thailand. The river flows through Sakon Nakhon Province then joins with two significant tributaries, Nam Bang River and Huay Can River (Figure 2.1) before joining the Mekong River at That Phanom district, Nakhon Phanom province. The flooded area along the river upstream of Nong Han is about 130 km^2 (Srisatit *et al.,* 1981). Drainage area of this river basin is around 3,440 km^2. The river is 20-40 m wide and has an annual discharge of 1,400 million m^3 (Pongsri *et al.,* 2008).

In this region, the ecology of rivers is strongly influenced by the annual monsoon cycle, which creates a characteristic pattern of seasonality; predictable periods of drought during the dry season alternating with intervals of increased discharge, when floodplains are inundated during the wet season with much of the precipitation occurring from June to early October. However, the mean annual rainfall in this area is lower than other regions of the Mekong, ranging from 1,000 to 1,500 mm/year. From a fisheries perspective, the Nam Kam River Basin belongs to the middle Mekong Migration System, which extends from upstream around Vientiane, Laos to Khone Falls in the south located near the Lao-Cambodian border (Poulsen *et al.* 2002).

2.1.2 Land used on the vicinity of river

The area around the Nam Kam River Basin is mostly rural agricultural land, which is the single most important economic activity in this river basin. More than 3,440 km^2 of land is cultivated to produce mainly rice, but also corn, tobacco and tomato. Community developments within this rural landscape affect the stream and river as rural and urban areas are the source of domestic wastes, while agricultural production is the source of nutrients, pesticides and sediment run-off. In addition, the river is facing drought problems in the dry season and extended flooding in the rainy season made worse because much of the floodplain has been reclaimed for urban development or agriculture.

2.1.3 The Nam Kam Royal Development project

The Nam Kam Royal Development project was constructed by damming the Nam Kam River and its tributaries (Nam Bang River and Huay Can River) between 1997 and 2007 following a suggestion of His Majesty the King Bhumibol Adulyadej of Thailand for the purpose of irrigation and flood protection. This project is one of the royal irrigation projects of Thailand initiatated by King Bhumibhol Adulyadej (King Rama IX), providing water to the plantations in the Nam Kam River Basin. Seven watergates were installed along the Nam Kam River and its tributaries turned the river into a cascade of impoundments. Four watergates were constructed on the Nam Kam mainstem, two on the Nam Bang River, and one watergate in the Huay Can River (Table 2.1 and Figure 2.1). The impoundment areas are regularly replenished by the Nam Kam River and are capable of storing up to 266.9 million m^3 of water at 137-152 m above mean sea level (m AMSL) with water surface area of 77,016 rai (12,323 ha). The main functions of the project are to store water for agricultural purposes in the area and protect adjacent areas from flooding. The series of watergates also reduce problems of water management in the area in the flood season by allowing more flood control. Construction was completed in 2009 and provides benefit for an agricultural area of more than 120,500 rai (19,280 ha). To assist fish migration, vertical slot pool-type fish passes with slopes of 1:12-1:5, various pool areas between 3.0-4.5 x 3 m^2, and 70-108 m long are constructed around each watergate (Figure 1b). The number of pools in each fish pass varies between 19 and 31 (Pongsri *et al.,* 2008, Royal Irrigation Department, personal communication).

It is responsibility of the Nam Kam River Basin Operation and Maintenance Project, Royal Irrigation Department (RID), Thailand to control all watergates in the Nam Kam River and tributaries but the Department of Fisheries, Thailand is responsible for controlling the Suraswadi Watergate, which is the gate that releases water from Nong Han Lake to the Nam Kam River system.

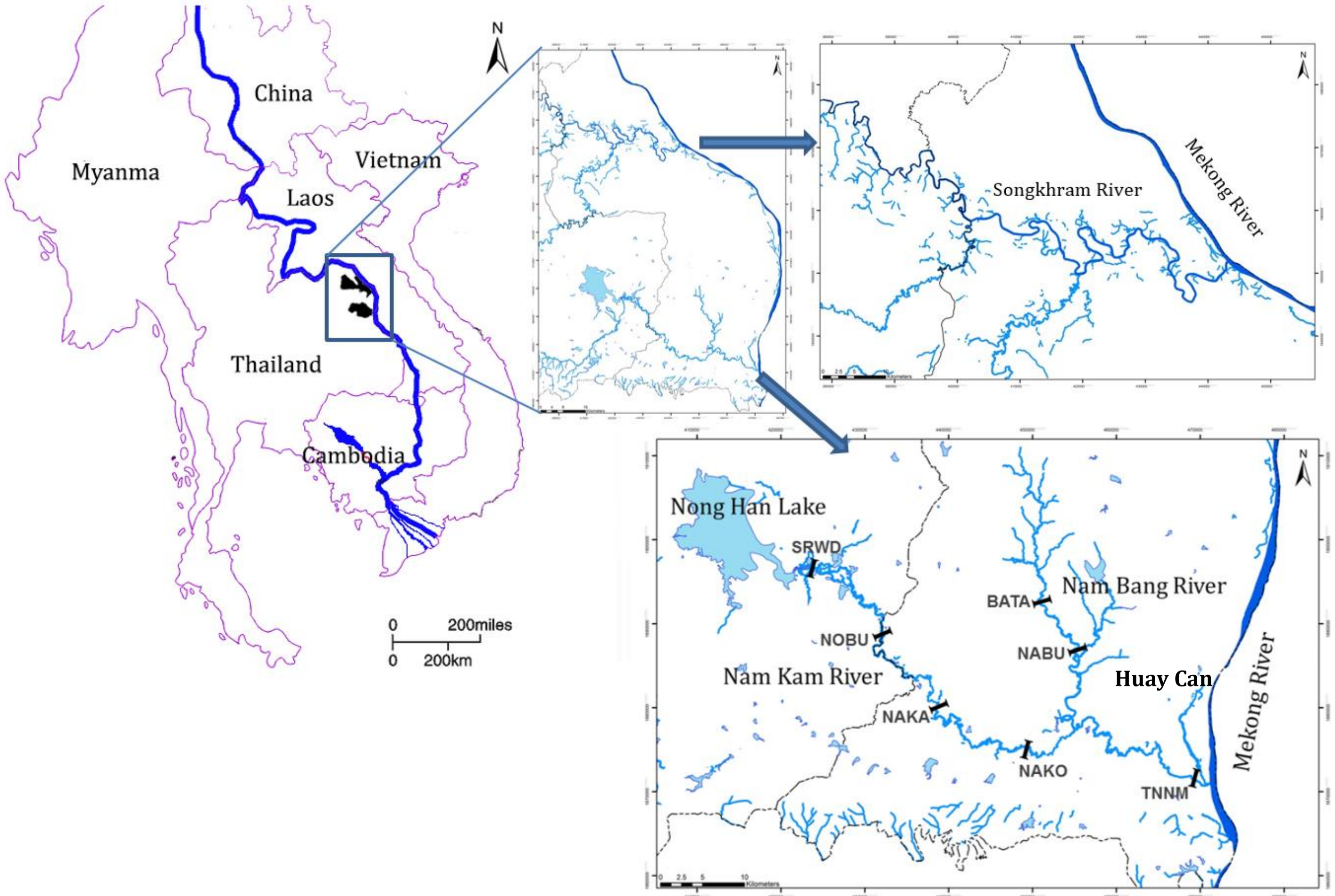


Figure 2.1 The location of study sites (the Nam Kam River system) and the reference river (Songkhram River); green dots represent location of 7 watergates on the Nam Kam River and its tributaries (a: Thoranit Naruemit Watergate, b: Na Koo Watergate, c: Na Karm Watergate, d: Nong Bueng Watergate, e: Suraswadi Watergate, f: Na Bua Watergate and g: Ban Tab Tao Watergate).

Table 2.1 Description of 7 watergates on the Nam Kam River system.

Watergate (distance from the Mekong river)	River	Location	Retention water level (Mm^3)	Normal retention level (m AMSL)	Max.water discharg (m^3/sec)	Benefit agricultural area (ha)
Suraswadi Watergate (119.3km)	Kam	N1896643 E0423744	266.9	157.0	230	9,600
Nong Bueng Watergate (92.3km)	Kam	N1888581 E0432001	1.8	152.7	170	2,016
Na Karm Watergate (66.5km)	Kam	N1879722 E0438825	3.1	148.0	245	432
Na Koo Watergate (43.2km)	Kam	N1875409 E0449491	8.8	143.6	305	4,032
Thoranit Naruemit Watergate (0.3km)	Kam	N1871005 E0469788	35.6	137.5	1,200	11,600
Ban Tab Tao Watergate (65.3km)	Bang	N1892320 E0450886	0.7	147.5	225	960
Na Bua Watergate (46.9km)	Bang	N1886803 E0455177	1.1	143.6	230	240

2.1.4 Reference river: Songkhram River

The Songkhram River is the second largest tributary of the Mekong River in Thailand. It is located 120 km to the north of where Nam Kam River joins the Mekong (Figure 2.1). This river is about 430 km long, flows eastward to join the Mekong River in Sri Songkhram district, Nong Kai province and has no dam along the course of the river. This river contributes about 2 percent of the total discharge of the Mekong River (Hortle & Sunthornratana, 2008). It has a drainage area of around 13,000 km^2. The water level rises more than 13 m from dry season level due to a reversal water flow from the flooded Mekong River in rainy season (Blake, 2006). The Songkram River is one of the Mekong tributaries where the mainstem remains undamaged with no modification to its natural hydrology. This is difference from the Nam Kam River which is highly regulated by a series of watergates and is the reason why the Songkhram is used as a control river.

2.1.5 Diversity and community structure of fishes in the Nam Kam River system.

An investigation into the species diversity and distribution of fish in Nam Kam River carried out by Srisatit *et al.* (1981), found 40 species of fish. Twenty three species were caught in the Suraswadi fish ladder and 23 species were found at the confluence with the Mekong River in the period before the four downstream watergates were constructed. Thereafter, Pongsri *et al.* (2008) assessed the diversity of fish migrating through the Suraswadi, Na Karm and Na Koo fish passes in 2006-2007, at the time when the other two downstream watergates were under the construction; they found 76 species of fishes from 22 families. Cyprinid fishes (Family Cyprinidae) were the most diverse group found, comprising 30 species. After watergate construction was completed in the Nam Kam River in 2009, 103 fish species from 24 families were found in the Nam Kam River when sampling by seine net at the fish passages and during gill nets survey (Ngoichansri *et al.*, 2013). A total of 95 species from 21 families were found in the fish passes and 66 species from 20 families were caught by gill nets. Cyprinid fishes were the most diverse with 52 species follow by 19 species of catfishes (Family Siluridae and Bagridae). From 2009-2010, Phomikong *et al.* (2014) found 54 species by electrofishing along the Nam Kam River and cyprinids were the most diverse group. The increased species number in this river is mostly attributed by different sampling methods.

Although the fish communities of the Nam Bang River have been studied before and after watergate construction little is known about the impact of fragmentation and watergate management on fish migration, which is one important element that affects diversity and population structure of fishes in the area.

2.2 Migration of freshwater fishes

Northcote (1984) defined migration as “movements that result in an alternation between two or more separate habitats, occur with a regular periodicity, and involve a large proportion of the population”. Quinn and Deriso (1999) stated that migration is “consistent and directional movement of some component of a population”, whereas movement is “a more general term that refers to any change in the location of individuals in a population”. Lucas and Baras (2001) indicated that there are many main types of fish migrations, such as feeding, seeking refuge, spawning migrations, post-displacement movements, re-colonization and exploratory migration. Migration also occurs in different directions: longitudinal migration takes place along the main river channel while lateral migration is the movement between floodplain and the main channel (Welcomme, 1979). Sometimes lateral migration is followed by longitudinal migration (Bao *et al.,* 2001). Many riverine fishes also require special environment conditions during some stage of their life history or growth so fishes migrate to upper or lower reaches of river and or into surrounding water bodies, especially on the floodplain. These movements are usually reproductive strategies: mature fish usually migrate upstream to their spawning area at the beginning of the rainy season while at the beginning of flood period eggs and fish larvae drift downstream and hatch in turbid water then get flushed onto flooded areas along the river bank, where they can occupy nursery and rearing grounds where they find shelter and food (Agostinho *et al.*, 2003). More than 15% of neotropical fish are migratory species that have a broad home range, including spawning, rearing and feeding habitats that are sometimes several hundred kilometers distance from each other (Carolsfeld *et al.,* 2003).

Migration of fishes is influenced by many factors, including flow, temperature and water quality, and habitat use may alter with changes in environmental conditions (Garner, 1997). In tropical river systems, the most important migration triggers are water level, current, discharge, precipitation, lunar cycle, water color, turbidity and the appearance of insects (Northcote, 1978). Also, Baran (2006) summarized that variation in 1) water discharge, 2) variation in water level, 3) the first rainfalls after dry season, 4) changing in water turbidity or water color and 5) natural food (apparition of insects) are five key environmental factors that stimulate or trigger migration of 165 migratory fishes in the lower Mekong system. The migration of fishes is also associated with the lunar phase as an environmental trigger, but this cue seems to depend on species and location (Poulsen *et al.,* 2004).

Migration is critical because it maintains genetic diversity through the exchange of reproductively successful individuals among the population (Hartl, 1980). It allows subpopulations to distribute genetic variation, which contributes to maintaining genetic variation within each subpopulation. An average exchange of one migrant individual per generation will maintain the same alleles in all populations, but much larger exchange is required to maintain similar allele frequencies among populations (Mills & Allendorf, 1996). Migration also improves adaptation to local environments because some alleles can be adaptive to specific environments but not in others (Yamamichi & Innan, 2012). Thus, understanding migration patterns is key to explaining sustainability of fish stocks (Knaepkens *et al.,* 2004) and it appears necessary for the continuance of viable populations of many migratory species.

2.2.1 Migration of fishes in the Mekong River Basin

The Mekong River provides an example of the relationship between fish ecology and the hydrological cycle (flood pulse concept viz Junk *et al*., 1989). The timing of fish migrations differ somewhat according to species and in different parts of the Mekong Basin, but this complex situation is amenable to generalization. In the Mekong, more than 87 per cent of known fish species are believed to be migratory and about 50 per cent of the catch is made up of long distance migrants (Baran *et al.,* 2007). Mekong fish species undertake movements up and down the Lower Mekong River; throughout the year and laterally to the floodplain during the flood period (Marsden & Baumgartner, 2014). Fish primarily migrate for breeding and feeding, and many species combine both types of migration. Breeding migrations are made, usually upstream, by adult fishes during the wet season as water levels rise. Adults spawn while the water level is still increasing to ensure that the water current brings their eggs and larvae on to nursery areas on downstream floodplains where they feed and grow (FAO, 1999). Adults returning from breeding areas also occupy these floodplains for feeding (Poulsen *et al.,* 2004). When the water level starts to decline most fish seek refuge in permanent water bodies, mainly in deep pools in the mainstem channel but others in floodplain water bodies (Figure 2.2). Movement of fish includes lateral migration between mainstem or tributaries and floodplains as well.

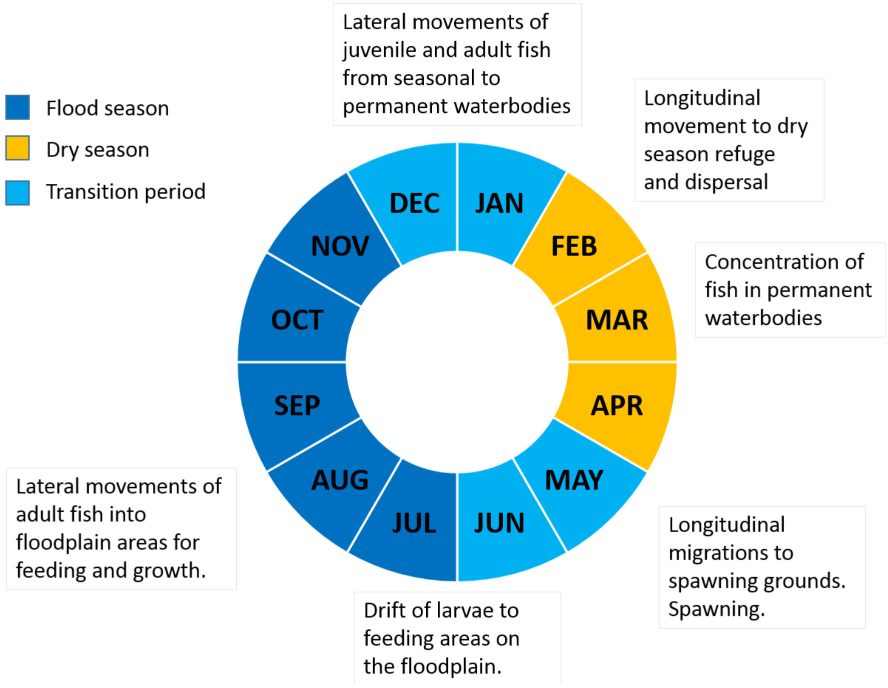


Figure 2.2 General life cycle for Mekong fish species (modified from Poulsen *et al.,* 2004).

Fish migration patterns in the Mekong River can be classified into three migration systems (upper, middle and lower migration; (Figure 2.3). The upper migration system covers the relative narrow, rapid and fast flowing channel in the upstream area. It extends from beyond the boundary of China to above Vientiane; this part has limited floodplain and is influenced by many small streams and tributaries. The middle migration system starts from above Vientiane to above Khone Fall. This system comprises major floodplains and tributaries of the Mekong. The lower migration system covers the area downstream of Khone Falls to the Mekong delta. This area connects to the Tonle Sap Lake, the biggest floodplain in Cambodia. At the onset of the rainy season, water level raises trigger many fish species to migrate from the Mekong mainstem to upstream spawning areas in the floodplains or tributaries. In general, floodplains act as nursery grounds and feeding habitat for Mekong fish species, while deep pools found along the mainstem river act as spawning areas for some species and refuge areas in the dry season for many species (Poulsen *et al.,* 2002).

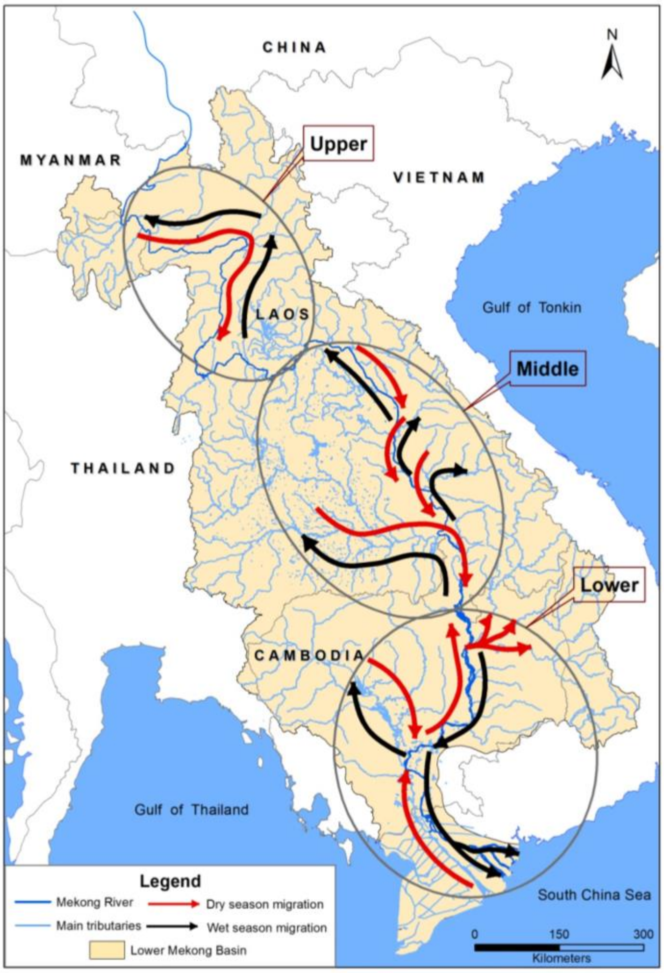


Figure 2.3 Generalized migration system in the Lower Mekong Basin
(Source; Poulsen *et al*., 2002)

Bardach (1959), Welcomme (1985, 2001), Welcomme *et al.* (2006), Poulsen *et al.* (2002), Baran (2006, 2010), Dugan (2008), Hortle (2009) and Valbo-Jørgensen *et al.* (2009) have characterized Mekong fish into guilds according to their ecology and migration patterns (Table 2.2). There are three main groups: viz white, grey and black fishes.

White fishes are species that undertake long-distance upstream migrations between the river and floodplains. They reside most of year in the main river channels and migrate to the floodplain area, including into the tributaries, in the flood season for spawning (and feeding) and returning to main river when waters recede at the end of flood season (Poulsen *et al.,* 2002). Fishes belonging to this guild are intolerant to low dissolved oxygen concentrations and are typically found in lotic environments (running water). This guild includes many cyprinids (Family Cyprinidae) and most pangasiids (Family Pangasiidae). Between 40-70 per cent of fish catches in Lower Mekong Basin (LMB) are long-distance migratory species (Barlow *et al.,* 2008). Due to their long distance migration, this group can be easily interrupted by any barrier constructed on the river.

Table 2.2 Behavioural guilds reactions to changes in hydrograph (after Welcomme *et al.,* 2006).

Guild	Behaviour		Response to changes in flow regimes
	General	**Specific**	
White fish rheophillic species	Long-distance migrants; One breeding season a year; Intolerant of low oxygen.	A. Main channel residents not migrating to floodplain; Predominantly psammophills, lithophils or pelagophils; Often have drifting eggs and larvae.	Tend to disappear when damming in a river that block migration route; When timing of high flow inconsistent with their breeding season; If flow excessive or too slow for the needs of drifting eggs larvae.
		B. Use floodplain for reproduction (breeding nursery) and feeding; Mainly phytophils; Spawning at floodplain; sometimes have drifting eggs and larvae.	Tend to disappear when damming in a river that blocking migration route; Damage when river disconnect to floodplain (fry and juveniles passed to inappropriate nursing ground).
Black fish limnophilic species	Floodplain residents move short distance between floodplain, swamps, and flooded forest; Repeat breeders with specialized reproductive behaviour; Predominantly polyphils, nest builders, parental carers; Resistant to low dissolved oxygen or anoxia (auxillary breathing adaptations).	A. Resistant to low dissolved oxygen tensions only	Tend to disappear when floodplain disconnected; May increase in population in shallow water, isolated wetlands and rice fields.
		B. Torelant of complete anoxia	Live in floodplain water bodies; Colony in rice field and ditch faunas.
Grey fish eurytopic species	Resistant to low dissolved oxygen; Repeat breeders; Predominantly phytophils but some nesters or parental carers; Short-distance migrants often with local populations.	A. Inhabit in main channel generally benthic	Be able to adapt to altered flow regime; Usually increase in population while other species decline; At risks when flows altered the sediment transport process and change the river bed.
		B. Reside in riparian vegetation	Be able to adapt to altered flow regime; Usually increase in population while other species decline; Impacted negatively by flow and management that changes riparian structure.
		C. Live in large and healthier oxygen in floodplain water bodies	Susceptible to isolation of floodplain but can live in river if flow slowed adequately; Often from in reservoirs.

Grey fish (which do not clearly belong to the black or white guilds) migrate to the floodplains in the wet season and will leave the floodplain or wetland when the water recedes and spend their dry season in tributaries or edges of the mainstem instead. They do not undertake long distance longitudinal migrations but more short distance movements and lateral migrations on to the floodplains. They are tolerant of low to medium oxygen concentrations. This group includes, for example, *Mystus* catfish.

Black fishes are non-migratory species that do not undertake longitudinal migration upstream and downstream, but migrate laterally between main channel and floodplain. Species of this guild are morphologically and physiologically adapted to extreme environmental conditions of low dissolved oxygen concentration and drought. Species belonging to this category are typically resident in floodplain habitats or inhabiting lentic environments (still water) and include snakeheads (Family Channidae), catfishes (Family Bagridae) and climbing perch (Family Anabantidae).

Each guild of fish responds to flow changes differently: black and grey fish are more tolerant to hydrological changes than white fish (Welcomme *et al.,* 2006). Understanding these dynamics on a species basis is essential for proper management of the fish resources and, although it is useful as a starting point, the categorization into "black fish" and "white fish" is too crude for management purposes. Therefore, Halls and Kshatriya (2009) suggested 10 migratory guilds of fish in the Lower Mekong River to help identify species that are most likely to be affected by hydropower development (Table 2.3). This categoration is an extension of the black-white-grey classification and is based on migration behaviour or connections of life history stages between critical habitats through the mainstem; the basis of their presence or absence as adult and larval or juvenile stages within the main habitats of the system which represent variation in the environmental guilds proposed by Welcomme *et al.* (2006). Most white fish are longitudinal migratory species including main channel resident, main channel spawner and catadromous species were categorized into the very high risk guild; semi-anadromous species were put in the high risk guild. Species that take lateral migration between mainstem and floodplain for reproductive purposes (floodplain spawners) were grouped as medium risk while generalist, floodplain resident (Black fish), estuarine resident and marine were categorized into the little or no impact guild. The likely impact of mainstem dams on migration of each guild was determined by the degree to which the mainstem acts as a channel or migration corridor between the critical habitats for each life history stage (Table 2.3).

Table 2.3 Migratory guilds proposed for mainstream dam impact forecasting (after Hall & Kshatriya (2009).

Guild #	Migratory guild Name	Potential range of habitat utilized	Typical characteristics	Likely impact of mainstream dams on migrations
1	Rithron resident guild	Rithron	• Resident in rapids torrents, rocky areas and pools in the rithron. • Generally insectivorous, algal scrapers or filter feeders, small in size, lithophilic or phytophilic with extended breeding seasons and suckers or spines to maintain position in the flow. • Limited migrations.	Little or no impact
2	Migratory main channel (and tributaries) resident guild	Marine to Rithron	• Long distance migrants spawning in the main channel (sometimes in rithron) upstream of adult feeding habitat in the main channel. • May migrate to refuges (deep pools) in the main channel during the dry season. • Pelagophilic members have drifting pelagic egg or larval stages returning to adult habitat utilising backwaters and slacks as nurseries. • Adults do not enter floodplain and may be piscivorous. • Lithophilic members may be anadromous with fry resident at upstream site for a certain period and may occupy upstream floodplain. • May also include psammophils (sand spawners). • Members vulnerable to overexploitation and tend to disappear when river is damned preventing longitudinal upstream migration. May respond favourably to fish passage facilities. • Includes anadromous species.	Very high
3	Migratory main channel spawner guild	Floodplains to Rithron	• Spawn in the main channel, tributaries or margins upstream of floodplain feeding and nursery habitat often with pelagic egg or larval stages. • Pelagophilic, lithophilic, phytophilic (in floodplain margins) or psammophilic. • Adults and drifting larvae return to floodplains to feed. • May migrate to refuges (deep pools) in the main channel during the dry season. • Tend to disappear when river is dammed preventing longitudinal migrations to spawning and refuge habitat.	Very high
4	Migratory main channel refuge seeker guild	Floodplains to potomon	• Undertake migrations from floodplain feeding and spawning habitat to refuges (deep pools) in the main channel during the dry season. • Predominantly phytophils. • Differ from main channel spawner in that spawning occurs on the floodplain with main channel used as refuge during dry season. • Threatened when river is dammed preventing lateral and longitudinal migrations to refuge habitat in main channel.	Medium

Table 2.3 (Cont.)

Guild #	Migratory guild Name	Potential range of habitat utilized	Typical characteristics	Likely impact of mainstream dams on migrations
5	Generalist guild	Floodplains and potomon	• Limited non-critical migrations in mainstream. • Highly adaptable, mobile and static elements in their genome make them highly adaptable to habitat modification. • Often repeat breeders or breed during both wet and dry seasons sometimes with nests and parental care. • Rheophilic or limnophilic; often tolerant of low dissolved oxygen concentrations. • May be semi-migratory often with sedentary local populations. • Benthic members are predominantly lithophils and psammophils and occupy centre of main channel with intolerance to low dissolved oxygen. May seek refuge in deep pools during dry season. • The riparian zone members typically occur amongst the vegetation of the main channel and fringing floodplains. • May undertake lateral migrations to floodplain to occupy similar habitats during flooding. • Often tolerant and low dissolved oxygen and exhibit wide range of breeding behaviour but predominantly phytophils. • This guild is especially well represented in most rivers.	Little or no impact.
6	Floodplain resident guild (Blackfish)	Floodplains	• Limited migrations between floodplains pools, river margins, swamps, and inundated foodplains. • Tolerant to low oxygen concentrations or complete anoxia. • Little or no impact. • Often repeat breeders, phytophils, nest builders, parental care or live bearers.	Little or no impact.
7	Estuarine resident guild	Estuary	• Limited migrations within the estuary in response to daily and seasonal variations in salinity. • Brackish water guild euryhaline and usually confined to brackish part of system. • Freshwater estuarine guild includes stenohaline species that inhabit freshwater component of estuarine system.	Little or no impact (if dam is upstream of estuary and does not influence salinity dynamics in estuary).
8	Semi-anadromous guild	Estuary and lower potomon	• Enters fresh/brackish waters to breed • Enters freshwaters as larvae/juveniles to use the area as a nursery, either obligate or opportunistic. • Impacted by river mouth dams that stop migration into the river.	High (for dams located in river mouths or lower potomon).
9	Catadromous guild	Marine to Rithron	• Reproduction, early feeding and growth at sea. • Juvenile or sub-adult migration to freshwater habitat often penetrating far upstream. Members vulnerable to over exploitation and tend to disappear when river is damned preventing longitudinal upstream migration. May respond favourably to fish passage facilities.	Very high
10	Marine guild	Estuary	Enters estuaries opportunistically	Little or no impact

2.2.2 Migration of fishes in the Nam Kam River system

The Nam Kam River system located in the middle Mekong migration system. Fish from Mekong mainstem mainstem migrate upstream during the wet season when the water is rising and enter the tributaries and related floodplains for reproduction and feeding. During the receding period fish leave the tributaries and floodplains and return to their dry season refuge areas in the Mekong River (Poulsen, 2002). Dominant fish species, abundance and period of migration in the Nam Kam River system vary year by year according to the timing of the rainy season. Srisatit *et al.* (1981) reported 24 species of fish with a daily average of 250,000 individuals per day, mostly small and sub-adult fish, migrated through the Suraswadi fish passes at the end of rainy season. The maximum number of fish moved through the passes when the flow was between 0.46-0.67 m/s in the day time. Pongsri *et al.* (2007) reported the migration of 55 fish through 3 fish passes in two periods; at the onset of rainy season and at the end of rainy season. The average number of fish migrating through the fish passes was 4,196 individuals per day with the larges number in Suraswadi fish pass (9,118) follow by Na Koo fish passes (2,368) and Na Karm fish passes (1,102), respectively. Migration was highest around the beginning of rainy season. Most of the fish were grey fishes smaller than 200 mm and only a few species were long-distance longitudinal migratory species. The most dominant species using the fish passes were small cyprinid species, such as *Rasbora argyrotaenia, Dangila lineatus, Osteochilus lini, Pristolepis fasciata, Osteochilus wandersii,* and *Hemibagrus nemurus.* Two of these species *Hemibagrus nemurus* and *Osteochilus wandersii,* (Figure 2.4) are target species of this research.

Figure 2.4 Two target species using in genetic diversity and migration pattern study. (Left: *Hemibagrus nemurus* (Valenciennes, 1840) and right: *Osteochilus hasselti* (Valenciennes, 1842)).

A previous study by Ngoichansri *et al.* (2013) found 103 fish species of 24 families in the Nam Kam River, but only 95 species migrate through the fish ways in the five watergates. Upstream migration was observed at the onset of rainy season (end of May) and during the rainy season. The common species found in the fish passes were *Sikukia gudgeri, Leiobarbus siamensis, Hemibagrus nemurus*, *and Osteochilus* *hasselti*. There was some correlation between intensity of migration and phase of the lunar cycle, but no relationship between fish abundance and water level, amount of discharge from the watergate or the amount of rainfall in the study area.

2.3 Hydrological flow in the Mekong mainstream and tributaries

The Lower Mekong Basin (LMB) covers the area downstream from Yunan, China through Lao PDR, Thailand and Cambodia before entering to the South China Sea via the Mekong Delta in Vietnam. The mean annual discharge of the Mekong is about 475 km^3. The major tributaries in this part of the Mekong Basin separate into two groups: tributaries that contribute most to the wet season flow, which are located on the left bank and drain the high rainfall area of Lao PDR; and tributaries that drain the low relief region of lower rainfall located on the right bank, mainly the Mun and Chi rivers that drain a large part of northeast Thailand. Climate, geology/landscape and land use are the major factors shaping the hydrology of these rivers.

The climate of the Mekong Basin is dominated by the southwest monsoon, which generates wet and dry seasons of more of less equal length. The monsoon season usually takes place from May until late September or early October, with the wettest months of the year in August and September and even October (in the delta) due to cyclones occurring over much of the area. Seasonal shifts in the distribution of sub-regional monthly rainfall patterns can be seen in different areas: rainfall is lower in the more northern regions, where the highest rainfall is generally observed in July, August and September, but rainfall is later (September and October) in the area downstream.

Seasonal flows in the Mekong can be quite changeable from year to year. Although the pattern of the annual hydrograph is predictable, its magnitude is not. During the dry season (December to May), the contribution from the Upper Mekong basin is proportionally much greater while the input from the major left bank tributaries declines (Figure 2.5). There are four distinct bio-hydrological seasons: dry season, transition season I, flood season and transition season II. The duration of each season is defined by specific flow thresholds and the date of the onset of seasons may vary from year to year (Table 2.4). Changes in flow during the transition season between the dry and flood season is important to migration of fish species. Hydrographs from Luang Prabang in 1988 are a good example of seasonal variation in the annual flow of the Mekong River (Figure 2.6). Towards the end of dry season or the beginning of first transition season, flow increases to twice the minimum discharge found in the dry season. At the end of transition season or the onset of flood season, the flow exceeds the long-term mean annual discharge and remains above this average for several months. The flow then drops below the value for long-term mean annual discharge at the end of flood season until the end of second transition season. At the beginning of the dry season average flow declines to less than 1% of mean annual flow (MRC, 2005).

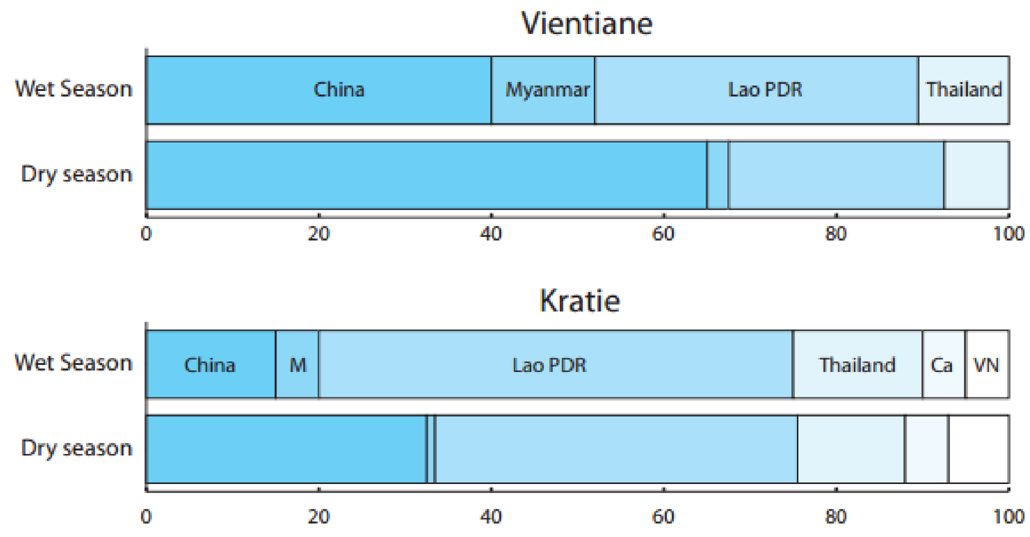


Figure 2.5 Sources of flow to the Mekong in the wet and dry seasons at upstream and downstream sites (after MRC, 2009).

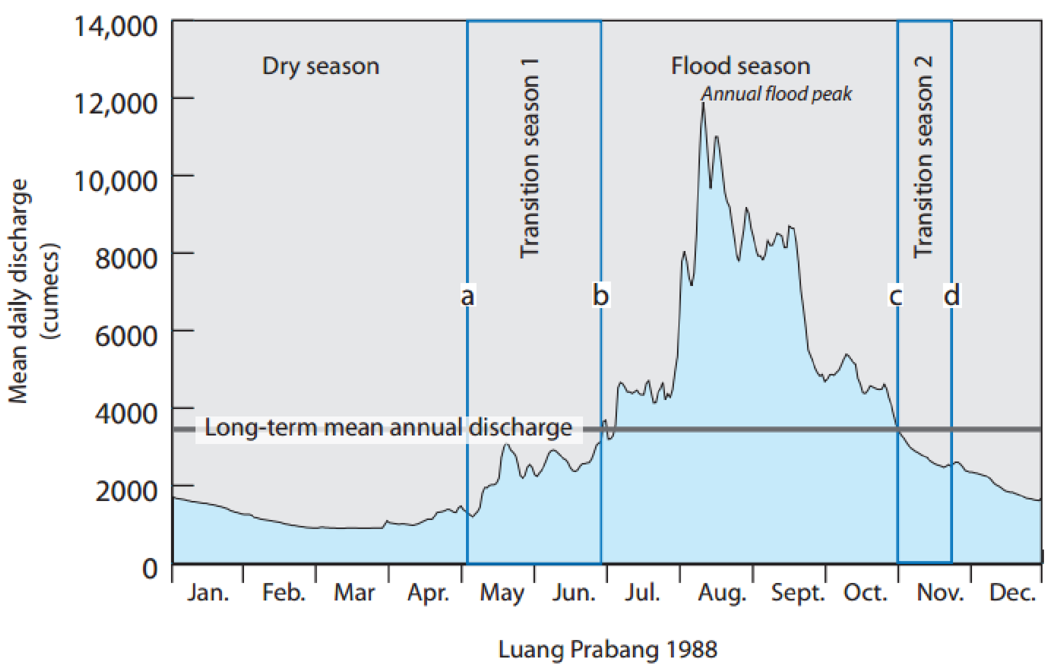


Figure 2.6 A typical hydrograph from the Mekong River illustrating the bio-hydrological season (after MRC, 2009).

Table 2.4 Characteristic of bio-hydrological season (after MRC, 2009).

Hydro-Biological season	Normal Start Period	Normal End Period	Significant hydrological parameters	Ecosystem influence
Dry season	Late November to early December on the mainstream upstream of Kratie. Further downstream, floodplain storage and the regulating influence of the Tonle Sap system delays the typical dry season start to January.	Typically May, throughout the Lower Basin	- Minimum flow and date. - Mean daily dry season discharge. - Coefficient of variation (%) of dry season daily flows	Dry season minimum indicates protential magnitude and timing of maximum stress. Mean specifies owerall conditions while the coefficient of the variance indicator offers a way to detect non-natural influences on dry season hydrology.
Transition season I	In a normal year would typically be confined to a few weeks in May/June		Number and magnitude of pre-flood season spates or freshes.	Early spates offer spawning cues for migratory fish and have positive impacts upon water quality. Particulary dissolved oxygen, and other variables.
Flood season	Typically June throughout the Lower Basin	From year to year can be quite variable, but generally early November in the upper reaches, and later further downstream	Each flood season is classified into one of four quartiles dependent upon whether the peak and volume are above/below their respective mean	The relationship between the peak and volume of the annual mainstream flood hydrograph is a key indication and habitat provision for fish and other aquatic organisms.
Transition season II	A Generally brief one to two week season during mid November in the upper reaches but tending to be longer and occur later downstream as over bank, wetland and lake storage influence emerge.		The average daily rate of flow recession (cumecs/day)	Indicates the rate of post flood drainage riparian wetland with triggers downstream fish migration and influences vegetation changes.

2.3.1 Flood and drought hydrology

Floods are most often measured in terms of maximum or peak discharge. Flood volume for each year can be determined from the daily discharge data. In the Mekong River there are other aspects of floods that are also important, for example, duration of flood, timing of flood, continuity, smoothness, rapidity of change and amplitude and flood volume (Figure 2.7). All these aspects need to be brought together for a complete description and analysis of flood occurrence and severity on a river.

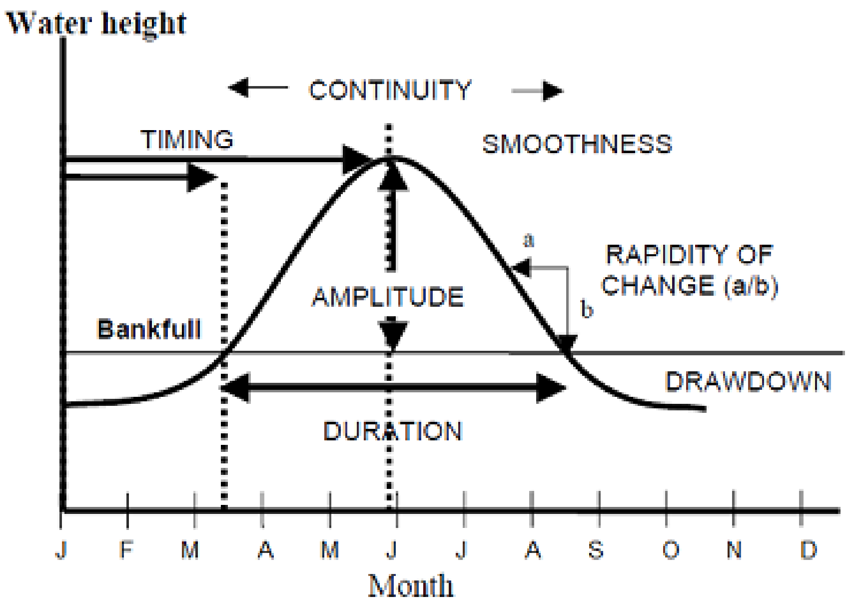


Figure 2.7 The important parameters of flood curve having biological significance (after Welcomme *et al.* 2004).

Fish life cycles are often related with timing of the flood period: the migratory season and breeding season of most species in the Mekong occur in the wet season when water levels are rising (Warren *et al.,* 2005). In regulated systems, discontinuity of floods result in interruption of the smooth sequence of flooding. This can disrupt some fish species that spawn during the onset of the wet season because eggs and larvae may die or drift onto the unsuitable habitat due to temporary declines the water level. Moreover, black and grey fish might lose breeding opportunities when floodplains dry out during low flow periods (Welcomme & Hall, 2004). Smoothness of flood curves is necessary for the spawning of white fish as temporary declines can delay larval drift. Fluctuations in water level will affect marginal spawning and nest building species if the littoral zone is flooded and then exposed. Rapidity of change in flow may affect many fish species directly because of exposure of nests of bottom breeding species. Rapid flow associated with transition in water discharge may flush away the eggs and larvae in marginal areas of floodplain and also pelagic and semi-pelagic larvae in the main river get difficult to reach their appropriate nursery and feeding habitats. Also, rapid retreat of the flood during the flood recession may increase the risk of mortality of species living in temporary pools in swamp and floodplain areas during this critical period. Amplitude of the flood creates more nursery and feeding habitat for fish: when water level rises to bankfull, it creates greater areas of submerged floodplain and floodplain vegetation. The longer the duration of flooding, the greater the amount of time available for feeding and growth, leading to a greater potential to survive and improved recruitment success (Welcomme, 1985). At the same time, longer flood periods may cause die out and decomposition of aquatic plant, which may contribute to de-oxygenated conditions and affect aquatic life in the river system.

Drought is described as the accumulation of water and moisture shortage measured in terms of rainfall, stream flow or soil moisture. In the Mekong basin, hydrological scarcity is measured in terms of mainstem flow and the degree to which it falls below normal or expected levels in any year. Drought flows in the Mekong can be considered as the below average cumulative hydrological conditions over the year as a whole or the minimum flow during the year over some duration of interest. This is used to emphasize the dry season hydrology as a basis for categorizing drought occurrences and severity from year to year (MRC, 2005).

2.3.2 Influence of hydrological characteristic changes on aquatic biodiversity

The biotic composition, structure and function of aquatic, wetland and riparian ecosystems depend largely on the hydrological regime (Gorman & Karr, 1978; Junk *et al.,* 1989; Poff & Ward, 1990; Sparks, 1992). There are four key principles about the effect of hydrology on aquatic biodiversity. Firstly, flow is a key component of physical habitat in the river channel, which in turn is a key driver of biotic composition. Secondly, life history strategies of aquatic species evolve mostly in direct response to the natural flow regimes. Thirdly, maintenance of natural patterns of longitudinal and lateral connectivity is key to the viability of populations of many riverine species. Finally, the invasion and success of alien species and introduced species in rivers is accelerated by the alteration of flow regimes (Bunn & Arthington, 2002). Hydrological variation plays a major role in shaping the biotic diversity within river ecosystems as it controls main habitat condition within river channels, floodplain, and riparian zone. Natural flow depends on local precipitation, size and the physical area of river basin for seasonal variation in discharge. In a small basin that responds to only local rainfall, flow variation may be very rapid and not as smooth as large basins like the Mekong where water is received from many tributaries (Richter *et al.,* 1998).

Alteration of flow regimes is often considered to be the most intense and continuing threat to species composition, abundance, and viability of river biota and may damage the sustainability of river fisheries and their associated floodplain wetlands (Bunn & Artington, 2002; Welcomme *et al.,* 2006; Naiman *et al.,* 1995; Sparks, 1995; Lundqvist, 1998; Ward *et al.,* 1999). Some fauna within river systems is often adapted to natural fluctuations in environmental conditions, so that altered stability in stream flow caused by river regulation may disturb environmental cues, especially associated with the reproductive cycle (Ward & Stanford, 1989): maintaining hydrological variation is needed to conserve local riverine biota and river ecosystem integrity.

The structure and continuity of native biotic communities within river ecosystems are heavily influenced by both spatial and temporal variation in environmental conditions (Poff & Ward, 1990; Stanford *et al.,* 1996). Spatially complex riverine environments present diverse habitats along longitudinal, lateral and vertical dimensions (Ward, 1989; Stanford & Ward, 1992), offering the possibility of spatial segregation of species and guilds, size classes and life stages (Schlosser, 1991; Stanford *et al.,* 1996, Poff *et al.,* 1997). While temporal variation in stream flow, water temperature, dissolved oxygen concentration, transport of sediment and organic matter and other environmental condition continually modify the suitability of particular aquatic habitat, imposing ‘environmental regimes’ influence the composition and structure of aquatic communities in three important ways; firstly shaping environmental conditions and their variation within particular habitats, secondly shaping the distribution and evolution of the mosaic of habitats and thirdly influencing the movement of organisms between habitats (Richter *et al.*, 1998).

2.4 Impact of dam construction on river systems

During the last century, dams have become a substantive tool for the management and utilization of water resources and it is estimated that more than 40% of dams service agriculture while 19% contribute to power production (WCD, 2000). Globally, the construction of dams for hydropower, irrigation and navigation has been a major cause of change to freshwater ecosystems. Over half of all large river systems in the world are moderately to highly fragment by dams and reservoirs (Nilsson *et al.,* 2005). Revenga *et al.* (2000) stated that strongly fragmented river systems are defined as "rivers with less than a quarter of their main channel remaining without dams, where the largest tributary has at least one dam, as well as rivers where the annual flow pattern has changed substantially." Fragmented rivers are only considered unaffected if their main channel has no dams or, if their tributaries have been dammed and the total river discharge has only declined by less than 2%.

Halls and Kshatriya (2009) stated that the impacts of dams on fisheries resources in the Lower Mekong Basin are varied, often overwhelming and typically facilitated through two major pathways: 1) modification of flows, and 2) effects of barrier and passage (Figure 2.8). Modified flows cause changes in flow volume, timing and duration and also water quality (i.e. temperature, dissolved oxygen, nutrient concentration and sediment load), resulting in changes in habitat and primary production. Barrier and passage effects impede fish migration, increase fish mortality via fish passage through turbines and reduce sedimentation. These all impact on the temporal and seasonal changes is fish abundance, biomass and diversity of fish (Figure 2.8).

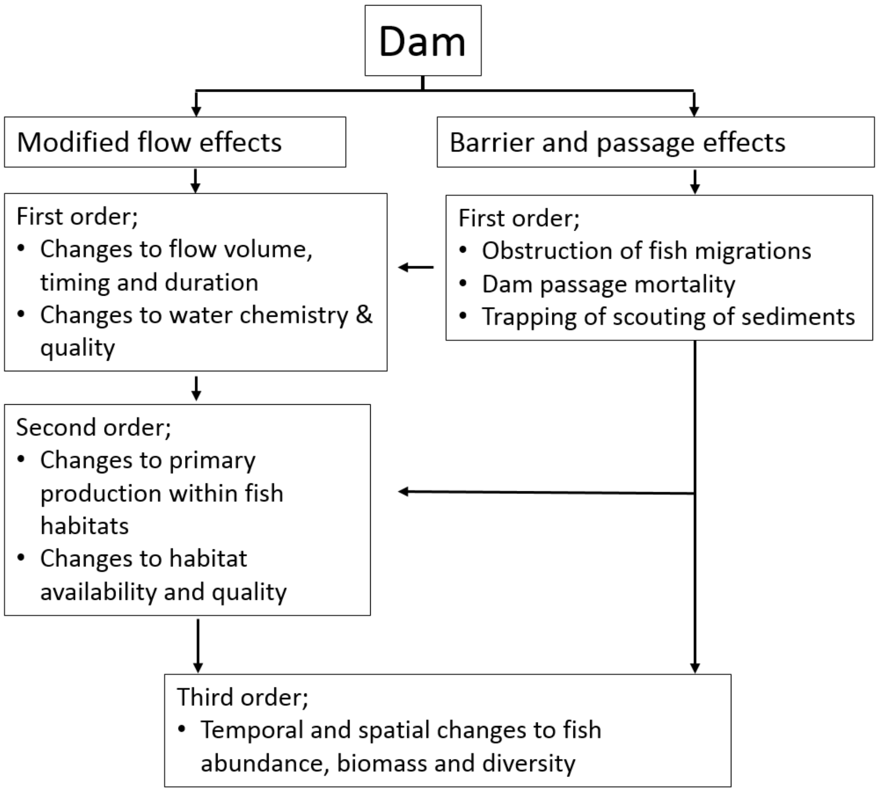


Figure 2.8 Dam impact pathways on fisheries resources (modified from Halls & Kshatriya, 2009).

2.4.1 Impact on different habitat types

Modification of rivers by processes such as flow regulation, water abstraction, channelization and dam construction has dramatically influenced the flow regimes, where flow is defined as discharge (the amount of water in the channel dictating wetted area) and velocity (the rate of movement of water). These modifications specifically compromise elements of the flow regime that are widely recognized as being of ecological important and essential in the maintenance of sustainable fisheries and the habitat on which they depend. The magnitude, frequency, duration timing and predictability of flow are vital components of a fish's habitat (Lytle & Poff, 2004). Connectivity between rivers and their floodplains is essential for the functioning and integrity of floodplain ecosystems.

Upstream effects

When a dam is constructed, it blocks longitudinal connectivity in the river system and forms an impoundment area upstream. After obstruction by dam, river are divided into four areas (or five if the reservoir has a second important tributary); tributaries, and upper, middle, and dam area (Figure 2.9). The middle and dam areas are usually lentic conditions while the upper and tributary areas are lotic conditions. Each dam will create a backwater effect which may impact on functioning of upstream habitats, the degree to which this happens will depend on the height of the dam wall, topography of the surrounding land and the gradient of the original river bed. The transformation from a running water ecosystem to reservoir habitat can result in temperature changes, chemical composition, dissolved oxygen levels and the physical properties in the reservoir, which may not be suitable for the aquatic fauna. The natural bed form, spawning and nursery grounds will be partly or permanently submerged by the reservoir, and riverbank vegetation and natural forests might be loss or submerged under the reservoir. The loss of these plants and vegetation through inundation has implications for biodiversity and household food security. Eggs and larvae of downstream migrating and drifting species may sink in the impoundment area. Fish population structure and the distribution of critical habitats relative to the proposed locations of mainstream dam sites will largely influence the degree of barrier and passage effects on fish populations and their fisheries. Catch compostion and volume of fish were shifted, white fish tend to replace by grey fish and some alien species that prefer lacustrine habitat when the river was inundeded by mainstem reservoir (Halls & Kshatriya, 2009, Cowx *et al*., 2015; Figure 2.10).

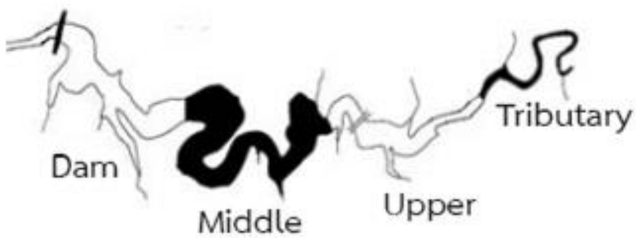


Figure 2.9 Diagram represented different locality in each reservoir into dam area, middle area, upper area, and tributary area (Modified from Drastik *et al.,* 2008).

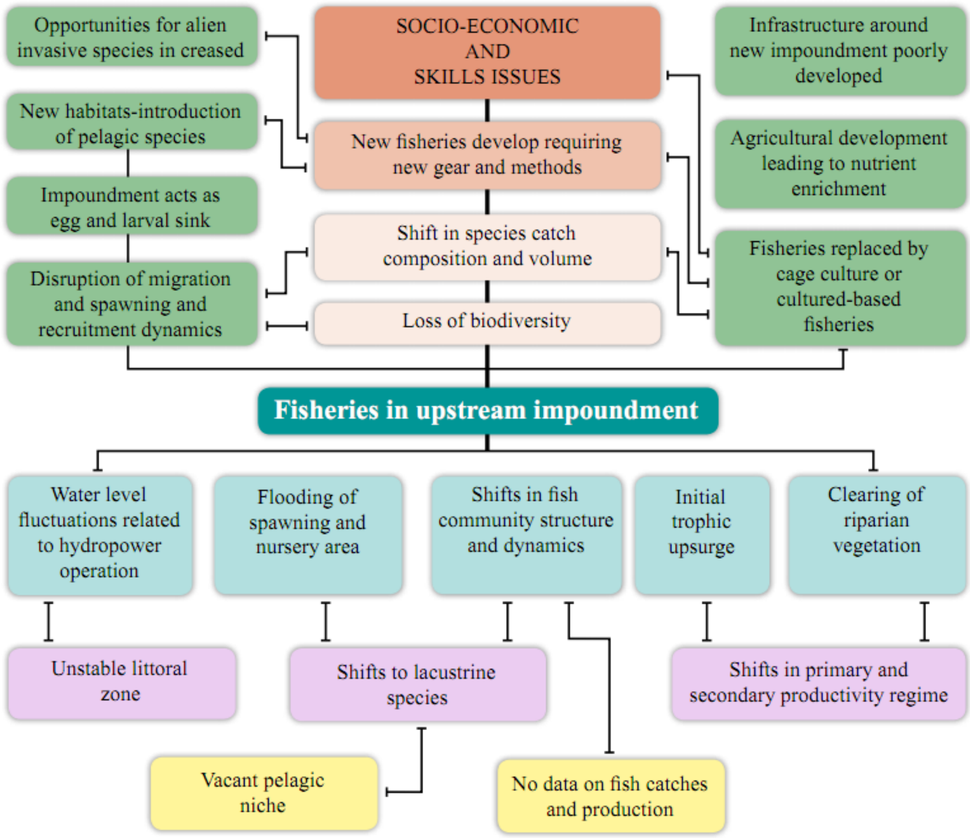


Figure 2.10 Cause and effect of the impact of impoundments on fisheries in tropical rivers (After Cowx *et al.*, 2015).

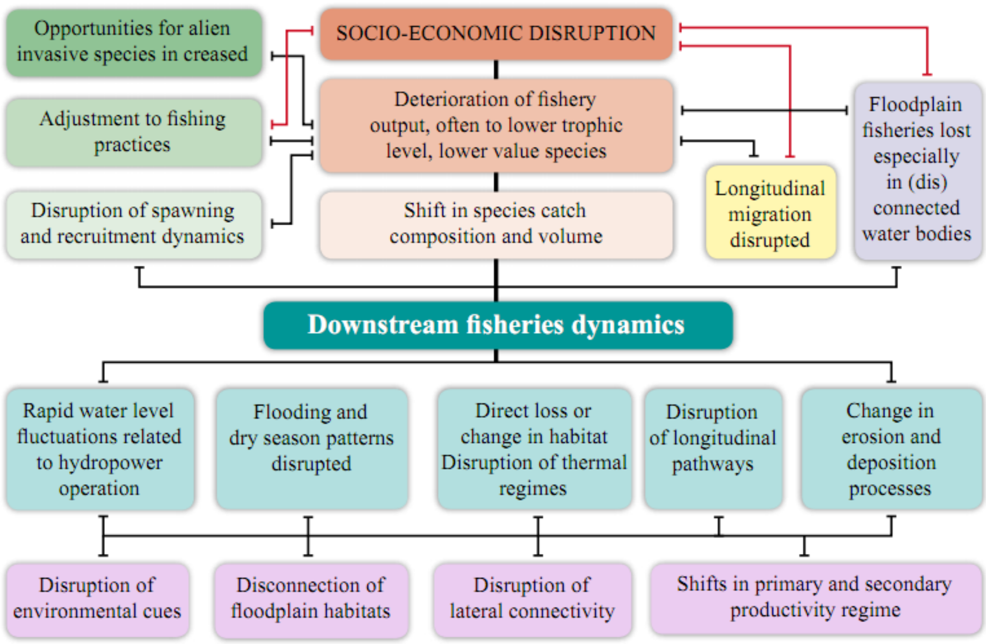


Figure 2.11 Cause and effect of the impact of flow regulation on downstream fisheries in tropical rivers (After Cowx *et al.*, 2015).

Downstream effects

In the area downstream, dam construction and operation can result in fluctuations in flows; causing disruption to environmental cues. Flooding and dry season patterns downstream are interrupted resulting in disconnection of floodplain habitats, the longitudinal pathway is disrupted and finally habitat is changed. The latter also encourages occupation in the area, and further drainage of the floodplain to create short term vegetable gardens to bring more income for the people along the riverside in dry season is prevalent. Dam operation can also cause severe erosion problems and deposition of sediment downstream, which cause major environment changes. Aquatic organisms and riparian life around and in the river are conditioned to the timing and flow cycles and are disrupted by regulation. Erosion can also occur downstream of the dam if the flow is heavily regulated and affect downstream ecosystems and riverbeds downstream sometimes for tens or even hundreds of kilometres below the dam (Figure 2.11).

Drastik *et al.* (2008) studying four cascade and two non-cascade reservoirs in the Czech-Republic, found major differences in these systems (cascade reservoir and non-cascade reservoir). High biomass and density of fish were observed in the tributary areas of non-cascade reservoirs and decreased toward the dam area while average fish weight was higher in the dam area and declined towards the tributary area. Tributary areas were usually eutrophic in the summer time and the trophic level declined toward the dams. This area is an important zone of the reservoir because it represents the productive part and is important for reproduction due to high densities of larvae and juvenile fish. However, in cascade reservoirs fish distribution was more complicated, with maximum biomass and density of fish in the dam area, while tributaries were usually inhabited by fish. The same distribution has been reported by many authors, sampled with different fishing gears, in European and American reservoirs (Vondracek *et al.,* 1989; Brosse *et al.,* 1999; Gido *et al.,* 2002; Matthews *et al.,* 2004). The same pattern was observed in Mekong River, high abundance of fish larvae and juvenile was observed in floodplains in tributaries, especially in the rainy season. For example, the main spawning area in the middle Mekong Migration System are floodplains associated with the tributaries or flood areas connected with the Tonle Sap in the lower Mekong Basin and (Poulsen *et al.,* 2002)

2.4.2 Influence of flow modification on fish populations

Rivers are increasingly fragmented by dams, resulting in disruption of natural flows, which play important roles in providing different habitat for aquatic animals to complete their lifecycle and support ecosystem functioning, but also resulting in changes in riverine animal communities. Water level fluctuations caused by dam operation are considered to be a major factor that influences fish distribution and the success of fish reproduction (Baras & Lucas, 2001). Variation in the natural discharge of a river alters over several time scales (e.g. hours, days, seasons, years) (Poff *et al.,* 1997). Dams are increasingly operated for multiple purposes resulting in different downstream hydrological impacts: dams for navigation and irrigation supply increase low flows in rivers, while dams for flood control reduce high flow in the wet season and hydropower dams can produce extremely short term flow fluctuations (hydropeaking) to generate electricity (Petts, 1984).

Flow changes affect fish populations and fish communities by disrupting and weakening spawning behavior and success, reducing growth and survival rates, reducing feeding and refuge opportunities and exposure to adverse environmental conditions (Halls & Kshatriya, 2009). Upstream dispersal is also needed to maintain populations of species with passively drifting eggs or larvae, and fishes that migrate upstream to spawn. Natural riverine habitats upstream of dams are critical for fish species dependent on such habitats, especially for reproduction, but these might be partly or permanently flooded by the reservoir after dam inundation. This issue has arisen in the Mun River, a major Mekong tributary in Thailand, where some fish species that use this type of habitat for their life cycle are at risk of disappearance after the dam construction. For example, some species use plants and vegetation as their refuge, feeding and spawning habitat, while others have adhesive and entangling eggs that they lay on vegetation, In addition, others need the rapids as their spawning grounds, for example *Pangasius larnaudii, Pangasius macronema, Pangasius micronema,* and *Pangasius pleurotaenia*, all belonging to the family Pangasiidae, and *Probarbus jullieni* belonging to the family Cyprinidae. Moreover, the fish catch in the post dam period of Pak Mun Dam declined over 50% and many fish species both downstream and upstream of the reservoir declined in abundance (Amornsakchai *et al.,* 2001).

Mainstem dams in the LMB have the potential to reduce the diversity of fish and the community size structure thereby possibly influencing ecosystem integrity and functioning. Overall catch will likely decrease if large, valuable, highly migratory species that are economically attractive to fishermen are no longer able to complete their life cycles. Populations of small species that respond negatively to environmental change may also decline further (Halls & Kshatriya, 2009).

The influence of flow on fish community structure can investigated by focusing on key topics in the broad field of hydro-ecology, spatial and temporal variation in fish community structure in response to flows, the effect of flow on fish migration and barriers to passage and the link between hydrodynamic performance and habitat.

To maintain adequate flow in the river systems, an improved knowledge of the flow (velocity and discharge) requirements of all fish species is essential, and clear guidelines on flow requirements to protect fish and fisheries are needed. Unfortunately, in Thailand this has not been done to quantify the influence of floods on fish community structure, especially on a broad scale. Studies need to be long term and sufficiently high resolution to be able to determine when a significant community change has occurred, and to relate this change to the specific flow events and define whether this change is detrimental to fish community health and value.

2.4.3 Impact of dam construction on genetic diversity

The presence of man-made barriers, such as weirs, watergates, locks, and dams, in rivers has serious consequences for fish species. They interrupt not just the movement between specific habitats, such as spawning, feeding and refuge area (Jungwirth *et al.,* 1998), but the barriers also genetically isolate and degrade the upstream populations (Meffe & Carroll, 1997; Puth & Wilson, 2001). It thus causes population decline and limits the possibilities for numerous fishes to realize their life cycles, and also isolates migrants from their spawning and nursery grounds (e.g. Barthem *et al.,* 1991; Wei *et al.,* 1997; Ruban, 1997). Besides the disappearance of habitats and possible reduction in distribution, it can initiate significant genetic differentiation between fish populations (Laroche & Durand, 2004).

Habitat change caused by seasonal isolation can also lead to isolation of populations, as was found for a critically species in Portugal isolated by intermittent drought conditions leading to differentiation of two subpopulations in upstream and downstream reaches (Henriques *et al.,* 2010). Incidence of high gene flow was found mainly from downstream to upstream, and suggests a preferential migration flow in the upstream direction.

Loss of connectivity can potentially obstructed exchange of individuals among populations, thereby accelerating the loss of genetic diversity because of genetic drift (Frankel and Soule, 1981; Hedrick, 2005). Genetic diversity is likely to decrease and populations could become extinct in a short time period because of inbreeding (Saccheri *et al.,* 1998; Westemeier *et al.,* 1998; Coltman *et al.,* 1999), thus reducing evolutionary potential in the long term, i.e. the ability of populations to adapt to future changes in biotic and abiotic factors such as climate changes (Frankel & Soule, 1981; Lande, 1998; Fraser & Bernatchez, 2001; Hedrick, 2005). However, recently constructed barriers have rarely been found to affect genetic diversity in natural populations, particularly for long-lived, large bodied species (e.g. Kyle & Strobeck, 2003; Sumner *et al.,* 2004).

Habitat fragmentation also has a harmful influence on population persistence (Wilcox & Murphy, 1985). Various studies have shown that some freshwater fishes (e.g., Winston *et al.,* 1991; Reyes-Gavilán *et al.,* 1996; Morita & Suzuki 1999), shellfishes (Watters, 1996; Kelner & Sietman, 2000), and crustaceans (Miya & Hamano, 1988; Holmquist *et al.,* 1998) were extirpated and that species richness decreased in habitats isolated by dams. Several studies also report genetic variation influenced by fragmentation of aquatic habitats, e.g. by barriers in a watershed on movement of coastal cutthroat trout (Wofford *et al.,* 2005), stream-dwelling char (Morita & Yamamoto, 2002; Yamamoto *et al.,* 2004), and redfin culter (Wang *et al.,* 2007). Other studies have found decline in genetic diversity caused from habitat fragmentation by road construction, i.e. desert bighorn sheep (Epps *et al.,* 2005), amphibians (Reh & Seitz, 1990, Dixo *et al.,* 2009) and beetles (Keller & Largiader, 2003). There is growing concern that habitat fragmentation will affect many wider varieties of taxa (e.g. Kramer-Schadt *et al.*, 2004; Malo *et al.,* 2004).

2.4.4 Impact of dam construction on fish migration

Dam construction provides a barrier to fish passage and impacts to fisheries resources in rivers. The major negative impact of a dam is the potential loss of fisheries as a consequence of obstructing fish migration routes and altering aquatic habitats both upstream and downstream of the dam (Larinier, 2012). River-floodplain connectivity allows fish to distribute freely and take advantage of different floodplain habitats for refuge, spawning, nursery and feeding. Fishes depend upon unobstructed movement between various habitat types over their life history (Schlosser & Angermeier, 1995).

However, not all species of river fish are threatened by obstructions, some have limited migrations that may not be compromised. Others may adapt easily to the new changeable habitat. The species most likely to be affected will be those that undertake significant (passive and active) migrations within the mainstem between critical habitats as part of their life history strategy, for example, species that migrate long distances between critical or functional habitat such as spawning, feeding and refuge habitats (Figure 2.12) either to complete their life cycles or to exploit seasonal variations in habitats (Halls & Kshatriya, 2009). Besides, mainstem construction has the potential to affect the integrity and functioning of the ecosystem by reducing diversity and the size structure of the community. The overall value of the catch may also decline if large, valuable highly migratory species that respond rapidly to environmental variation may also decline further, reducing their resilience to climate change and leading to greater fluctuation in annual landings (Amoros & Bornette, 2002; Starr, 2009).

Halls and Kshatriya (2009) modeled the cumulative effect of mainstream hydropower dams in the Mekong River. Migration is modeled by specifying the relative amount of individuals that move from one habitat to another in each time step. In cases where there are single or multiple dams blocking the migration route, the rates are reduced by the efficiency of fish passage. Dams can deny or weaken fish ability to access to critical or upstream spawning habitat but also have the potential to reduce population survival rates as mature fish and their offspring returning to downstream feeding and refuge habitat pass through dam turbines, by-pass structures, or over dam spillways. The combination of diminished survival rates and spawning success can lead to significant reductions in exploitable fish biomass and species extinctions.

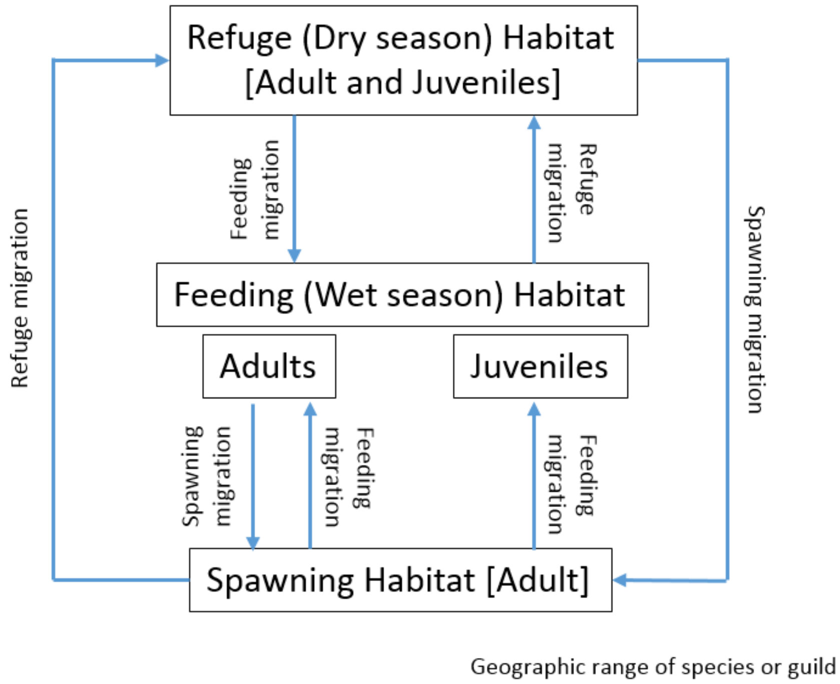


Figure 2.12 Schematic representation of potential fish migrations between critical habitats (modified from Lucas & Baras, 2001).

Habitat fragmentation has been directly related with the declining population of flathead chub and other pelagic spawning cyprinids in the Great Plain of central North America (Gido *et al.,* 2010; Perkin & Gido, 2011). Corresponding with the habitat change are massive declines in the distribution and abundance of fishes belonging to the pelagic spawning reproductive guild. Recruitment bottlenecks associated with loss of drifting eggs and larvae were a key factor in these eradications (Platania & Altenbach, 1998; Dudley & Platania, 2007) but upstream movement also played an important role in maintaining population (Fausch & Bestgen, 1997; Luttrell *et al.,* 1999). Dams can limit access of fish to upstream reaches and fragmentation of this upstream reach can cause a decreasing population. For example, Pak Mun Dam on the Mun tributary of the Mekong in Thailand, which is located 5.5 km upstream from its confluence, seriously affects the migration of rheophilic fish species and several migratory species at the beginning of the rainy season. The head pond flooded their spawning ground and the fish pass was a complete failure and resulted in loss and decline of many fish species (Amornsakchai *et al.,* 2001).

2.5 Conclusion

The Nam Kam River system is different from the other tributaries of Mekong River in Thailand because it has been obstructed by a series of run of river watergates on it mainstem and tributary. Damming in the main stem river offers an opportunity to improve water supply for irrigation and control flooding in flood season, but their construction also brings many changes to hydrology and habitat both downstream and upstream of the infrastructure and may cause significant changes on fisheries resource including biodiversity loss and fish assemblage pattern changes, blocked migration of fish and reduced production of fish in the river system.

Therefore, to manage the watergate operation in the river to benefit fisheries resources as well as protect water for irrigation supply, there is growing need to understand more about the likely impacts of watergate operation in this river system. Moreover, the fish passage facilities installed in the river system need to be assess for their effectiveness and how they could be used to find solutions to mitigate the impact and increase opportunity of fish migration through the fish pass facilities and the watergates to enhance the fisheries in the Nam Kam River system.

Chapter 3: Hydrological change in the Nam Kam River system.

3.1 Introduction

Over the past 20 years, the Lower Mekong Basin has been subjected to considerable number of dam development projects. Over 124 dams have been built or are under construction on the Mekong mainstem and its tributaries, and a further 41 are due for completion by 2030 and a further 11 dams are proposed for the mainstem (Baran & Myschowoda, 2009; MRC, 2011) of which two (Xayaburi and Don Sahong) are in construction. The Nam Kam River, the third largest tributary of the Mekong in northeast Thailand, has a cascade of seven run-of-the-river-watergates on the mainstem and its main tributary constructed under the Nam Kam Royal Development project for irrigation and flood protection. Consequently, flow in this river system is heavily modified by watergate operation. Before construction, seasonal flow in the Nam Kam River system was quite changeable from year to year. Source water in this river system was mainly contributed by releasing water from Nong Han Lake, which is located upstream, and input from precipitation falling over the river basin. Although the pattern of the annual hydrograph is predictable, the timing and magnitude of each cycle is different and unpredictable. After becoming operational, watergates have transformed the river into a series of cascading pools, and most of the riverine environment has been replaced with pool habitat, especially in dry season.

Alternation of flow regimes is a key driver to ecological sustainability in rivers and their associated floodplain wetlands (Naiman *et al.,* 1995; Sparks, 1995; Lundqvist, 1998; Ward *et al.,* 1999). Population structure, species composition, relative abundance of fishes and viability of river biota are strongly related to the annual hydrological regime in the main channel and the associate habitat structure (Welcomme, 1985; Meffe & Sheldon, 1988; Junk *et al.,* 1989; Bunn & Artington, 2002; Welcomme *et al*., 2006). Fish life cycles are strongly related with timing of the flood period: the migratory and breeding seasons of most species of fish in the Mekong River usually occur in the wet season when water level is rising (Warren *et al.*, 2005). Moreover, floods perform an important role in connecting various habitats and increase environmental heterogeneity (Ward *et al.,* 2002; Thoms *et al.,* 2005). Flooding enhances hydrological and ecological connectivity between the mainstem channel and the floodplain area, so is important for the integrity and ecosystem functioning, and is a major driving variable of ecological processes, biotic interactions and productivity of the river system (Junk *et al.,* 1989). Thus, the series of watergates in the Nam Kam River system might alter river habitat, which affect fish diversity and the functional organization of fish communities in this regulated river. Hydrological change such as timing, continuity, smoothness, rapidity of change, amplitude and duration of flow might affects the fish species, populations and community stability. Furthermore, the annual changes in flow of water might influence fish production in the floodplains by limiting or increasing access to and occupation of the spawning and feeding grounds of fish.

This chapter investigates changes in the hydrology and habitat characteristics of the Nam Kam River system (both spatial and temporal changes) to understand better how the altered flow regime from watergate operation affects fisheries resources both in term of fish diversity and population structure in the Nam Kam River and its tributaries.

3.2 Objective

To compare spatial and temporal changes in hydrological and habitat characteristics in the Nam Kam River system before and after watergate operation and compare with a reference river (Songkhram River) with no obstruction on the main stream.

3.3 Methodology

3.3.1 Hydrological data collection and habitat description

A series of three watergates was constructed in the Nam Kam River between 1995 and 1999 under the Nam Kam Royal development project for flood control and irrigation. Based on hydrological data recorded by RID and DoF from 2008 and 2011 to 2015, the series of watergates in Nam Kam River and its tributaries start to release water for flood control purposes around the onset of rainy season (end of May to June) of each year. The first watergate, Na Karm (NAKA), was constructed between 1995 and 1997, follow by Na Koo (NAKO; 1996-1999), and Nong Bueng (NOBU; 1997-2000). Ban Tabtao (BATA) and Na Bua (NABU) watergates were constructed on the Nam Bang River in 2003-2005 and 2005-2007, respectively. At the same time, the most downstream watergate, Thoranit Naruemit (TNNM), was constructed from 2006-2009.

Hydrological data and watergate operation in this river have been recorded daily. Water level (metre above mean sea level: m AMSL), and daily stream flow data (m^3/s) in the main stem river since 1996 were obtained from the hydrological gauging stations at the nearest Nationwide Hydrological Centres (Kh68: Nam Kam River, Kh69A: Nam Bang River, Kh55: Songkhram River and Kh17: the Mekong River). These records were provided by the Water Management Division Bureau of Water

Management and Hydrology, Royal Irrigation Department (RID), Thailand (Figure 3.1). Rainfall data in each river were provided by Nakhon Phanom and Sakon Nakhon Meteorological station of the Thai Meteorological Department. Irrigation operational management since 2009 such as vertical lift gate height and vertical lift gate time (both at watergate and fish passes), discharge or rate of flow and cumulative discharge at each watergate were obtained from the Nam Kam River Basin Operation and Maintenance Project, Royal Irrigation Department (RID), Thailand and Sakon Nakhon Inland Fisheries Research and Development Center, Department of Fisheries (DoF), Thailand. Turbidity (FTU) was measured using absortomatic method (HACH DR/2000) at each sampling site (Figure 3.1). Locations and photographs of the sampling sites are shown in Table 3.1 and Figure 3.1-3.2.

Table 3.1 Locations of hydrological sampling sites at each watergate, sampling sites and RID hydrological gauging stations.

Hydrological sampling sites at watergate		Locations	
SRWD	Suraswadi Watergate	423747.32 E	1896648.90 N
NOBU	Nong Bueng Watergate	432002.43 E	1888602.89 N
NAKA	Na Karm Watergate	438828.00 E	1879746.00 N
NAKO	Na Koo Watergate	449492.00 E	1875405.00 N
TNNM	Thoranit Naruemit Watergate	469796.23 E	1870994.73 N
BATA	Ban Tabtao Watergate	450880.00 E	1892349.00 N
NABU	Na Bua Watergate	455182.00 E	1886792.00 N
Hydrological gauging stations			
Kh.55	Songkhram River	420557.79 E	1950084.34 N
Kh.68	Nam Bang River	454624.58 E	1881212.50 N
Kh.69A	Nam Kam River	447711.00 E	1874705.46 N
Kh.17	Mekong River	471184.76 E	1875588.68 N

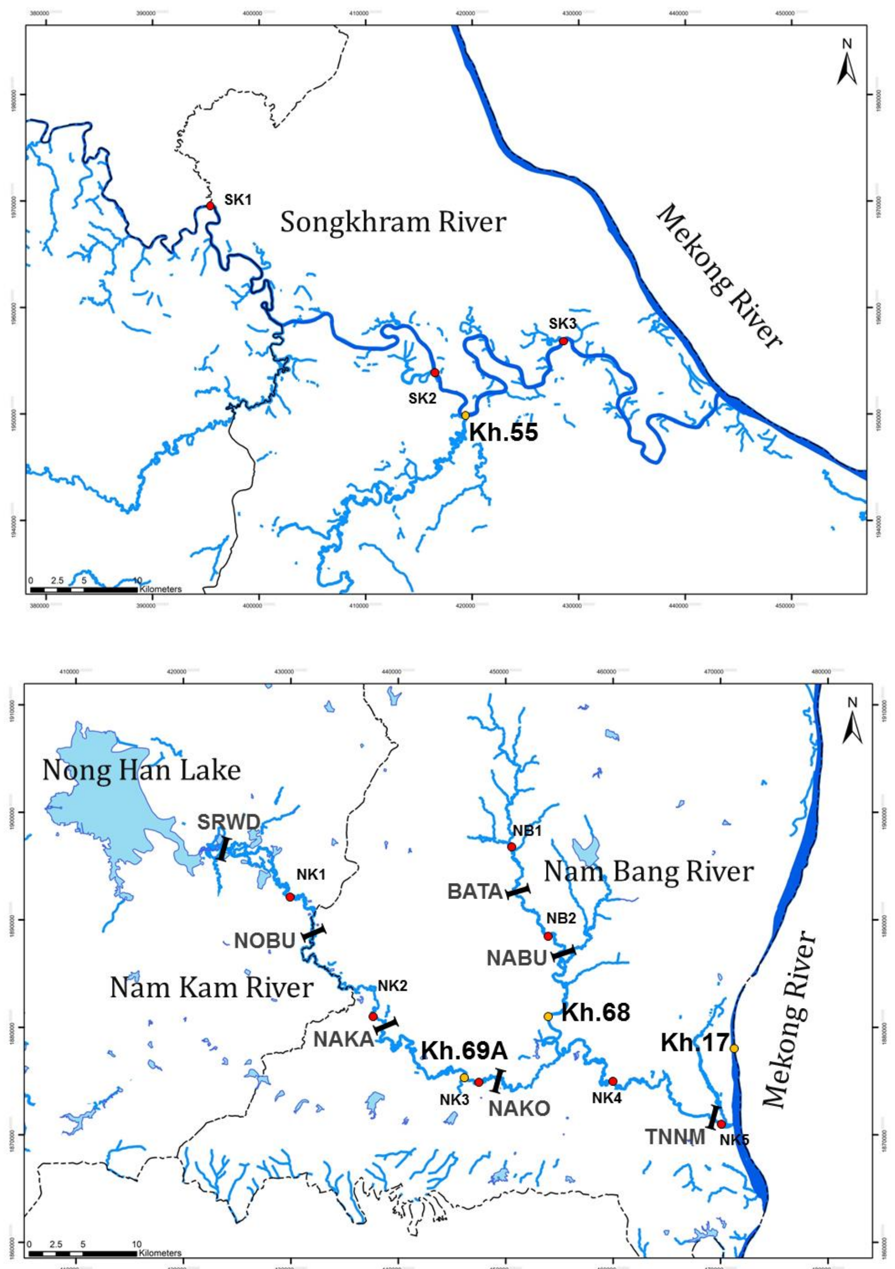
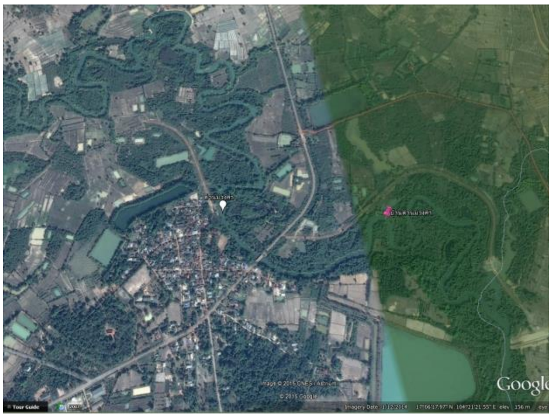
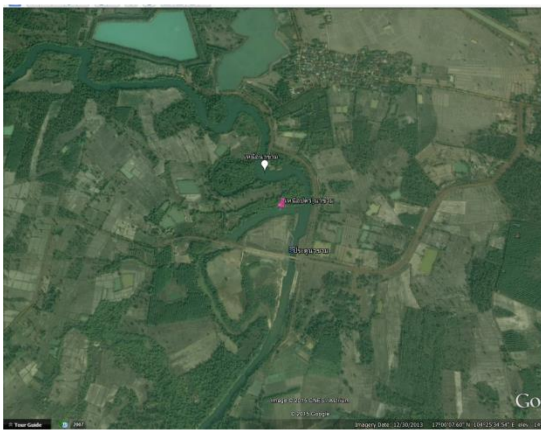


Figure 3.1 Location of hydrological and habitat sampling site: red dots represent sampling sites, black bars represent hydrological sampling sites at each watergate, orange dots represent RID hydrological gauging stations (Kh.55, Kh.68, Kh.69A, and Kh.17) in each river.

NK1: Ban Dan Muang Kam Village



NK2: Na Karm Village



NK3: Na Koo Village

Figure 3.2 Locations and photograph of the sampling sites in Nam Kam River and its tributary

NK4: Kud La-A


NK5: Ban Nam Kam Village


NB1: Ban Pak E-too Village

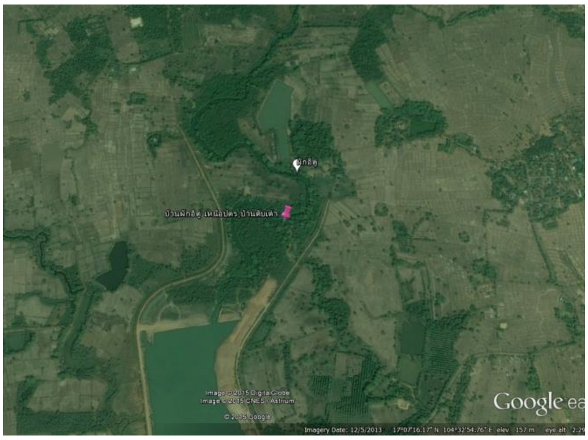



Figure 3.2 (Cont.)

NB2: Na Bua Village

Figure 3.2 (Cont.)

3.3.2 Data analysis

The Value of hydrologic attributed for each 32 hydrologic parameters (Table 3.2) were calculated based on mean daily flow data and the timing of watergate construction using The Indicators of Hydrologic Alteration (IHA) software (The Nature Conservancy, 2009; Ruth & Richter, 2007). Consequently assessment of the hydrological impact of watergate development in the Nam Kam River system was evaluated using hydrological data from five sampling sites, focusing on the most downstream watergate (TNNM) and upstream watergates (NOBU, NAKO, BATA and NABU). Daily flow data of each watergates were devided into pre- and post- alteration periods according to the timing of watergate operation except SRWD and NAKA due to, unfortunately, pre-construction flow records are not available for SRWD, and flow data from NAKA only started in the year of construction (1996). Details of data used in this study are given in Table 3.2. Due to daily stream flow and precipitation data of the post-alteration flow records at the gauging station in the Nam Kam and Nam Bang rivers were not available, therefore the flow record from each watergates from year of operation until 2014 were used in the analysis as the post-alteration period data (Table 3.2). Calculated values of IHA were present as a percentage deviation of pre-impact condition in relation to post- impact condition.

The ‘Range of Variability Approach’ is a tool for assessing hydrological alteration in terms of streamflow magnitude, timing, frequency, duration, and rate of change, at available stream gauge sites throughout a river basin (Richter *et al.,* 1998). A summary of hydrologic parameters used in RVA and their features is shown in Table 3.3. IHA prarmeters were categorise into five groups: magnitude of montly water conditions, magnigude and duration of annual extreme condition, timing of annual extreme water condition, frequency and duration of high and low pulse, and rate and frequency of water condition changes.

RVA was used to guide efforts to restore or maintain the natural stream flow regime of the rivers using the range of natural variability in different ecologically relevant flow parameters as the basis for setting management targets. RVA divides hydrological data into pre-impact and post-impact flow regime periods, and compares the two periods to determine flow changes that occurred between the two periods. Then flow management or restoration targets (the RVA targets) are prescribed on the basis of natural variability in streamflow characteristics. Annual hydrographs were used to compare with the RVA targets to see which targets were met and which targets need to be improve.

To map the degree of hydrologic alteration, median absolute degree and percentile values of 33 indicators of hydrologic alteration (0-100%) of each watergate were ranked and divided into three classes of alteration: 1) little or no alteration (0-33%); 2) moderate alteration (34-67%); 3) high degree alteration (68-100%). 33^{rd} and 67^{th} percentiles were computed for all 32 hydrologic alteration indicators as the lower and upper limits of the RVA target range for all watergates. The top 11 indicators that have changes above the RVA high target (more than 67%) were used to estimate mean absolute value, which indicated the degree of hydrologic alteration of each watergate. This method was applied to display each mapped river segment with appropriate levels of hydrologic alteration against baseline detected with in each river segment according to Richter *et al.* (1998).

Spatial and temporal changes in hydrological characteristics and habitat characteristics of the Nam Kam River system were compared with the period before operation and unregulated river. Paired-sample t-tests were used to determine if the flow duration curves in the periods before and after the watergates became operational in both rivers was significantly different.

Table 3.2 Pre and post dam period and the period that watergates finished construction in the Nam Kam River system. Year in parentheses are the period that hydrological data (discharge) were recorded and used in the IHA analyses.

Watergate	River	Pre-operation	Construction	Post-operation
Suraswadi	Nam Kam	--no data recorded--	1992-1993	1994-present (2010-2014)
Nong Bueng	Nam Kam	1996-1999 (1996-1999)	1997-2000	2001-present (2008-2014)
Na Karm	Nam Kam	--no data recorded--	1995-1997	1998-present (2008-2014)
Na Koo	Nam Kam	1996-1998 (1996-1998)	1996-1999	2000-present (2008-2014)
Thoranit Naruemit	Nam Kam	1996-2008 (1996-2005)	2006-2009	2010-present (2011-2014)
Ban Tabtao	Nam Bang	1996-2004 (1996-2003)	2003-2005	2006-present (2008-2014)
Na Bua	Nam Bang	1996-2006 (1996-2003)	2005-2007	2008-present (2008-2014)

Table 3.3 Summary of 32 hydrological parameters used in Range of Variability Approach (RVA) and their characteristics (after Richter *et al.,* 1998).

IHA statistics group	Regime characteristic	Hydrological parameters
Group 1: Magnitude of monthly water condition	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water condition	Magnitude Duration	Annual minima 1-day means
		Annual minima 3-day means
		Annual minima 7-day means
		Annual minima 30-day means
		Annual minima 90-day means
		Annual maxima 1-day means
		Annual maxima 3-day means
		Annual maxima 7-day means
		Annual maxima 30-day means
		Annual maxima 90-day means
		No. of zero days
Group 3: Timing of Annual Extreme Water Conditions	Timing	Julian date of each annual 1-day minimum
		Julian date of each annual 1-day maximum
Group 4: Frequency and Duration of High/Low Pulse	Frequency Duration	No. of high pulses each year
		No. of low pulse each year
		Mean duration of high pulses within each year (days)
		Mean duration of low pulses within each year (days)
Group 5: Rate/Frequency of water condition changes	Rates of change Frequency	No. of rises
		No. of falls
		No. of reversals

3.4 Results

3.4.1 Watergate and fish pass operation in the Nam Kam River system

Normally the most upstream watergate, SRWD, starts to open when the water level in Nong Han Lake rises over 70-80% of retention level, which is 266.9 million cubic metres (Mm^3) at a water level 157 m AMSL. In this period the vertical distance of the gate at SRWD is lifted 0.05-1.00 m, resulting in a water discharge of 6.89-195.40 m^3/s into the Nam Kam River system. To maintain water level and prevent floods destroying agricultural and residential areas along the river, the other three watergates downstream (NOBU, NAKA, NAKO) open successively to the same vertical lift gate height or narrower. The most downstream watergate, TNNM, normally opened around two or three weeks after all watergates upstream opened to release the water and after water build up at the downstream area to the Mekong River at a stream flow around 8.13-573.47 m^3/s. In the Nam Bang River, as soon as the upstream watergate, BATA, starts to release the water, NABU is opened subsequently and this results in a stream flow of 1.30-236.35 m^3/s. Sluice gates at all watergates were lifted to their maximum capacity at the height of the flood period (around the end of July to August) resulting in a flow of 0.52-341.55 m^3/s. Sluice gates remained open depending on the rainfall until the end of September or November of some years, and this operation resulted in discharge of 1.30-251.53 m^3/s (Table 3.4).

Watergate management, such as the opening, duration and vertical lift gate height were increased or decreased according to water volume above the watergate, retention level and water level below each watergate at that particular time. At the end of wet season (around middle of October to November), RID then maintains water volume by decreasing the vertical lift gate height or closes the watergates to store water for irrigation purposes. All watergates are usually kept closed during the dry season to store water for agricultural activities, but in some years, they may operate for a short period (a few days to a week) according two main demands; farmers' needs and to prepare the water retention area for the oncoming wet season (Figure 3.3).

All fish passes at the watergates are usually kept open during the wet season with a vertical lift gate height of 0.30-2.00 m depended on the water volume of the impoundment above the watergate. Fish passes were closed at the same time as the main watergate in the dry season. Velocities observed at the fish passes changed according to the vertical lift gate height and water level above the watergate area (ranging between 2.22-3.68 m/s). In the dry season, fish passes sometime dried up or sometimes had a small volume of the water in the passes due to the water level in the upstream area not reaching the entrance level of the most upstream pool of the fish pass.

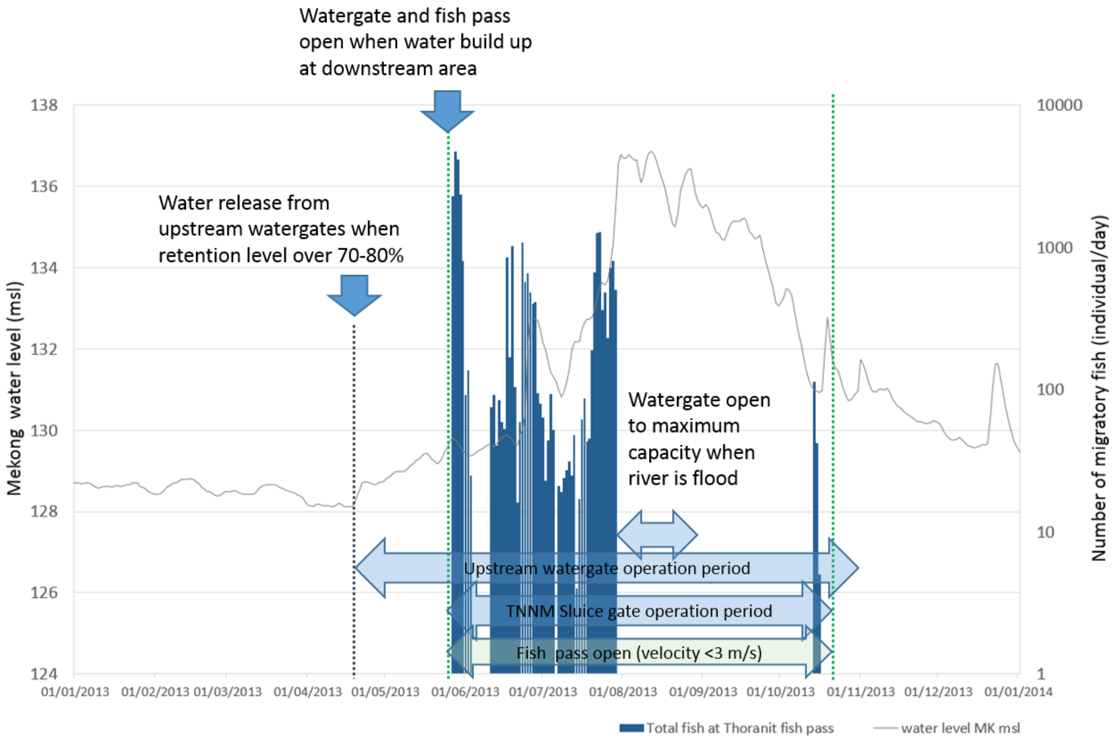


Figure 3.3 Flood cycle of the Mekong River and watergate and fish pass operation schedule in the Nam Kam River system.

T able 3.4 Flow changes by watergate operation at each watergate in the regulated Nam Kam River System compared with the unregulated Songkhram River (2010-2014)

Season	Discharge (m3/s)									
	Before Operated by weirs		After Operated by weirs							Unregulated river
	Nam Kam 1996-1997	Nam Bang 1996-1997	Suraswadi 2010-2015	Nong Bueng 2008-2015	Na Karm 2008-2015	Na Koo 2008-2015	Thoranit Naruemit 2011-2015	Ban Tabtao 2008-2015	Na Bua 2008-2015	Songkhram River 2010-2014
onset of rainy season (May)	2.30-46.75	0.52-12.53	4.40-94.54	1.64-142.07	1.80-163.38	0.64-76.67	10.87-173.93	1.81-65.41	0.96-61.61	0.00-223.60
flood season (June-September)	7.75-341.50	9.69-137.51	2.33-341.55	0.73-265.13	2.05-289.66	1.68-211.63	8.13-573.47	1.13-232.33	2.10-236.35	0.00-1,626.00
end of flood period (October-November)	3.75-233.40	0.79-36.76	2.24-188.33	1.30-251.53	1.82-240.69	1.76-163.02	11.99-479.11	1.10-61.49	2.58-83.99	4.00-1,240.6
dry period (December-April)	0.60-26.20	0.47-1.30	6.95-195.40	0.72-92.17	0.63-110.95	1.83-103.33	15.85-152.27	1.22-99.89	41.92-61.61	0.00-344.00
Number of zero flow days	0	0	0-267	137-231	111-228	126-226	211-249	194-278	227-277	44-171

3.4.2 Guidelines for operation

Watergate management in the Nam Kam River system was based on 3 operating criteria under the responsibility of the Nam Kam Royal development project: 1) the most upstream watergate (SRWD) which controls water from Nong Han into the river system, 2) the new series of upstream watergates (NOBU, NAKA, NAKO, BATA and NABU) and 3) the most downstream watergate (TNNM) controlling flow in this river especially in the downstream area before release to the Mekong River. Fish passage facilities at each watergate are fully opened in the rainy season following the main sluice gates operation. The upper and lower operating rule curves at each watergate were used to guide and manage the water level in the area above the gate and discharge of each watergate. Suraswadi Watergate (SRWD) operation is managed by DoF, while operation of the rest of the watergates in the river system is the responsibility of RID. However, operation of each watergate and associated fish passes in the river are coordinated between watergate managers. Water is released after storage for irrigation supply to the area above that particular watergate.

1. SRWD sluice gates are operated in accordance with the SRWDs rule curve controlled by DoF since 1985.
2. The series of 5 watergates in the upstream area (NOBU, NAKA, NAKO, BATA and NABU) are operated in accordance with the rule curve of each watergate, except in the flood period when all sluice gates are fully opened to release water to the downstream reaches.
3. The most downstream watergate, TNNM, is operated in accordance with its own rule curve except during the flood period when all the sluice gates are fully opened when water levels downstream of the watergate are higher than water levels in the Mekong River and closed when it is lower than water level in the Mekong River.

However, during critical situations like monsoon flooding or droughts, the watergates are managed according to suggestions/orders from the Flood Control and Water Management Centre under the RID.

3.4.3 Hydrological changes resulting from watergate operation

The annual flow regime in the Nam Kam River and its tributaries are similar to other Mekong tributaries as they are mainly driven by the monsoon, seasonal rain and tropical storms. There are two different flow periods, wet season and dry season, which create a diversity of habitat and influence aquatic flora and fauna in the river channel, bank or area alongside the river and floodplain. Before the series of watergates was operational (1996), average discharge in the Nam Kam River was higher than in its tributary both in the wet (June-September) and dry seasons

(January-April). In the wet season, discharge in the Nam Kam River ranged from 7.75 to 341.50 m^3/s while in the Nam Bang discharge ranged from 9.69 to 137.51 m^3/s. In the dry season, the Nam Kam discharge ranged from 0.06 to 26.20 m^3/s while in the Nam Bang discharge ranged from 0.47 to 1.30 m^3/s (Table 3.4) These different values of discharge indicate seasonal variation between the dry and wet seasons in this river system before the watergates were constructed and largely reflect the size of the catchment of each river.

Watergate operation created a variable discharge between seasons. Discharge varied between the mainstem and tributary: discharge in the mainstem Nam Kam ranged from 0.73-573.47 m^3/s while in the tributary it ranged from 1.13-236.35 m^3/s in the wet season. In dry season, the Nam Kam mainstem discharge ranged from 0.63-195.40 m^3/s compared with 1.22-61.61 m^3/s in the tributary (Table 3.4). After regulation by the watergates, maximum discharge of the river system increased in wet and dry season, and fluctuated greater than before regulation by the watergates.

Duration of the flooding period was longer in the Nam Kam River after regulation by the watergates than before watergates were operated. The river used to flow all year round before the watergates were constructed (1996-1997), with the flood period between May and September. After the watergates were operated, flooding was delayed from June to November, and the river was impounded on some days in the wet season and all days during the dry season due to the watergates being closed to store water for agricultural supply. Moreover, the number of zero flow days after being regulated by watergates increased in later years (Table 3.4). Watergates located in the upstream area delay the flood period in the downstream area by temporarily storing water. Moreover, water storage at the end of the flood season also delayed the onset of the dry period in this river system.

3.4.4 Flow and discharge changes

Flow and discharge changes causing from upstream watergates operation (Nong Bueng, Na Karm, Na Koo, Ban Tabtao and Na Bua watergates)

Watergate operation for flood control at the most upstream watergates created higher flow in the wet season (June-September) due to these watergates needing to release water quickly to the downstream area to prevent flooding along the river, especially above and below NOBU. Flows were also reduced at the end of flood season (September-October) because all sluice gates start to delay water and close to store water for the next dry season. Watergate operation in the Nam Bang River (BATA and NABU) slightly reduced the size of the peak flood in the wet season (June-October) in the downstream area, but the regularity of the flood cycle was more stable

(Table 3.4 and Figures 3.4-3.5)

Watergate operation on the Nam Kam River removed lower flows at the start of the flood cycle, while watergates in the Nam Bang River matched the start of the flood cycle with natural conditions but the onset of low flows at the end of wet season was earlier (April-May and October-December) (Figure 3.4-3.5). The period of no discharge in the river started at the end of rainy season and continued from 0-278 days depending on year (Tables 3.4).

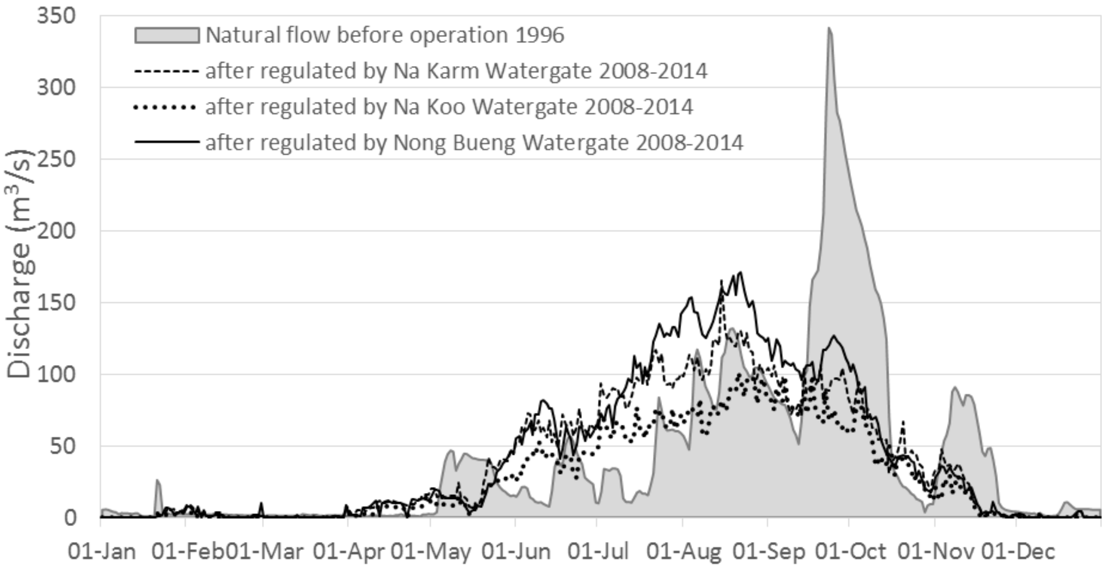


Figure 3.4 Annual discharges at three upstream watergates in the Nam Kam River before (1996) and after (2008-2014) upstream watergates construction.

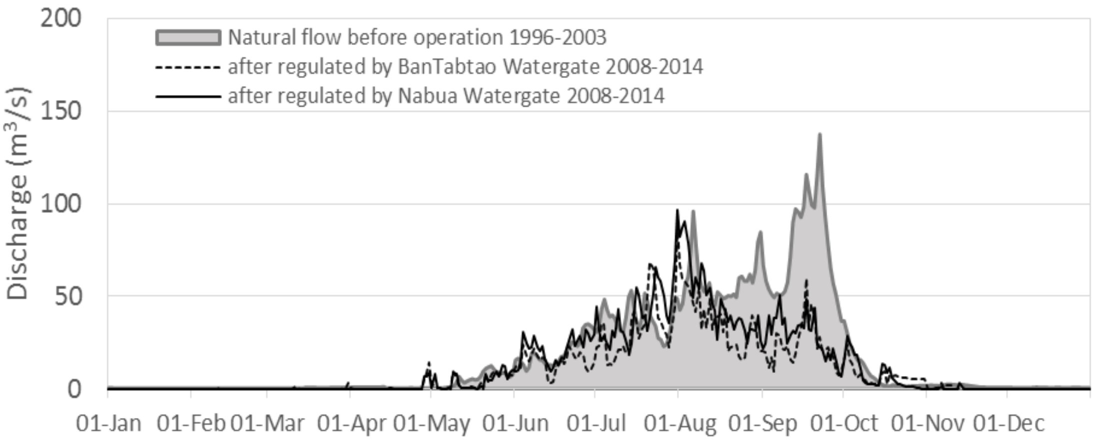


Figure 3.5 Annual discharges at two upstream watergates in the Nam Bang River before (1996-2003) and after (2008-2014) watergate construction.

Hydrological alteration at the upstream watergates

Seasonal patterns of flow in the Nam Kam River system have been altered by watergate operation. IHA analysis showed the increased median monthly flow at NOBU, but decreased median monthly flow at NAKO and two watergates in the Nam Bang River (BATA and NABU) during the wet season (Table 3.5 and Figure 3.6). Before all watergates were operated, the monthly flow of the Nam Kam River system in the wet season (June to September) ranged from 12.95 to 124.80 m^3/s, but post alteration it ranges between 6.14 and 164.40 m^3/s. This also supported a decreasing trend in Nam Kam River at the end of wet season (October to November) while the Nam Bang River was already static from November and throughout the dry season (December to April) (Figures 3.4-3.5) Between 1996 and 2005, the dry season discharge in the Nam Kam River ranged from 0.10-1.30 m^3/s and in the Nam Bang River from 0.01-0.19 m^3/s. After the most downstream watergate operation, monthly flow was absolutely zero throughout the dry season (Table 3.5 and Figure 3.6).

The watergate operation delayed downstream water increases at the onset of the rainy season. Timing of the flood was delayed by 1-2 months after watergate operation. It usually started when the monthly flow at each watergate increased around April to May before watergates were constructed, but after watergate construction the flood started to increase in May to June (Figure 3.6).

Flow continued to increase to a peak earlier than before watergate construction, for example, peak flow was observed in August at the upstream watergate (NOBU) while it peaked one month earlier; from September to August, at the other downstream watergates (NAKO, BATA, NABU and TNNM) (Figure 3.6).

Table 3.5 IHA non-parametric RVA scored card results for each watergate from pre-operation period and post-operation period.

	Nong Bueng		Na Koo		Ban Tabtao		Na Bua		Thoranit Naruemit	
	Pre-impact period: 1996-1999	Post-impact period: 2008-2015	Pre-impact period: 1996-1998	Post-impact period: 2008-2015	Pre-impact period: 1996-2003	Post-impact period: 2008-2015	Pre-impact period: 1996-2003	Post-impact period: 2008-2015	Pre-impact period: 1996-2005	Post-impact period: 2011-2015
Parameter Group #1										
April	0.79	0.00	1.30	0.00	0.01	0.00	0.01	0.00	0.29	0.00
May	8.58	0.00	3.65	0.69	0.15	0.00	0.15	0.00	8.58	0.00
June	25.91	54.18	24.40	31.77	12.95	6.14	12.95	10.26	46.80	0.00
July	61.63	90.03	75.25	62.23	22.20	16.70	22.20	14.91	73.83	67.97
August	109.40	164.40	102.20	79.69	45.10	19.94	45.10	22.34	109.40	210.60
September	93.60	90.84	124.80	75.92	55.39	9.63	55.39	11.85	133.80	134.30
October	23.40	27.54	8.60	26.38	2.59	0.00	2.59	1.83	35.50	0.00
November	19.28	7.74	7.90	4.19	0.41	0.00	0.41	0.00	10.98	0.00
December	0.51	0.00	0.84	0.00	0.19	0.00	0.19	0.00	0.51	0.00
January	0.29	0.00	0.52	0.00	0.01	0.00	0.01	0.00	0.12	0.00
February	0.14	0.00	0.28	0.00	0.01	0.00	0.01	0.00	0.00	0.00
March	0.10	0.00	0.20	0.00	0.02	0.00	0.02	0.00	0.00	0.00
Parameter Group #2										
1-day minimum	0.04	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-day minimum	0.05	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7-day minimum	0.06	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-day minimum	0.14	0.00	0.28	0.00	0.01	0.00	0.01	0.00	0.00	0.00
90-day minimum	0.25	0.51	0.48	0.00	0.01	0.00	0.01	0.00	0.13	0.00
1-day maximum	231.90	231.20	234.90	160.90	237.30	184.30	237.30	147.40	247.50	430.60
3-day maximum	228.60	216.80	233.00	137.50	220.30	144.10	220.30	124.50	245.80	405.70
7-day maximum	219.00	210.70	223.20	119.60	174.40	102.50	174.40	104.30	237.30	320.60
30-day maximum	160.30	200.50	188.10	99.90	98.55	55.86	98.55	62.46	177.00	234.10
90-day maximum	110.40	130.90	125.00	75.41	66.42	29.32	66.42	36.70	122.10	188.40
Number of zero days	33.00	162.00	0.00	175.50	56.00	245.00	56.00	234.50	62.00	249.00
Base flow index	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Parameter Group #3										
Date of minimum	92.50	92.00	92.00	92.00	92.00	92.00	92.00	92.00	92.00	92.00
Date of maximum	256.00	242.00	245.00	233.00	250.50	208.50	250.50	215.00	260.00	205.00
Parameter Group #4										
Low pulse count	5.50	8.00	5.00	6.00	1.00	8.00	1.00	6.00	1.50	8.00
Low pulse duration	4.00	5.50	20.50	4.50	80.75	3.50	80.75	3.25	5.00	3.50
High pulse count	4.50	6.50	5.00	8.50	2.50	11.50	2.50	10.50	5.50	8.00
High pulse duration	6.75	9.75	5.00	3.00	36.50	3.25	36.50	3.00	17.00	6.00
The low pulse threshold is										
The high pulse threshold is										
Parameter Group #5										
Rise rate	2.38	4.76	1.55	10.52	1.43	7.52	1.43	8.95	2.80	18.64
Fall rate	-1.01	-3.62	-0.61	-7.61	-1.35	-6.67	-1.35	-6.87	-4.08	-27.19
Number of reversals	88.00	76.00	95.00	90.50	55.50	59.50	55.50	59.00	70.50	63.00

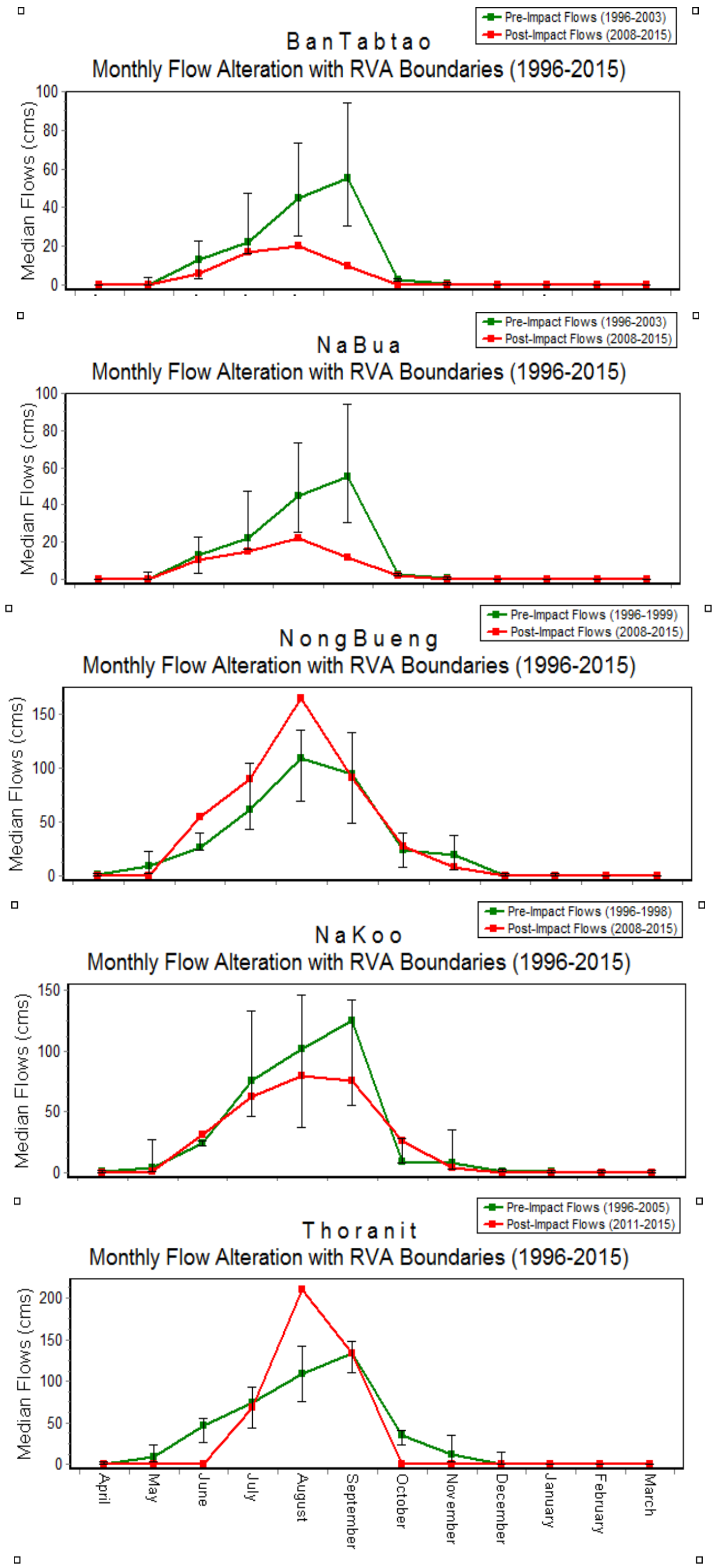


Figure 3.6 Median monthly flow alteration at each sampling sites in Nam Kam River and its tributary from pre-operation period and post-operation period of all watergates. The upper and lower boundary for RVA based on pre-impact data are also shown as upper and lower ranges of the pre-impact flow.

After regulation of the Nam Kam River the mean 1- 3- 7- and 30-day minimum flows decreased from 0.04-0.08 to 0 in Nam Kam River and remained 0 in the Nam Bang River. The 90-day minimum flow decreased except at NOBU. Moreover the low pulse duration at almost all watergates also decreased after regulation except at NOBU (Table 3.5). Overall the minimum flow cycle in the dry season decreased after watergate construction. The 1- 3- 7- 30- and 90- day maximum flows in the post-alteration period mostly decreased as a result of watergate operation. Daily mean flow in the post-operation period has been changed by the watergate operation because the watergates are closed before the flood dissipates to store water for irrigation. The average number of zero flow days increased from 0-56 days/year to 162-245 days/year after the watergates were operated. The number of zero flow day in the Nam Kam River is less than Nam Bang River (Table 3.5). The median Julian date of each annual 1-day maximum at all watergates was later after watergate operation started but the mean Julian date of the annual minimum is more or less the same as before watergate construction. The median count of low and high pulses at most of the watergates increased, but duration of low and high pulses was reduced in the post-watergate operation period (Table 3.5). Rate of rise and fall of discharge in all sections also increased post-watergate operation (Table 3.5).

A paired-samples t-test indicated that the flow duration curves varied significantly between the periods before and after the watergates became operational in both rivers ($P \leq 0.05$). Flow in 1996 represents the natural flow regime of Nam Kam mainstem before watergate operation, while 1996-2004 represents the natural flow regime in the Nam Bang River. The flow duration curves in the upstream area of the Nam Kam mainstem after the NAKO was constructed in 1996-1999 showed high flows (Q0-Q35) were slightly decreased and mid-range flows (Q40) dramatically declined. NOBU, which has been in operation since year 2000, also reduced high and mid-flows (Figure 3.7).

The modified flow duration curve for the Nam Bang River was more extreme than the Nam Kam mainstem because the river was only flowing for 75.7 percent of total flow days due to it being stagnant during the dry season of post regulation by the watergate. The hydrological regime in the Nam Kam tributary was also impact by watergate operation. High flows (Q0-Q30) in the Nam Bang have slightly decreased after the river was regulated by both watergates in 2007, Q33.2 at BATA and Q35.1 at NABU decreased dramatically and low flows have disappeared after both watergates were operated. The period of flow has decreased to around 35 per cent of total flow days (Figure 3.8)

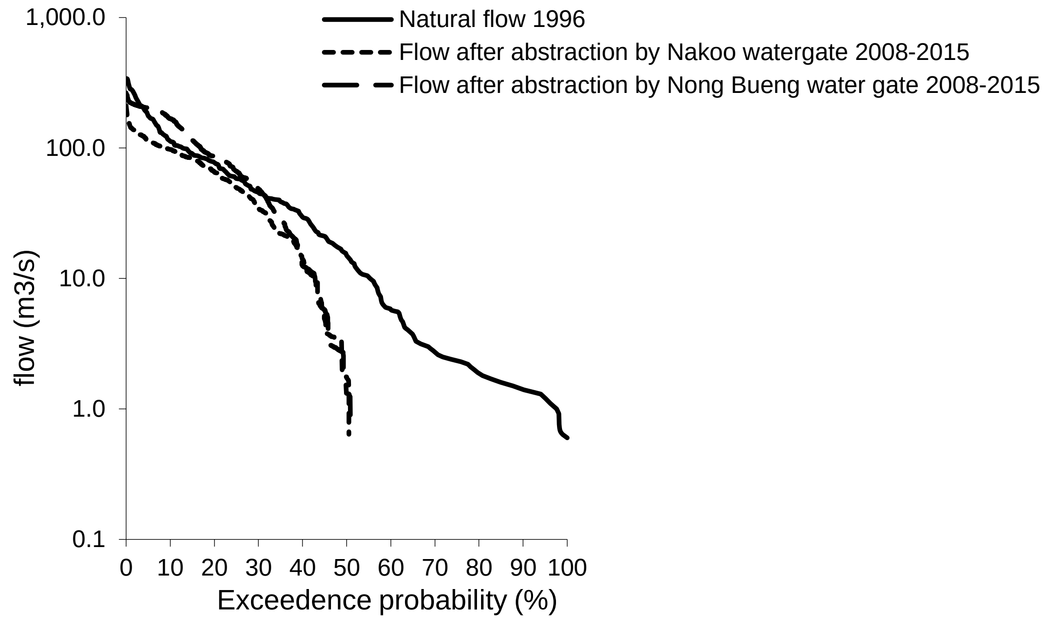


Figure 3.7 Flow duration curve of Nam Kam River before and after modification by upstream watergates (Nong Bueng and Na Koo). The flow duration curve after abstraction by Na Koo and Nong Bueng watergates does not move towards 0 on the Y axis because the data comprise many zero flow days caused by watergate closure in the dry season.

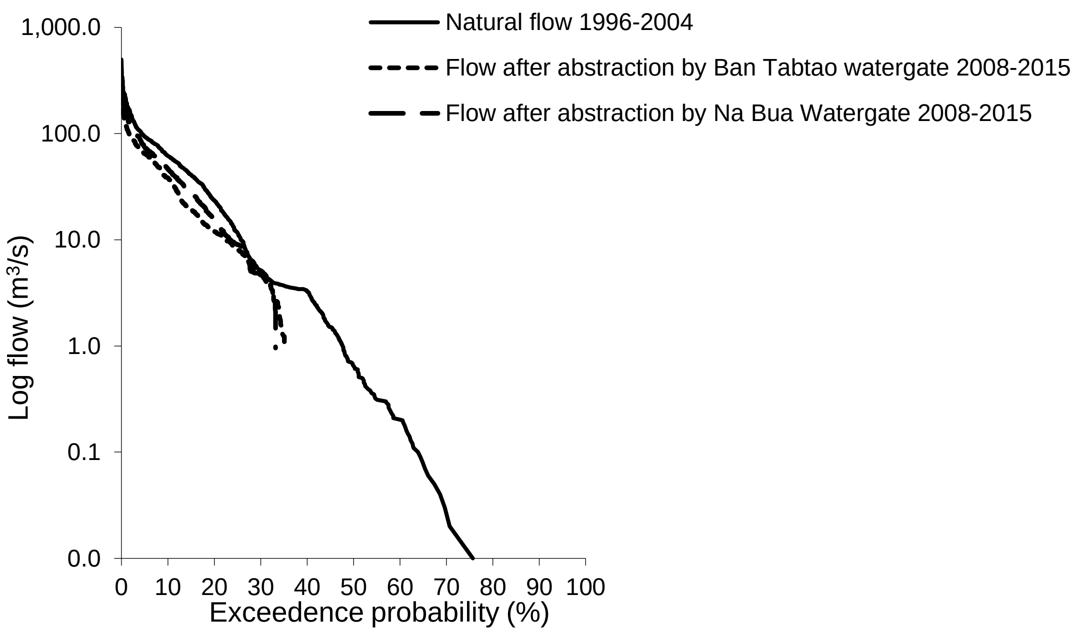


Figure 3.8 Flow duration curve of Nam Bang River before and after modification by watergate operation. The exceedance probability at the pre-alteration period does not reach Q100 because the river was stagnant more than 20 percent of the year. The flow duration curve after abstraction by Ban Tabtao and Na Bua watergates does not move towards 0 on the Y axis because the data comprise many zero flow days caused by watergate closure in the dry season.

Flow and discharge changes caused by watergate operation of the most downstream watergate

TNNM was opened within two weeks of the upstream watergates starting to release water in the flood season. Discharge in this area increased to the highest level when all sluice gates were lifted around 1.00-3.00 m and declined when all sluice gates were raised to their maximum capacity in the high flood period. Watergate operation at the most downstream watergate created a fluctuating flow regime with both large and small floods common between June and September, due to this watergate controlling water volume in the whole river system and releasing it to Mekong River. The watergate also created static flow at the onset and the end of the wet season (May-June and October-December) and blocked flows throughout the dry season (December-April) (Figure 3.9).

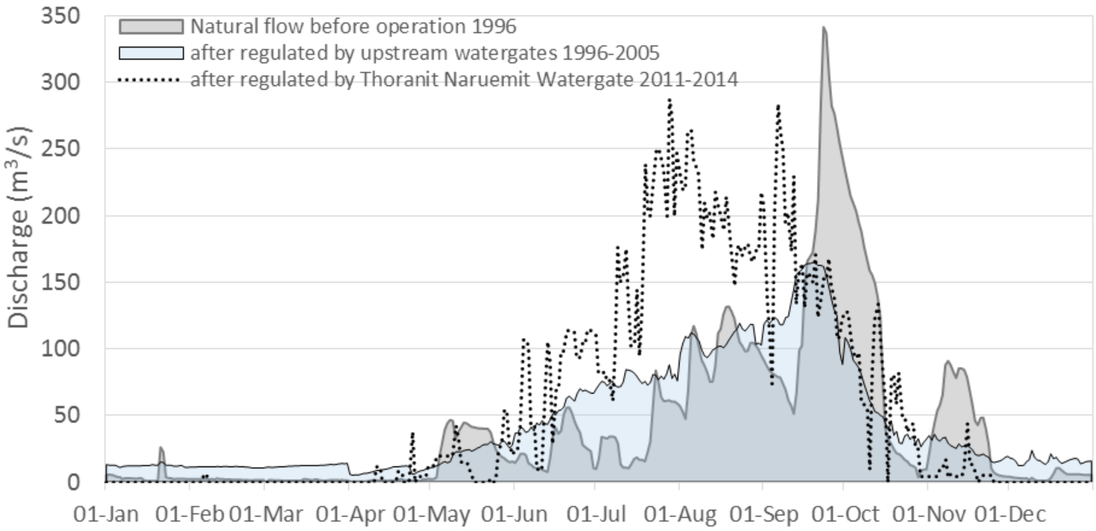


Figure 3.9 Annual discharge of Nam Kam River at the most downstream watergates (2011-2014) compared with the period before operation (1996-2005).

Hydrologic alteration at Thoranit Naruemit Watergate

The influence of watergate operation on the hydrological regime was systematically studied using the IHA analysis. The most significant change was an increase in median monthly flow throughout the post-alteration period in the wet season. Before the most downstream watergate became operational, the monthly flow in the wet season (June to September) ranged from 46.80-133.80 m^3/s, and monthly flow in the post alteration period range increased to between 67.97 and 210.6 m^3/s. It also increased dramatically from pre to post-alteration in August (from 109.40 to 210.60 m^3/s). In the post-alteration period flows decreased dramatically from 134.30 m^3/s in September to zero in October (Table 3.5). Between 1996 and 2005, dry season discharge in the Nam Kam River ranged from 0.12 to 8.58 m^3/s while after the most downstream watergate became operational, the monthly flows are absolutely zero throughout dry season. After the Nam Kam River was regulated by TNNM, IHA analysis indicates mean 1-day minimum flow remained at 0.00 m^3/s but the 1-day maximum flow was up from 247.50-430.60 m^3/s indicating high seasonal variation between the dry and wet seasons (Table 3.5). The 7- 30- and 90-day maximum flows in the post-alteration period increased significantly indicating that weekly, monthly and seasonal maximum flow cycles are influenced by TNNM operation. The average number of zero flow days increased significantly from 62 days/year in the pre-operation period up to 249 days/year after TNNM was operational. Daily mean flow in the post-operation period has been altered by the watergate operation, since watergates were closed to store water for irrigation earlier than the natural flood recession before construction (Table 3.5).

The flow characteristics expressed by the duration curves indicate that flows in the pre-operation, construction and post-operation periods were significantly different ($P<0.001$). High (Q0-Q20) and mid-range flows (Q20-Q60) increased slightly in the wet season while the number of no flow days increased dramatically from 24 % in the construction phase to about 70% in the post-construction phase due to the accumulated impact from the upstream watergate abstraction. After the most downstream watergate, TNNM, was operated, high flow events (Q0-Q20) were more common in the wet season, mid-range flow (Q30-Q36) declined dramatically due to water abstraction above TNNM, the mid-range flow and the extreme low flows (Q36-Q76.9) in this river were lost due to all sluice gates being closed to retain water at the end of the flood season and during the dry season (Figure 3.10).

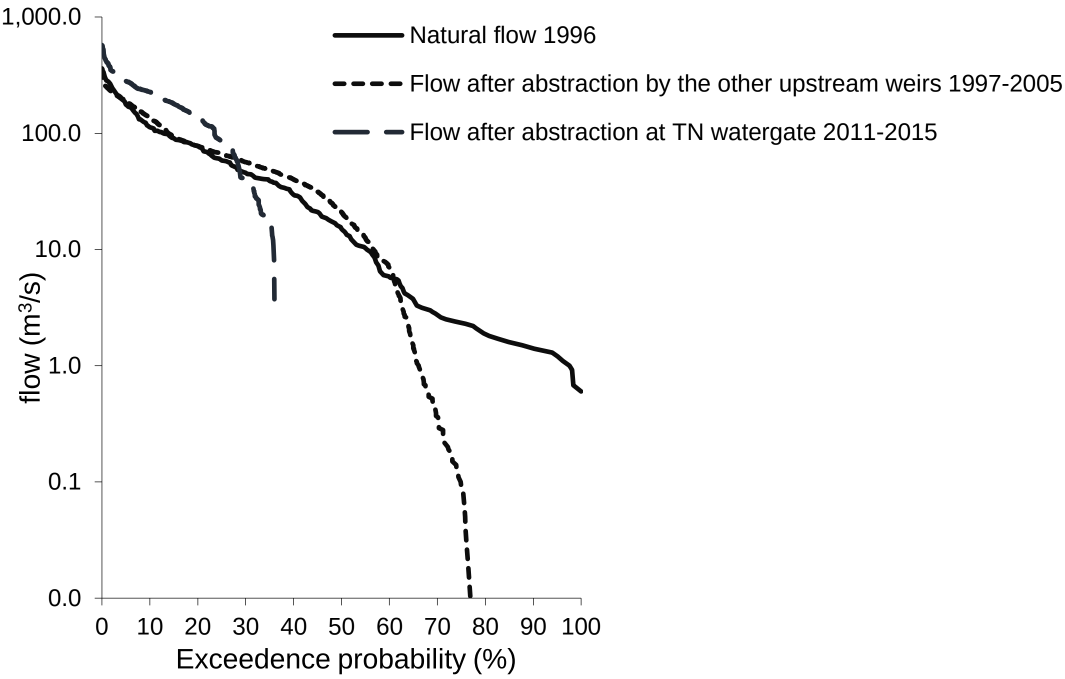


Figure 3.10 Flow duration curve of Nam Kam River at the most downstream watergate, Thoranit Naruemit. The flow duration curve after abstraction by the others upstream watergates does not move towards 0 on the Y axis because the data comprise many zero flow days caused by watergate closure in the dry season.

Flow and discharge changes in the unregulated Songkhram River

To give an indication of the changes that have occurred in the Nam Kam system, the annual discharge and hydrological cycle of the unregulated river Songkhram River are described. The flow patterns in the regulated Nam Kam and unregulated Songkhram River were very different. Discharge in the Songkhram River started to increase from 0.00-223.60 m^3/s at the onset of rainy season around the middle to end of June. Stream flow continued to increase to peak in the flood season, with the maximum flow observed in September 2013 (1,626.00 m^3/s). Discharge declined gradually at the end of flood season (October-November: from 4.00 to 1,240.60 m^3/s). Dry season flow in Songkhram River ranged between 0.00-344.00 m^3/s. The number of days with zero flow in Songkhram River varies between 44 and 171 days per year and occurs in dry season before the onset of flood season (Table 3.4).

In general, natural flow depends on rainfall and geographical area of the river basin. However, discharge in the Nam Kam River is controlled by the most upstream watergate and increases earlier than in the Songkhram River when the upstream watergate releases water from Nong Han to adjust the retention level of the lake for the next rainy season. In addition, flow in the Nam Kam River fluctuates more widely as a result of the watergate operation than the smoother transition seen in the flood cycle in the Songkhram River. Flow in the Nam Kam River increased slower than the unregulated Songkhram River due to watergate operation in each block of river delaying water in the first period of the flood season. When all watergates were closed to store water at the end of the flood season, stream flow was blocked to maintain water volume in the floodplains above each watergate. Therefore, water level in this period remained until the end of the flood season while water in the unregulated Songkhram River was dissipated, resulting in a longer flood period in the regulated Nam Kam River compared with the unregulated Songkhram River (Figures 3.4-3.5, 3.9 and 3.12).

The flow characteristics expressed by the duration curves for the Songkhram River from 2010-2015 indicate the river was flowing for just 70 per cent of total flow days because of low dry season flows (Figure 3.11). For example, zero flow days were observed occasionally from Jan to May 2014 (Figure 3.12).

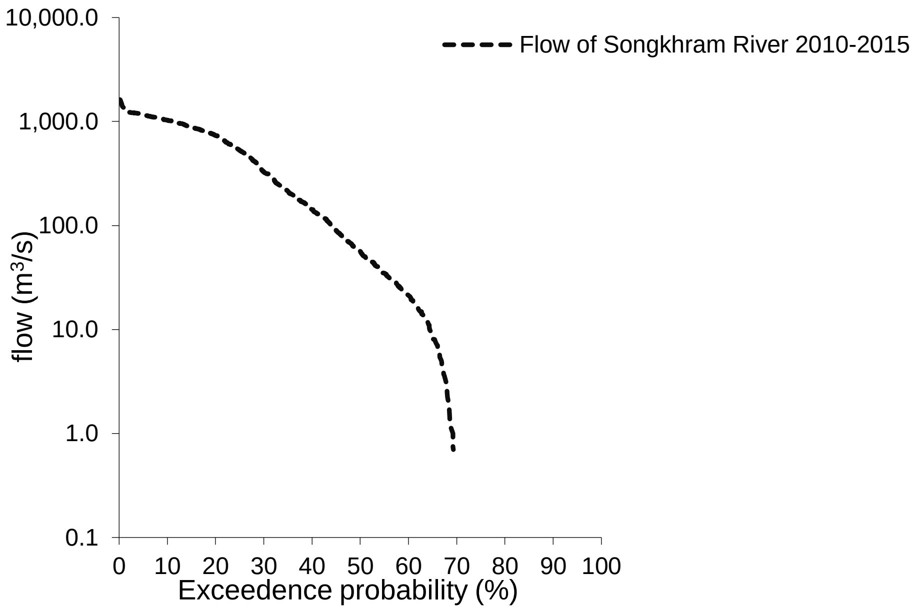


Figure 3.11 Flow duration curve of Songkhram River from 2010-2015. The flow duration curve in Songkhram River does not move towards 0 on the Y axis because the data comprise many zero flow days caused by watergate closure in the dry season.

Figure 3.12 Annual discharge of Songkhram River in 2014

3.4.5 Annual water level changes

Water levels in the Nam Kam and Nam Bang started rising at the onset of the rainy season from the end of May to June due to the increasing rainfall and discharge from Nong Han, which has to release water to provide spare capacity for the upcoming rain. Water levels in both rivers steadily increase to reach their peaks around early August. Fluctuations in water level were generally observed in both regulated rivers (Nam Kam and Nam Bang River), and was related to watergate management. After all of the watergates were opened to maximum capacity to prevent flooding, water levels in both rivers declined dramatically around the end of August. All watergates were slowly closed at the end of the flood season and this caused a gradual reduction in discharge until the end of November / early December in the Nam Kam River but occurred at the end of October in the Nam Bang River (Figure 3.13). Water level in Nam Kam after the watergates were fully operational ranged between 145.87 and 151.08 m AMSL while the water level in the Nam Bang ranged between 135.31 and 142.41 m AMSL. Water storage in the river system resulted in the average water level being higher after the watergates became operational than before they were operating, especially in the dry season when all watergates were closed to store water (147.87 compared with 146.79 m AMSL in the Nam Kam River, 137.58 and 136.02 m AMSL in the Nam Bang River). Water level in both rivers fluctuated in accordance with discharge from the upstream watergates plus rainfall above the river basin. The situation in the downstream area below TNNM is different as it is also supported by flooding from the Mekong River upstream of the confluence of the Nam Kam River in the flood season (June to October). By contrast, water levels in the unregulated Songkhram River and Mekong River started rising in mid-June and increased gradually to peak in August. Water levels fluctuated until September and gradually declined in October. In general, natural flow depends on rainfall and geographical area of the river basin (Figure 3.13).

Water level above and below NAKO, which is closest to the RID gauging station (Kh369A) at NAKO, was used to compare water levels before (1996-1997) and after 2008-2014) the series of watergates was constructed. Average water level from the end of wet season (mid-September to October) through the dry season (November to May) was higher in the area above the watergate post construction (142.32 and 140.46 m AMSL) because the watergates were closed to store water, but it was lower in the area below the watergate (138.08 and 140.46 m AMSL). By contrast water level in the early wet season (June to mid-September) was slightly lower in the area above the watergate than before regulation (143.07 and 143.65 m AMSL) and lower at the area downstream (139.06 and 143.65 m AMSL). Water level declined earlier than prior to regulation because of the release to floodwater; this was supported by the high discharge observed in the wet season.

To sum up, annual discharge and annual water level of water in the Nam Kam and its tributary differed from the unregulated Songkhram River (Figures 3.4-3.5, 3.9 and 3.12-3.13); discharge and water level fluctuated more strongly in the Nam Kam River and its tributary as a result of flow regulation in the river system. The Nam Kam and Nam Bang rivers are regulated principally to provide water for irrigation during the low rainfall season and release water to control flooding during flood season. The series of run-of-river watergates in the Nam Kam River system has the storage capacity to absorb small to intermediate volumes of flood water whilst water abstraction will reduce the mean annual volume of stored water in the dry season.

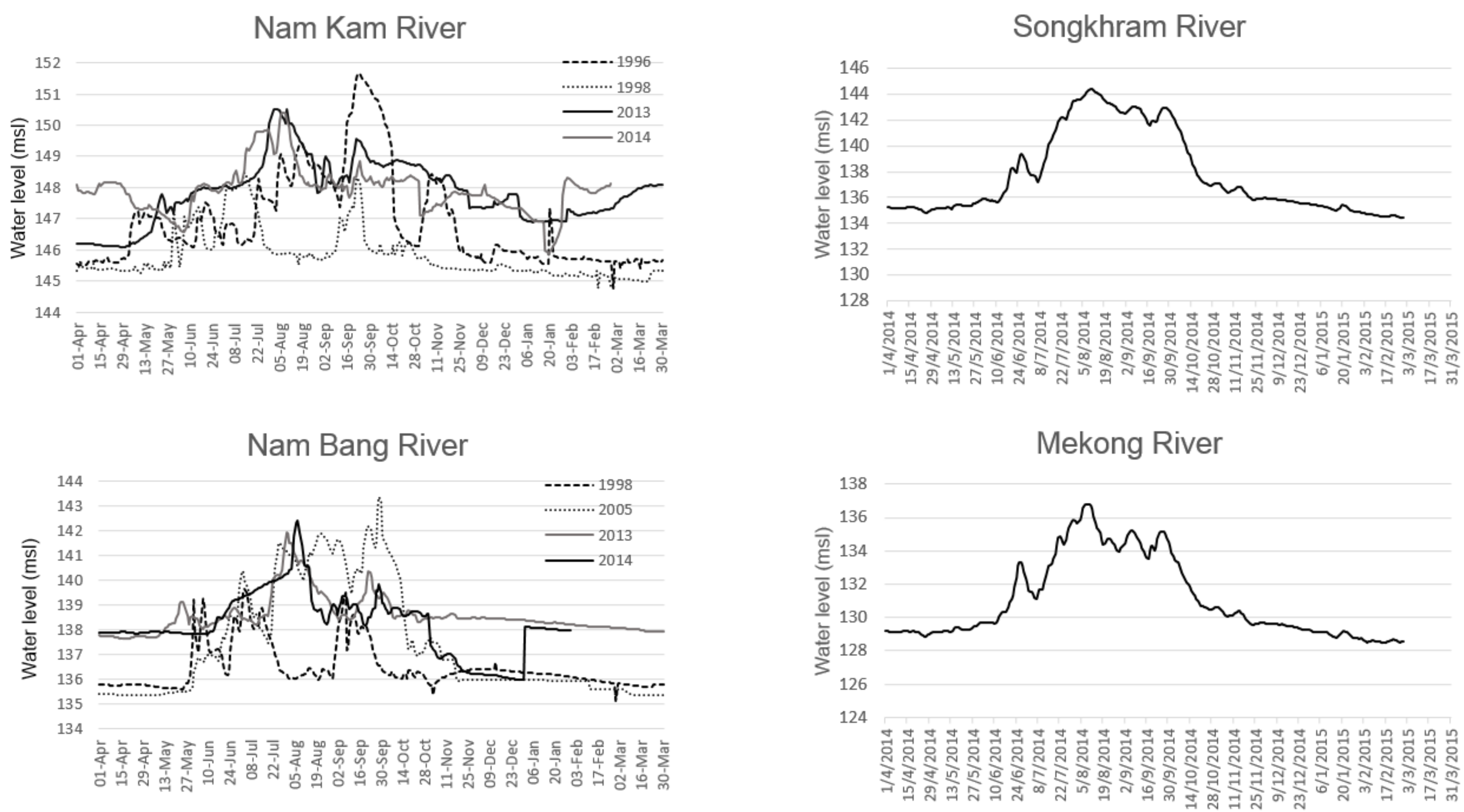


Figure 3.13 Water level changes in the Nam Kam River and Nam Bang River; Black line represents water level after watergates fully operational (2013 and 2014), dotted line represents water level in reference year before operated (1996, 1998, 2005) compared with the unregulated river Songkhram River and the Mekong River (April 2014-March 2015).

3.4.6 Habitat characteristics of study sites throughout an annual cycle

Habitat types in the Nam Kam River system are diverse, comprising permanent floodplain areas, seasonal floodplains and the mainstem channel (Figure 3.2). The characteristics of habitat throughout an annual cycle were mostly floodplain area connected with the mainstem river. The upstream habitat is flat land, covered with grass, bushes and some areas where human communities reside, permanent ponds and paddy fields that are covered by shallow layer of water (about 1 meter) when connected with the main channel of the Nam Kam River in flood season. The downstream floodplain is a complex riverine floodplain wetland with a variety of habitats represented, including various permanent and seasonal floodplain lakes, grassland, crop fields, and some permanent streams.

When the watergates were constructed, water level, flow regulation, amplitude of flood and timing of flood in the floodplain were changed in accordance with the watergate operation. Many upstream flooded habitats expanded because of the higher water level above the watergates. Many new floodplains above the watergates were created when the river flooded over, for example, NK2, NK3, NB2 and NB1 floodplains. On the other hand, some floodplains were disconnected from the mainstem, for example during the surveys in 2014, the downstream floodplain of NAKO, where fish larvae and juveniles have been found by fisherman in the previous wet season (Fisherman, personal communication), was disconnected from the mainstem river due to sedimentation at the downstream area of the watergate in wet season and it dried out in the dry season (Figure 3.14).

When the watergates were closed to store water in the dry season, the water levels below the watergates were less than before the series of watergates were operated. The number of zero flow days at each river section increased after the watergates were operated, and river sections have become stagnant for longer period.

Water level at NK1 started to increase in May or June according to water released from SRWD. Water level increases fluctuated until they reach the highest level around August and fluctuated until the end of November. Other downstream watergates were opened subsequently to control flood by passing water to downstream section, therefore flow curve was similar in each section, but a decrease in discharge was observed from upstream to downstream in the Nam Kam River (Figure 3.4-3.5). The flood period of the most downstream floodplain, NK4 was longer than it used to be before a series of watergates were constructed in 1996. It has the longest period of flooding compared with the other floodplains in the river system due to TNNM needing to store water for the next dry season. After operation by the watergates, the size of the floodplain in the dry season increased due to this area being changed to be a retention area of TNNM. Water level in each section at the end of dry season was usually lower due to water releases to prepare the retention level for the upstream water.

Figure 3.14 Disconnection of floodplain and the main stream river at the downstream of Na Koo watergate at the post-operation period (2011-2014). The arrow shows the disconnected floodplain caused by sedimentation at the downstream area of the Na Koo watergate.

3.4.7 Rainfall in Nam Kam River Basin

Rainfall in the Nam Kam River Basin varies between locations (average rainfall above different watergates in the period of fish sampling in 2014 are shown in Table 3.6), but the general cycle is more or less the same between areas. In 2014 the rains started at June, although there was a small amount observed from March to May. Rainfall increased gradually from June to July and decreased until stopping around September. Small amounts of rainfall were still observed in some areas after September but the number of rainy days was only a few per month. As a result of climate change, the rainy season in 2014 was later than previous years and the cumulative rainfall was less than 2011 and 2012 but about the same as 2013. The year 2015 was an extremely low rainfall year and probably the result of the el Nino cycle seen across the Mekong region (Figure 3.15) A delayed rainy season and reduced rainfall can have serious implications for the way the watergates are operated and thus, potentially, fish migration.

Table 3.6 Average rainfall (mm) above the watergates in the Nam Kam River system from January 2014-March 2015.

	Suras wadi	Nong Bueng	Na Karm	Na Koo	Thoranit Naruemit	Na Bua	Ban Tabtao	Average
Jan-14	0	0	0	0	0	0	0	0
Feb-14	0	0	0	0	0	0	0	0
Mar-14	0.4	0.8	0.3	1.2	0.3	0.1	0.1	0.5
Apr-14	4	3.2	2	3.4	3.4	2.7	1.7	2.9
May-14	4.5	1.7	3.7	3	3.3	4.2	4.3	3.5
Jun-14	11.1	10.7	11.2	11.4	8.3	18.2	11.9	11.8
Jul-14	20.2	10	11.3	10.9	14.5	15.9	13.4	13.7
Aug-14	6.9	11.1	8.6	9.4	6.8	10.9	8.5	8.9
Sep-14	11.1	4.5	4.8	7.2	3.1	4.2	5.7	5.8
Oct-14	1.9	0	0.1	0	0	0	0.6	0.4
Nov-14	0.7	0	0.2	0	0.1	1.1	0	0.3
Dec-14	0	0	0	0	0	0	0	0
Jan-15	0.1	0	0	0	0	0	0	0.1
Feb-15	2.5	0	0	0	0	0	0	0.4

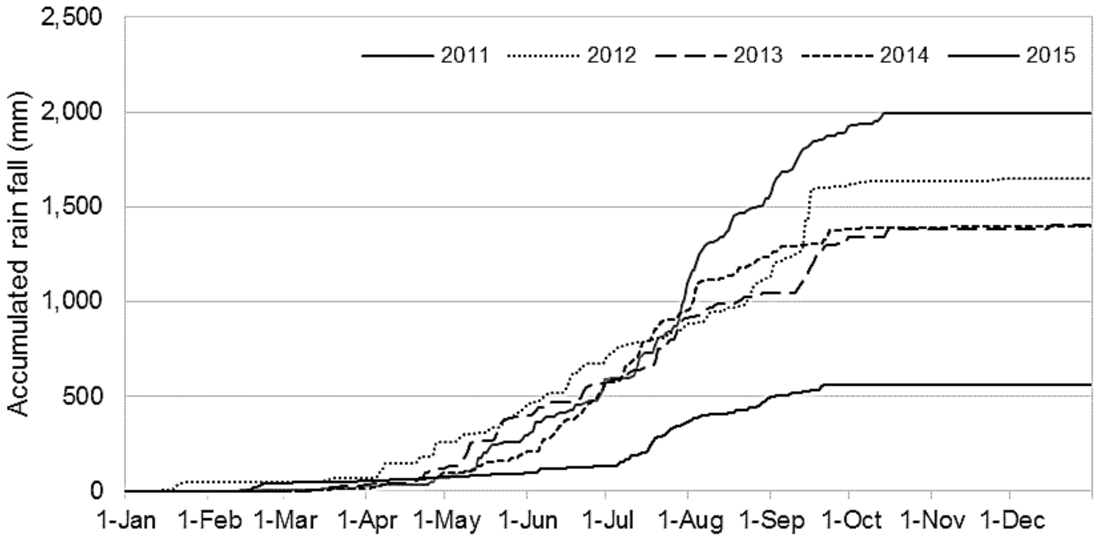


Figure 3.15 Accumulated rainfall in the Nam Kam River system from 2011-2015.

3.4.8 Water quality changes

Water quality in the upstream impounded sections in the dry season of 2015 was severely affected by closure of all the watergates to store water for many consecutive months. Stagnant water was observed, water color turned green because of blooms of filamentous green algae (*Spirogyra* sp.) and phytoplankton was observed in some upstream impoundment areas; aquatic plants were also observed along the shoreline. Chlorophyll A in this period was high; up to 1.902 µg/L (Figure 3.16) but was not indicative of eutrophication.

Figure 3.16 Blooming of filamentous green algae suggesting environmental changes in the impoundment upstream area of Na Karm Watergate in the 2015 dry season.

The turbidity changes caused from watergate operation in the Nam Kam River system, turbidity in Nam Kam and Nam Bang rivers are different according to the sources of water and the operation of each watergate in each river. Turbidity of Nam Kam River was mainly depended on the upstream operation at SRWD which controlled the main sources of water from Nong Han Lake. The longer distance in Nam Kam River and the number of barriers did not reduce and trap the sediment in the river (Table 3.7) Turbidity in the dry season decreased at most sampling sites because the water was stagnant and sediments deposit (Table 3.7). Turbidity in Nam Bang River was different, the main source of water in this river is runoff from the area above the upstream watergate. High turbidity was observed in Nam Bang when the watergates were operated with the maximum capacity at the onset of rainy season, due to the higher discharge and works below BATA, since the end of the dry season.

Table 3.7 Turbidity (FTU) observed at different sampling sites in the Nam Kam River system from June 2014-February 2015.

	Dan Muang Kham	Na Karm	Na Koo	Kud la-A	Nam Kam	Na Bua	Ban Tabtao	Average
Jun-14	63	22	28	85	110	156	134	85.43
Aug-14	24	13	22	74	39	13	24	29.86
Oct-14	4	2	6	4	4	7	9	5.14
Feb-15	4	2	1	3	2	7	14	4.71

3.4.9 Spatial variation mapping of hydrological alteration at a stream-network scale

The range of possible average value of all 33 hydrologic alteration indicators were ranked and divided into three classes of alteration. 33rd and 67th percentiles of indicator of hydrologic alteration were computed for as the lower and upper limits of the RVA target range for all watergates (Figure 3.17). The ranked median absolute degrees and percentile value of 33 indicators of hydrologic alteration for 5 watergates on Nam Kam River system showed that 1-day minimum ranked first in all hydrologic alteration values altered, i.e. this parameter exhibited the highest hydrologic alteration from the watergate operation, followed by date of minimum, high pulse duration, October, 1-day maximum, March, August, 30-day maximum, base flow index, 3-day maximum and date of maximum (Table 3.8 and Figure 3.18) all with IHA percentiles exceeding to 67% (>0.81) and thus were the characteristics most strongly affected by construction and operation of the watergate located upstream. Thus these values were used to determine the average hydrologic alteration in the Nam Kam River system (Table 3.8 and Figure 3.18)

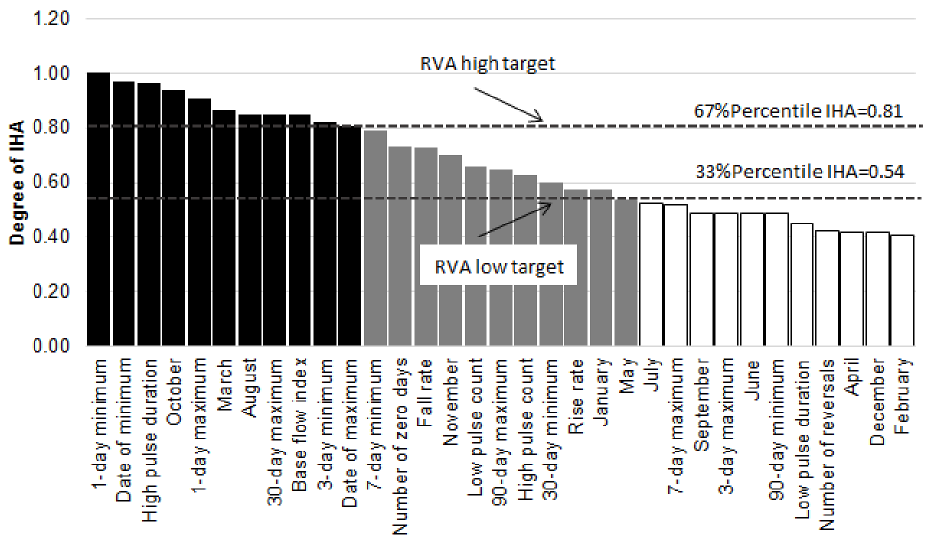


Figure 3.17 Ranked median absolute degrees and percentile value of 33 indicators of hydrologic alteration for 5 watergates on Nam Kam River system.

Table 3.8 Degree of hydrologic alteration at 5 watergates on the Nam Kam River system.

	1-day minimum	Date of minimum	High pulse duration	October	1-day maximum	March	August	30-day maximum	Base flow index	3-day minimum	Date of maximum	mean absolute value
Nong Bueng	1.00	-	1.00	-	-	0.25	0.50	0.50	0.25	1.00	0.75	0.66(M)
Na Koo	1.00	0.88	1.00	1.25	1.63	1.25	2.00	1.25	1.00	0.63	1.63	1.23(H)
Ban Tabtao	1.00	1.00	1.00	1.00	0.75	1.00	0.25	0.75	1.00	1.00	0.33	0.83(H)
NaBua	1.00	1.00	0.83	1.00	0.75	0.83	0.50	0.75	1.00	1.00	0.33	0.82(H)
Thoranit naruemit	1.00	1.00	1.00	0.50	0.50	1.00	1.00	1.00	1.00	0.50	1.00	0.86(H)

Degrees of hydrologic alteration are assigned based on distinct pattern of equal range: (1)0-33% (L, Low) represents little or no alteration; (2) 34-67% (M, Median) represents moderate alteration and (3)68-100% (H, High) represents a high degree of alteration. Average values are based upon absolute value of each item. Threshold; IHA67% =0.81, IHA 33%=0.54.

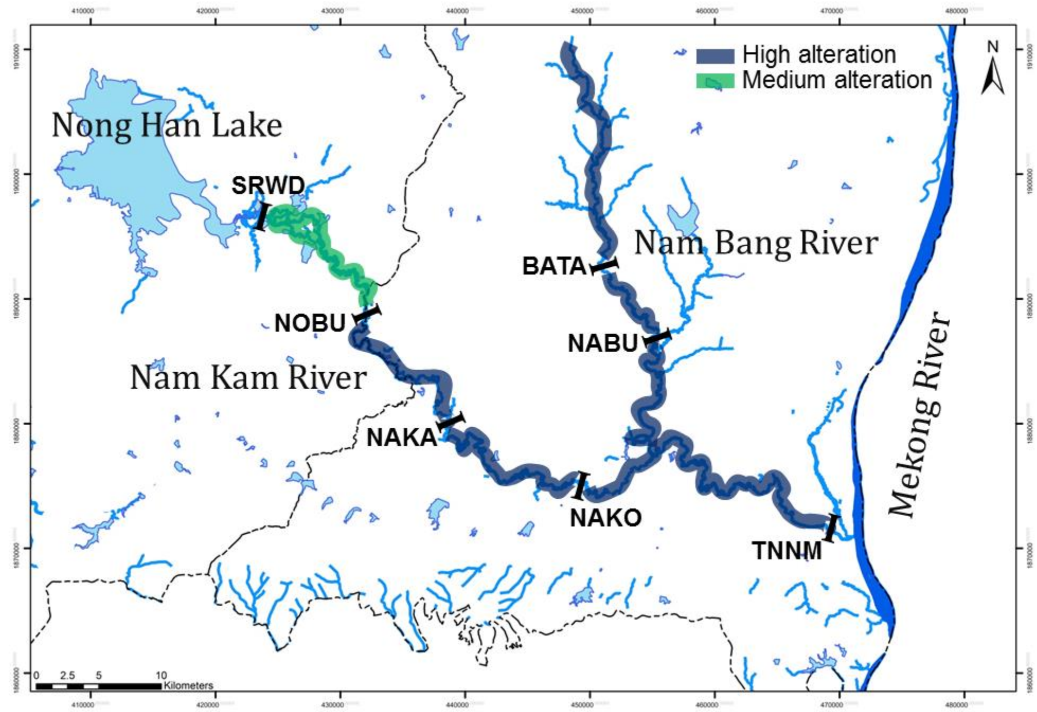


Figure 3.18 Spatial distribution of averaged hydrologic alteration across all 10 hydrologic parameters summarized in Table 3.8. Light green zone represents river section exhibiting medium alteration (hydrologic alteration value 34-67%, Blue zones represent highly altered river section (hydrologic alteration value 68-100%). SRWD: Suraswadi Watergate, NOBU: Nong Bueng Watergate, NAKA: Na Karm Watergate, NAKO: Na Koo Watergate, TNNM: Thoranit Naruemit Watergate, BATA: Ban Tabtao Watergate and NABU: Na Bua Watergate.

NAKO was rank in the first place among all watergates in influencing hydrological alteration in the Nam Kam River system. The next most important watergates altering the hydrologic regimes were TNNM, BATA, NABU and NOBU, respectively (Table 3.8). NAKO was influenced greatly by August, October and March, date of maximum, 1-day and 30-day maximum. Hydrologic alteration at TNNM was well illustrated by 1-day minimum, date of minimum, high pulse duration, March, August, 30-day maximum, base flow index and date of maximum. Results for BATA indicated the influence of the watergate was greatest on 1-day and 3-day minimum, date of minimum, high pulse duration, October, March and base flow index. Regulation at NABU affected 1-day minimum, date of minimum, October, base flow index and 3-day minimum. Regulation of NOBU strongly impacted on 1- and 3- day minimum and high pulse duration (Table 3.8). Watergates that operated upstream (SRWD, NOBU and NAKA) collectively resulted in a remarkable hydrological alteration detected at NAKO, follow by TNNM which is located downstream. Magnitude (decreasing and increasing of median flow) and duration of annual extreme flow from mean value of March, August and October are the result of flood control activity. NOBU and TNNM increased high flow in the peak flood period (August and October) due to the need to quickly released water to downstream areas while NAKO, BATA and NABU delayed and decreased flow when it did not open to the greatest capacity in the flood season resulting in high hydrologic alternation. Also, the highest monthly median discharge was increased at NOBU and TNNM while it declined at NAKO, BATA and NABU. The date of minimum and maximum describe the timing of annual extreme flow. Watergate operation increased the frequency of high flow pulsing but reduced duration of high pulse at all watergates except NOBU, where high pulse duration was increased. It created many short pulses of high flow rather than high pulse of long duration after operation of the watergate. Rise rate increased at all watergate indicating the probability of fish being trapped on the floodplain, but the number of flow reversals decreased in the Nam Kam River while it increased in Nam Bang River.

All watergates are operated for irrigation and flood control and significantly changed natural flow regimes in the river after completion of constructions in 2009. This result caused considerable impact in the Nam Kam River system both in the mainstem and its tributary (0.82-1.23) and was categorized as high alteration except for NOBU, which is located in the upstream area (Figure 3.18). This might result from NOBU usually being operated at the same time as SRWD and was always discharging water to prevent flooding above and below the watergate. However, degree of alteration at NOBU was categorized as medium (0.66) (Table 3.8 and Figure 3.18).

3.5 Discussion

3.5.1 Watergate management in the Nam Kam River system

The development of water resources in Thailand is not just for hydropower but mostly for irrigation and flood mitigation, especially in the Mekong River Basin (Siriyuvasak, 2008). The Nam Kam River system is a major Mekong tributary in Thailand that has been fragmented by a series of irrigation watergates, but is unique in that the gates are fitted with fish passage facilities and the gate are usually opened to control flood water in the rainy season and closed to store water for agricultural supply in the dry season.

The sluice gates are mainly operated in accordance with individual rule curves but all watergates need to work together, this is coordinated between watergate managers from DoF and RID. The operational schedule depends on rainfall, inflow or discharge from the upstream area, retention levels of water in the areas above the watergates and water level downstream of the watergates. When the most upstream watergate is opened the downstream watergates were systematically opened to control flooding in the river system. The most downstream watergate controls water in the whole river system before release to the Mekong River. The watergate operation results in a different hydrological patterns in the Nam Kam and the impact of this operation on spatial and temporal changes in hydrological profile and habitat characteristics of the river was evaluated.

These changes were compared with another big Mekong tributary in Thailand, the Songkhram River, which has no dam construction on the main river and the flow regime is near natural. Another river, the Mun has one run-of-river hydropower dam at the confluence of the Mun and Mekong River. This river is regulated by sluice gate operation during the rainy season (May to August) to support fish migration and to protect local fisheries and is similar to the Nam Kam River (Jutagate *et al.,* 2005, 2007). However, this dam is used to store water to generate hydropower and to mitigate the impact of flood and irregular flow. Therefore, the regulation of each river is different.

3.5.2 Impact of watergate operation on hydrological changes of Nam Kam River and its tributary.

Watergates in the Nam Kam River system are operated for two purposes; irrigation and flood control, these resulting in hydrologic alteration in different ways according to their operation schedules.

Discharge and flow changes

The Nam Kam River system is a lightly fragmented river system due to the construction and operation of watergates to control floods and for irrigation. It now has low runoff potential and provides storage for irrigation in the dry season, resulting in a modified flow regime. To investigate the impact of watergate operation on the flow regime, the IHA program was used to compare the pre-operational hydrological regime with the regime after the watergates became operational.

Generally, flow alteration would be expected to be greater close to the dam and gradually dissipate with distance downstream if there is only one dam. In the Nam Kam River system, flow has been modified by a cascade of structures and varies along the river according to the operational schedule of individual watergates. Overall, operation of the watergates in the Nam Kam River system for flood control created high and low flows in the wet season while the operation for irrigation at the end of flood period created low to zero flows due to water storage in the dry season; the zero flow period caused by watergate operation is longer than observed before the series of watergates were constructed (Tables 3.4-3.5).

The seasonal storage of water in Nong Han Lake also acts as a huge natural regulator for flow in Nam Kam River. The upstream watergate NOBU receives water from Nong Han, although creating high flows in the wet season (June to October), this section was only ranked medium alteration after regulation because it mostly passes water from SRWD through the downstream area to prevent flooding of communities, agricultural area and enable fishing activities above and below the watergate. Compared with other downstream watergates (NAKO, BATA and NABU) it reduces the size of the flood in the river in wet season by delaying and storing water. By contrast, the most downstream watergate in the Nam Kam, TNNM, created a greater impact on the hydrological regime than the other upstream watergates. It creates high flow in the wet season, large and small floods were commonly found from June to September due to this watergate controlling the water volume of the whole river system before release to the Mekong River in the flood period. The watergate also removes low flows at the end of the wet season (October-November) and creates zero flow throughout the dry season (December- April) (Figures 3.4-3.5 and 3.9).

Sluice gate operation such as in the Nam Kam unavoidably induced high hydrologic alteration, which has severely changed the natural balance of eco-flow regimes. This causes considerable threats to aquatic species and consequently has resulted in adverse ecological effects, alteration fish migration patterns, and drastic reduction of fisheries resources, issues will be investigated in Chapters 4-7.

It should be noted these changes are very different from those experienced with hydropower dams, such as in the Lanchang-Jiang cascade in the Upper Mekong Basin which has reduced the range of hydrological variability during the wet season and increased the range of discharge during dry season due to water being managed for power generation (Räsänen *et al.,* 2012). Similarly it is different from Xiaolangdi reservoir which aims to reduce flooding impact and sediment deposition in the middle and lower Yellow River Basin in China. This reservoir reduces flow in wet season due to reservoir regulation for the flood control, irrigation and electricity generation and especially reduces the high pulse duration at the onset and end of the rainy season (Yang *et al.*, 2008).

Water level changes

Annual water level in the regulated Nam Kam and the Nam Bang differed considerably from the natural regime before the watergates became operational. Water levels fluctuated considerably at all watergates both upstream and downstream of the watergates. This is related to the discharge regime created by the gate operation. Water level change also increases the flooded area upstream. Watergate closure to store water for agricultural supply in the dry season (December to April), results in about 1-2 meters rise in water level at the area above each watergate, while the water level below the watergates was less than before the gates were installed (Figure 3.13). This will have considerable impact on the ecology of the system because the magnitude and frequency of low and high flows regulates many ecological processes, for example recruitment of fish in the river (Meffe & Minckley, 1987).

The upstream watergates, NOBU, NAKA and NAKO, operated to retain water at the end of dry season, resulted in a slight increase in water level in the Nam Kam River but also retained water at the onset of rainy season to mitigate flooding in the downstream area, resulting in water level in the Nam Kam River system rising around one month later than before the construction of the watergates (Figure 3.13). After peaking, the release pattern operated to reduce flooding in the high flood period resulted an earlier fall in water levels, which declined around one month earlier than the naturalized hydrological regime (Figure 3.13). This was supported by the high discharge observed at all watergates at the end of the flood season (Figures 3.4-3.5 and 3.9). Importantly, these high flows might affect the ecology and habitat for fish downstream, and ultimately fish production. The same situation has been predicted for the annual flooding of the Tonle Sap, Cambodia. After development of hydropower reservoirs upstream development, the onset of annual flood is expected to be delayed and the duration shortened with considerable impacts on fish production (Baran *et al.*, 2009).

Under natural conditions, the water level in the Nam Kam River increased at the onset of the rainy season and this was supported by increasing water level in the Mekong River. However, this has been altered in the current regulated flow regime because the most downstream watergate will not open if the water level downstream is higher than the water level in the river system upstream. Closure of the watergate at the onset of the flood season would prevent the back flow of water from the Mekong River and also obstruct the spawning migration of fish. This issue of watergate management for fish migration is discussed in Chapter 7.

Frequency and duration of flood changes

Watergate operation increased the frequency but also reduced the duration of high and low pulses at most of watergates in the Nam Kam River system, except NOBU which was longer and happened more often than before the watergate was operational. This occurs because the floodplain above NOBU is quite flat and usually floods over the bank by the water released from the SRWD. A shorter duration flooding periods were created by watergate operation but flooding occurred more often in the river system (Table 3.5). High flow pulses and small floods were commonly observed as a result of operation at the upstream watergates. This increased frequency or duration of high flow levels may displace organism that are susceptible to higher flows, such as fish larvae and deposited eggs (Richter *et al.,* 1997), causing washout or if flows cannot drift downstream to reach suitable floodplain or nursery habitats. Rearing and refuge habitat are also severely impaired by frequent flow variation. Some species of fish could be stranded in the floodplain due to rapid changes of water level and flow (Petts, 1984). Moreover, frequent moderately high flows could effectively transport sediment through the channel causing altered erosion and deposition processes (Poff *et al.,* 1997). The impact of thee hydrological and habitat changes on adult, larvae and juvenile fish are investigated in Chapters 4 and 5.

Water seems to be retained in the Nam Kam River floodplains longer (around 6-7 months a year) at about 1-2 meters higher water level than before regulation because the watergates are closed before the end of flood season until the next rainy season (Figure 3.13). The longer duration of the higher water levels may benefit fish larval development and nutrient exchange between floodplain and river (Baran *et al.*, 2007). However, if the flood duration is too long it may negatively impact on the fish populations, for example through die-back situations which will severely impact on intolerant aquatic organisms or short flood flows that might disrupt the life cycle of fish.

The magnitude and duration of flood and dry season flows were highly dependent on operational schedule at the various watergates. All watergates also created a longer period of static water or no flow days in the dry season (December to May) due retention of water for irrigation. This increases the availability of water in the dry season but it can inhibit movement and migration of fish, these issues are discussed in Chapters 4 and 7.

Timing of flood changes

The life cycle of fishes in the Mekong River Basin are frequently related with the timing of the flood period, with migration of fishes and the breeding season mostly occurring at the onset of flood season. After the Nam Kam River was regulated by a series of watergates, the timing of flood has changed according to watergate operation. Timing of the flood at the onset of the rainy season was delayed due to each watergate retaining water for flood control downstream (Figures 3.4-3.5 and 3.9). Many fish species use the seasonal flow peak as a cue for spawning migration, and elimination of this peak by flow regulation can directly reduce production of local populations of particular species. Modification in the timing of floods can lead to loss of seasonal flow peaks and eliminate spawning or migratory cues for fish or reduce access to the spawning or nursery habitat (Richter *et al.,* 1997). The low flow pulses observed in this period may benefit recruitment of migratory species but the delayed annual flood associated with delayed opening of the most downstream watergate might not support migration of fish from the Mekong River. The impact of these annual changes on fish population structure and diversity is investigated in Chapter 4.

Habitat changes

The operation of the watergates was according to the flood situation in each year and the rule curves for each watergate which has been created from the recorded data (RID, personal communication). Although the watergates interrupted connectivity and created habitat fragmentation (Kang *et al.,* 2009), the fluctuations in water level also resulted in habitat changes both above and below the watergate, and this could impact on the ecology of the system. Flooding in the Nam Kam River and its tributary creates many new fish habitats. Paddy fields or vegetable fields used in the dry season could be suitable rearing and nursery grounds for fish when the river floods out of bank. This was observed in NK1, where the land is flat and covered by shallow water in the flood season. Similarly NK4 is a seasonal floodplain that connects with the river almost year round (Figure 3.2), the inundated period is now longer than it used to be before the watergates were constructed in 1996. Moreover, the size of the floodplain has expanded since the most downstream watergate was closed at the end of flood season. Vegetation in the area comprises bushes, grass land, and aquatic plants that are able to growth under flooded conditions and are suitable for fish feeding and rearing. However, the increased inundation also destroyed some marginal flooded forest that that cannot tolerate being permanently flooded. In addition, some seasonal floodplains have been created after the watergates became operational, for example; NK3 and NB2 floodplain which filled up and connected with the mainstem Nam Kam and Nam Bang during 2014 flooding cycle (Figure 3.2).

Although the longer period of flood is of benefit to some groups of fish larvae for development and feeding, thus leading to higher fish production (Welcomme, 1985; Baran & Myschowoda, 2009), the longer flood can also create poorer conditions after all the watergates were completely closed. Water quality, especially turbidity increased, and filamentous green algae and phytoplankton bloomed in the upstream impoundment area in the dry season. In addition, the longer flood period may cause die out and decomposition of aquatic plants which require seasonal flooding, and these contributed to deoxygenate conditions in the river system. This results in reduced water quality and impacts some groups of fish, especially white and grey fish, while black fish can often tolerate this situation. However, de-oxygenation and die-back was not observed during sampling year (Fisherman, personal communication) and during 2009-2010 (Phomikong, personal communication) due to the sluice gates being opened for a short period in the dry season creating movement of water and reducing the possibility of dieback. Longer observations are urgently needed to determine if this situation is likely to occur, but spillway releases of water could ameliorate this scenario by aerating the water below the watergate.

Flood inflow might create high turbidity; the siltation was possibly occurred at Nong Han Lake before flowing in to Nam Kam River. Sediment would be transported and then settle in the river distance. However, the longer distance in Nam Kam River and the number of barriers did not reduce and trap the sediment in the river as it has been studied in Mekong River by Kummu *et al.* (2010) due to the distance between each watergates is quite short (20-30 km) and the watergates usually pass the water to downstream by fully open sluice gates in flood season.

Watergate operation could also result in floodplain habitat being disconnected from the main river, as was observed at floodplain below NAKO (Figuer 3.14), and this may result in loss of breeding opportunities for black and grey fish, as eggs and larvae might die or drift to the unsuitable habitat when water levels temporarily decline (Welcomme & Halls, 2004). The impact of hydrological changes (frequency, timing, magnitude, duration and rate of change) caused by watergate operation on diversity and abundance of fish, recruitment process, genetic diversity and migration of fish and will be investigated in Chapters 4-7.

Chapter 4: Population structure and distribution of fish in the Nam Kam River system

4.1 Introduction

The Mekong River is well known as a route for many long distance migratory fishes with most of the production originating from floodplains and tributaries in the middle and the lower part of the basin (Poulsen *et al*., 2002; Baran *et al.*, 2007). A considerable number of dams has recently been proposed for this area (Dugan, 2008; MRC, 2011), causing serious concern over possible declines in fish species diversity and fisheries production (ICEM, 2010; MRC, 2011, 2016). In addition to the many dam projects proposed in both the mainstem and tributaries, there are thousands of dams and weirs in the Thai tributaries of the Mekong basin constructed for irrigation, flood control, and hydropower generation (Thalerngkietleela *et al.,* 2013). Construction of many of these has also largely ignored migration of fishes in the river basin and to what extent they might affect fish production. In the Nam Kam River, Phomikong *et al.* (2014) studied fish diversity in the river system, Srisatit *et al*. (1981) studied fish species composition at the most upstream fish pass and reach connecting it with the Mekong River, while Pongsri *et al.* (2008) and Ngoichansri *et al.* (2013) investigated the diversity of fish in the fish passes associated with watergates in the Nam Kam River. The Nam Bang River, the main tributary of the Nam Kam, has not been studied despite it also having watergates and fish passage facilities. The diversity and distribution of fish in the whole river system has not been studied and little is known about the impact of watergate management on fish migration and habitat fragmentation, which is known to affect diversity and population structure of fishes in the area.

The Nam Kam River system is obstructed by seven watergates on the mainstem and its tributary, which fragments the river's habitat into many sections. Flow in this river system is regulated by watergate operation; sluice gates can be easily operated and they are usually fully opened during the flood season or when the water level is high and closed to store water in the dry season. Thus the river habitat is connected in the wet season and each section isolated during the dry season by the watergate operation. This series of watergates has altered river habitat in the Nam Kam River system, which might affect species composition and diversity of fishes in the river. Moreover habitat fragmentation can directly result in reduction in distribution and abundance of fish (Gido *et al.,* 2010). Halls and Kshatriya (2009) highlighted that dams modify flow and obstruct fish passage; flow modification creates habitat changes both upstream and downstream of dam, disrupts spawning behavior and reduces spawning success, reduces growth and survival rates because of loss of feeding and refuge opportunities. Barriers obstruct fish migration by diminishing fish access to the upstream spawning habitat, interrupting ecological connectivity of the river system and fragmenting habitat, reducing the population survival rate as fish cannot return to downstream feeding and refuge habitats. All of this can lead to significant fish stock depletion (Roberts, 2001; Halls & Kshatriya, 2009). The effect of dams on fisheries production is also highly dependent on the location, design and operation of the dam. Baran *et al.* (2007) mentioned that dams built on the mainstem will have a much greater impact than dams built on tributaries, while those located in the middle and lower part of the LMB will have a greater impact on fish production than dams located in the upper part of the basin. The cumulative effects of barriers will also potentially lead to the differentiation of the fish assemblages between each section of the river system and between regulated and unregulated sections of the river.

The aims of this chapter is to determine whether there is seasonal spatial variation in the diversity, relative abundance and distribution of fish species along the longitudinal profile of the highly regulated Nam Kam River system during the annual flood cycle compared with the unmodified, unregulated Songkhram River. In addition, the factors that affect fish distribution in each habitat types and the likely ecological impact of watergate operation and hydrological changes on the fish population and community structures will be elucidated.

4.2 Objectives

The objectives of the study are to:

1. Describe the distribution, diversity and abundance of fishes in the Nam Kam River and it tributary and investigate shifts in community structure through an annual cycle.
2. Assess the likely impacts of watergates and fish passage operation and hydrological changes on fish populations in each section of the Nam Kam River and its tributary.

4.3 Methodology

4.3.1 Sampling and data collection

Sampling was carried out using 2-m deep gill nets with 6 different mesh sizes of 20, 30, 40, 55, 70 and 90 mm. All 6 mesh size nets were randomly joined. At each sampling sites, 3 sets of gill nets were used and set for 12 hr (18.00-06.00).

Fish were collected from 6 sampling sites above each of the irrigation watergates along the Nam Kam River and it tributary (Nam Bang River) and one site in the main stream river between the last watergate and the Mekong River. Three reference sampling sites were sampled in the Songkhram River, which has no watergates to act as a control (Table 4.1 and Figure 4.1).

To account for seasonal flooding variability in the Nam Kam River and representing the different periods of watergate operation, sampling was carried out at each site 4 times during the period: June 2014 represented the beginning of the rainy season when water level in the reference river increased, and the watergates started to open in the study river; August 2014 represented the middle of rainy season and high flood period in the reference river and all watergates in the study river were fully open and the water started to decline; October 2014 represented the receding flood, and when the watergates were closed to store water for the next dry season; February 2015 represented the dry season in the river system and all watergates were already closed for irrigation supply.

Fish caught were identified using a field guide (Rainboth, 1996), counted, weighed to nearest 0.1 g and measured to nearest 0.1 cm length.

Table 4.1 Locations of gill net sampling sites in the Nam Kam River basin.

Gill net sampling sites for fishes		Locations	
NK1	Ban Dan Muang Kam Village	432159.59 E	1890652.50 N
NK2	Na Karm Village	438781.00 E	1880120.00 N
NK3	Na Koo Village	449212.00 E	1875313.00 N
NK4	Kud La-A	460369.83 E	1874453.82 N
NK5	Ban Nam Kam Village	471026.90 E	1870852.34 N
NB1	Ban Pak E-too Village	451304.00 E	1893376.00 N
NB2	Na Bua Village	455101.00 E	1887000.00 N
SK1	Ban Tha Pan Hong Village	395249.36 E	1969675.20 N
SK2	Kud Sing	416237.00 E	1953827.00 N
SK3	Huay Auan	427868.21 E	1956797.07 N

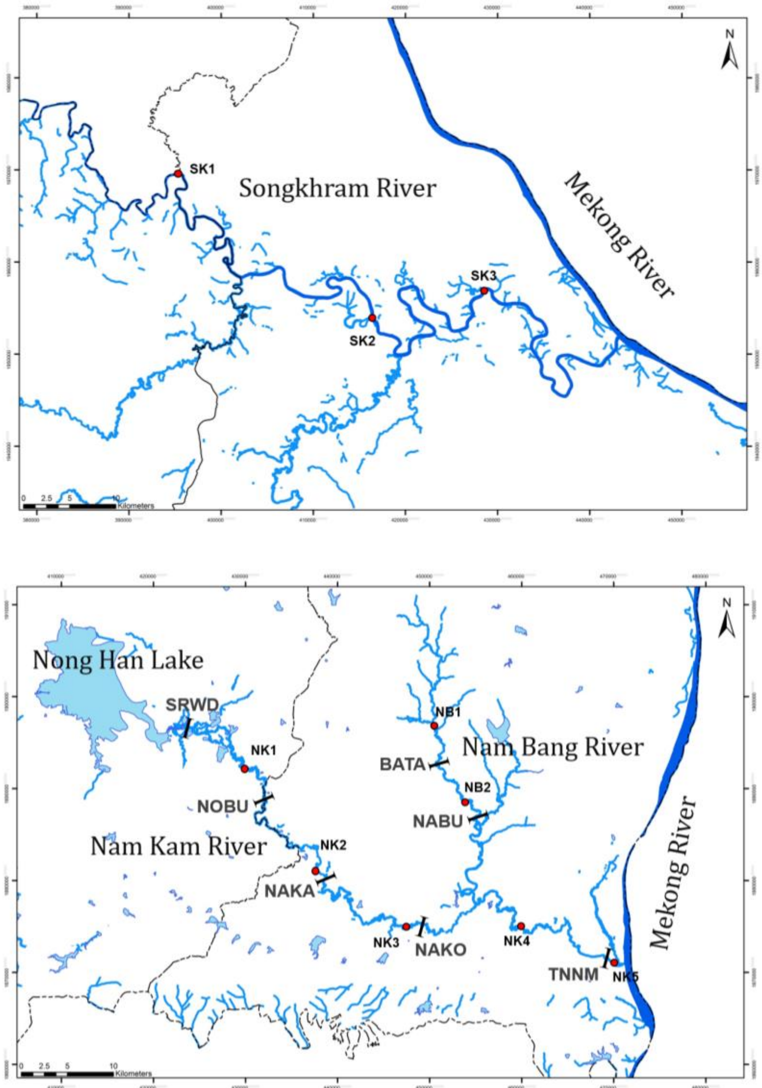


Figure 4.1 Location of the gill net sampling sites for population structure and distribution of fishes in Nam Kam River, its tributary and Songkhram River (red dots represent sampling sites).

4.3.2 Data analysis

To assess distribution, abundance and diversity of fishes in Nam Kam River and its tributary and monitor shifts in community structure throughout and annual cycle:

1. the relative abundance of fish species from gill netting was defined as the number of individuals per unit area of net (catch per unit effort: CPUE; g/hr/100 m^2);
2. the Shannon-Wiener (H') diversity index, Margalef's species richness (d) and Pielou's measure of evenness (J) were applied to investigate spatial variations in diversity and evenness of fish catches performed in PRIMER, version 6 (Clark & Warwick, 2001);
3. the relative abundance of fishes was calculated to investigate similarity in species composition between sites and times using a Bray-Curtis similarity matrix (Bray

& Curtis, 1957) and was grouped using hierarchical agglomerative clustering (complete linkage). Species compositions of each group were computed using SIMPER analysis to identifiy key differences in species in each sampling site regardless of abundance. Both were performed in PRIMER, version 6 (Clark & Warwick, 2001);

4. Multi-dimensional scaling (MDS) analyses were used to establish population structure and relationship between the relative abundance of fish species at the different sites and time.
5. fish species distribution in the main habitats of the system were categorized based on their presence or absence. Species were then grouped according to their guild (as described in Table 2.2), proposed for mainstem dam impact forecasting by Welcomme *et al.* (2006) and Halls & Kshatriya (2009), to determine the variability in community structure between different sections of the river.
6. Key differences of fish diversity, abundance and CPUE by weight of fishes in each site, sampling time and river were compared with two-way analysis of variance (ANOVA) (sites, times and rivers were tested as factors for discriminating the differences observed). Multiple comparisons were applied when ANOVA results revealed significant differences. A paired-samples t-test was used to determine differentiation between the regulated Nam Kam river system and the unregualte Songkhram River and between area above and below TNNM. All statistic analyses were performed using multivariate analysis of variance or MANOVA which is an ANOVA test for difference between two or more group with many dependent variables using PERMANOVA add on in PRIMER, version 6 and IBM SPSS version 23.0.

4.4 Results

4.4.1 Hydrology and watergate management during the sampling period

After the watergates were completed, flow regulation in the Nam Kam River system has been managed differently according to flood conditions, and thus the flow regime on each sampling occasion was dependent on the operation at the time of sampling (Table 4.2).

The first sampling was performed in June 2014 two weeks after the watergates were opened at the beginning of the rainy season and water in the river system started to increase. At the same time, the RID started to release water by opening the downstream watergate. In this period flow was relatively high, and flow changes likely triggered the migration of fish because huge numbers of fish were observed migrating from the Mekong River into the Nam Kam River system via the most downstream fish pass. The fish population in the Nam Kam River system in this period represents the resident population plus migratory species. Fisherman tends not to fish during this period given that it was a high flow period.

The second sampling was carried out in August after most watergates in the Nam Kam system were opened to maximum capacity to release water. Migratory fish had already migrated through the watergates to the upstream area, therefore the population structure in the river system was likely supplemented by fish from the Mekong River and young of the year recruitment. In this period, water level in the Nam Kam declined gradually compared with the unregulated Songkhram River, which was still overbank. Some fish may migrate downstream when the water receded after the watergates were opened to release water.

The third sampling in October was done at the end of the rainy season, one week before the most downstream watergate was closed and started to store water. Water level in each sampling site started to decrease in the Nam Kam system but was still high in the Songkhram River. Fish migrated downstream as the water receded due to release before the watergates were completely closed at the end of October. Fisherman in the lower area of the Nam Kam River caught a lot of fishes in this period (local fishermen, personal communication).

The last survey in February represents the dry season, when all watergates are completely closed to maintain the water between the end of October and until the next rainy season. Water level was constant, with no discharge from any watergate in the river system. Differences were noted between each part of the river cascade that were regulated by watergate operation. At the same time water levels in the Songkhram were low and dried out in some areas.

Table 4.2 Minimum maximum and average discharge (m^3/s) of Nam Kam River system during the sampling period (June 2014 to February 2015).

Site	Month	Discharge		
		Min	Max	Ave.
NK1	Jun-14	2.55	37.06	20.95
	Aug-14	20.46	262.73	126.3
	Oct-14	2.24	98.55	36.38
	Feb-15	2.73	7.03	5.83
NK2	Jun-14	0.73	64.7	32.78
	Aug-14	22.5	265.13	158.27
	Oct-14	11.4	93.78	53.81
	Feb-15	2.83	27.66	7.08
NK3	Jun-14	2.02	96.71	52.82
	Aug-14	39.79	235.82	154.71
	Oct-14	2.89	114.3	59.91
	Feb-15	2.16	22.79	4.75
NK4	Jun-14	21.17	68.43	34.43
	Aug-14	18.87	157.18	88.1
	Oct-14	5.13	127.72	63.42
	Feb-15	2.46	6.95	4.63
NK5	Jun-14	41.39	172.71	109.04
	Aug-14	37.42	525.85	254.57
	Oct-14	17.49	305.92	104.34
	Feb-15	19.79	20.4	20.02
NB1	Jun-14	9.29	54.98	29.68
	Aug-14	3.69	210.04	41.63
	Oct-14	3.94	74.67	19.6
	Feb-15	0	0	0
NB2	Jun-14	10.12	128.17	63.3
	Aug-14	4.38	128.36	42.77
	Oct-14	2.61	80.72	16.52
	Feb-15	0	2.58	0

4.4.2 Diversity of fishes

A total of 78 fish species were observed in the Nam Kam and its tributary. Most fish species found in both the Nam Kam River and its tributary were from the Family Cyprinidae (39 species and 4 unknown cyprinid larvae) followed by Family Osphronemidae (6 species), Family Cobitidae and Family Bagridae (5 species each) and Family Siluridae (4 species). Among these, two species are threatened by extinction according to the IUCN Red List: *Probarbus jullieni* and *Tenualosa thibaudeaui.* Three introduced species: *Cyprinus carpio. Oreochromis niloticus*, and *Clarias gareipinus* and one hybrid species: *Clarias macrocephalus* × *Clarias gareipinus* were observed.

The diversity of fish species caught by gill net in the Nam Kam River system varied considerably between sampling sites. The largest number of species (64 species) was found at the most downstream site, NK5, while moderate numbers of species (36-43 species) were found in the sites upstream of each watergate (NK1-4 and NB1-2). The same pattern was found in the Songkhram River: SK3, the most downstream floodplain had the highest number of species (64 sp.), followed by SK2 (62 species) and SK1 (54 species) (Table 4.3).

Table 4.3 Number of species caught by gillnetting in the 10 sampling sites on the four sampling occasions.

<table>
<tr><th>No. of species</th><th>NK1</th><th>NK2</th><th>NK3</th><th>NK4</th><th>NK5</th><th>NB1</th><th>NB2</th><th>SK1</th><th>SK2</th><th>SK3</th></tr>
<tr><td>Jun-14</td><td>21</td><td>13</td><td>25</td><td>15</td><td>22</td><td>20</td><td>20</td><td>17</td><td>32</td><td>29</td></tr>
<tr><td>Aug-14</td><td>30</td><td>26</td><td>26</td><td>27</td><td>21</td><td>33</td><td>33</td><td>25</td><td>36</td><td>30</td></tr>
<tr><td>Oct-14</td><td>26</td><td>22</td><td>19</td><td>27</td><td>38</td><td>13</td><td>23</td><td>37</td><td>53</td><td>43</td></tr>
<tr><td>Feb-15</td><td>24</td><td>18</td><td>17</td><td>27</td><td>32</td><td>16</td><td>30</td><td>28</td><td>26</td><td>29</td></tr>
<tr><td>average</td><td>40</td><td>36</td><td>38</td><td>43</td><td rowspan="2">64</td><td>41</td><td>43</td><td>54</td><td>62</td><td>64</td></tr>
<tr><td></td><td colspan="4">Upstream area (NK1-4)=53</td><td colspan="2" rowspan="2">NB=51</td><td colspan="3" rowspan="2">SK=76</td></tr>
<tr><td></td><td colspan="5">NK=75</td></tr>
<tr><td></td><td colspan="7">Nam Kam and its tributary=78</td><td colspan="3" rowspan="2">Unregulated river=76</td></tr>
<tr><td></td><td colspan="7">Regulated river=60</td></tr>
</table>

The total number of fish species observed in the Nam Kam River was higher than in the Nam Bang River (75 and 51 species). Analysis of Variance revealed that average number of fish species in each site of the Nam Kam River and its tributary were significantly lower than found in the Songkhram River (24, 26 and 32 species: $P \leq 0.05$). The number of species observed above the TNNM (NK1-4 and NB1-2) was less than the downstream area (60 and 64 species), and also less than the Songkhram River (76 species; Table 4.3). The presence of barriers in the Nam Kam River system has affected the distribution and diversity of fish in the river. Most of the sections obstructed by watergates had low species diversity, except the NK1 floodplain which is located in the most upstream area (Table 4.3).

Common species observed in the Nam Kam River were *Parambassis siamensis, Oxyeleotris marmoratus, Puntioplites proctozystron, Cyclocheilichthys armatus, Hampala dispar, Notopterus notopterus, Dangila lineatus, Osteochilus hasselti, Rasbora dusoensis* and *Pristolepis fasciata. Puntius brevis* had a high frequency of occurrence in most of samples, while *Cyclocheilichthys armatus, Parambassis siamensis, Rasbora dusoensis, Dangila lineatus, Mystus mysticetus, Osteochilus hasselti, Oxyeleotris marmoratus, Pristolepis fasciata, Puntioplites proctozystron*, and *Thynnichthys thynnoides* were present in most samples from the Nam Bang River. Common species found in the Songkhram River were *Mystus singaringan, Parambassis siamensis, Puntioplites proctozystron, Sikukia stejnegeri, Dangila lineatus, Mystus mysticetus, Puntius brevis, Barbodes altus, Hampala dispar, Osteochilus lini, Pristolepis fasciata* and *Thynnichthys thynnoides.*

Some species of fish, like *Rasbora trilineata, Trichogaster pectoralis, Clarias gareipinus, Tetraodon chochichinensis, Tetraodon fangi, Mystus atrifasciatus, Kryptopterus geminus,* and *Mystacoleucus marginatus*, were observed only in the

Nam Kam River, while *Hemisilurus mekongensis, Lobocheilus melanotaenia, Hemibagrus filamentus, Paralaubuca typus* and *Cosmochilus harmandi* were only observed in the Nam Bang River. Sixteen species were observed only in the area below the TNNM at the end of the flood season and were not observed above the watergate. Among these, 15 species were white fish and one species was a grey fish (Table 4.4). Several species were also only found above the TNNM and included three whitefish species, one grey fish and two black fish species. Twenty two species of fish were observed only in the Songkhram River (Table 4.4) and most were white and grey fishes.

Table 4.4 Key species differences between regulated river and unregulated river from June 2014-Feb 2015. (Sources; Pongsri *et al.,* 2008; Ngoichansri *et al.,* 2013 and this study)

Species observed only area in Nam Kam and its tributary; *Regulated river*	**Species observed in only Songkhram River;** *Unregulated river*
Hypsibarbus malcomi (WF)	*Hypostomus plecostomus* (GF)
Mystacoleucus marginatus (WF)	*Acanthopsis* sp.1 (GF)
Lobocheilus melanotaenia (WF)	*Acanthopsis* sp.2 (GF)
Rasbora trilineata (GF)	*Leiocassis siamensis* (GF)
Clarias gareipinus (BF)	*Paralaubuca riveroi* (GF)
Trichogaster pectoralis (BF)	*Euryglossa harmandi* (GF)
	Toxotes chatareus (GF)
Species observed only downstream area of Thoranit Naruemit water gate	*Probarbus jullieni* (WF) *,-
	Pangasius larnaudii (WF) *,**,***
Probabus jullieni (WF) *,-	*Pangasius macronema* (WF) *,***
Pangasius larnaudii (WF) *,**,***	*Tenualosa thibaudeaui* (WF) *
Cyclocheilichthys enoplos (WF) *,-	*Labeo chrysophekadion* (WF) *,**, -
Hemibagrus wyckioides (WF) *	*Puntioplites falcifer* (WF)
Pangasius macronema (WF) * ,***	*Syncrossus helodes* (WF)
Pseudolais pleurotaenia (WF) *	*Yasuhikotakia modesta* (WF)
Tenualosa thibaudeaui (WF) *	*Hypsibarbus lageri* (WF)
Labeo chrysophekadion (WF) *,**,-	*Osteochilus melanopleura* (WF) *
Osteochilus melanopleura (WF) *	*Kryptopterus macrocephalus* (WF)
Phalacronotus bleekeri (WF) *,**,***	*Phalacronotus bleekeri* (WF) *,**,***
Mystus bocourti (WF) *,***	*Barbichthys nitidus* (WF)
Raiamas guttatus (WF) *,-	*Puntigrus tetrazona* (WF)
Cyprinus carpio (WF) *,**, -	*Mystus bocourti* (WF) *,***
Kryptopterus macrocephalus (WF)	
Botia sp.1 (WF)	
Toxotes chatareus (GF)	

GF: Greyfish, WF: Whitefish, and BF: Blackfish

** has been observed migrate through Thoranit Naruemit fish pass in 2012 and 2013*

*** has been observed at the upstream area of Thoranit Naruemit watergate in 2012 or 2013*

**** late migrating species in 2014*

- has been observed at the upstream fish passed in 2008

The Shannon-Wiener diversity index for the Songkhram River was higher than the Nam Kam River and its tributary but no significant difference was observed between the three rivers (ranged from 3.05-3.64, 2.77-3.18 and 2.84-3.19, respectively). Average species richness exhibited a similar outcome with the Songkhram River having higher species richness than the Nam Kam River and its tributary (ranging from 26-44, 19-27 and 20-28, respectively; Table 4.**Error! Reference source not found.**5).

Table 4.5 Average±SD of species richness and Shannon-Wiener diversity index per site in 10 sampling sites 4 sampling times. Number in parenthesis represent number of total species.

	Species richness			Diversity index; H'(log e)		
	Nam Kam	Nam Bang	Songkhram	Nam Kam	Nam Bang	Songkhram
Jun-14	19±6(43)	20±0(27)	26±8(45)	2.77±0.29	2.86±0.04	3.05±0.31
Aug-14	27±2(52)	28±7(39)	30±6(48)	3.18±0.08	3.19±0.25	3.24±0.20
Oct-14	24±4(49)	22±12(31)	44±8(59)	3.02±0.15	2.84±0.66	3.64±0.16
Feb-15	22±5(41)	23±10(31)	28±2(46)	2.88±0.19	2.95±4.67	3.14±0.08

4.4.3 Abundance and fish catches

Songkhram River

Abundance and fish catch in the Songkhram River were varies between sites. SK2, which is a large productive floodplain, showed the highest abundance of fish and CPUE by weight (390 fish/100m^2/night and 2,138 g/100m^2/night, respectively) followed by SK3, the downstream floodplain (179 fish/100m^2/night and 1,010 g/100m^2/night), and SK1 (78 fish/100m^2/night and 557 g/100m^2/night) throughout the sampling period (Table 4.6-4.7).

Table 4.6 Abundance of fish catches by gill net in 10 sampling sites 4 sampling times (individuals/100m^2/night).

CPUE by number	NK1	NK2	NK3	NK4	NK5	NB1	NB2	SK1	SK2	SK3
Jun-14	14	12	56	11	35	8	15	32	319	138
Aug-14	52	46	26	21	12	44	17	64	152	129
Oct-14	39	16	11	54	45	17	45	179	871	347
Feb-15	25	15	9	29	18	22	203	35	219	104
average	33	22	25	29	27	23	70	78	390	179
	Upstream area (NK1-4)=27					NB=46		SK=216		
	NK=27									
	Nam Kam and its tributary=33							Unregulated river=216		
	Regulated river=34									

Table 4.7 Catch per unit effort by gillnetting in 10 sampling sites on four sampling occasions (g/100m^2/night).

<table>
<tr><th>CPUE by weight</th><th>NK1</th><th>NK2</th><th>NK3</th><th>NK4</th><th>NK5</th><th>NB1</th><th>NB2</th><th>SK1</th><th>SK2</th><th>SK3</th></tr>
<tr><td>Jun-14</td><td>210</td><td>229</td><td>319</td><td>104</td><td>297</td><td>145</td><td>221</td><td>281</td><td>2,326</td><td>920</td></tr>
<tr><td>Aug-14</td><td>484</td><td>616</td><td>444</td><td>426</td><td>277</td><td>546</td><td>349</td><td>465</td><td>1,062</td><td>646</td></tr>
<tr><td>Oct-14</td><td>527</td><td>255</td><td>263</td><td>327</td><td>573</td><td>139</td><td>666</td><td>1,122</td><td>4,114</td><td>1,578</td></tr>
<tr><td>Feb-15</td><td>425</td><td>241</td><td>189</td><td>424</td><td>300</td><td>206</td><td>1,039</td><td>358</td><td>1,052</td><td>897</td></tr>
<tr><td>average</td><td>411</td><td>335</td><td>304</td><td>320</td><td rowspan="2">362</td><td>259</td><td>569</td><td>557</td><td>2,138</td><td>1,010</td></tr>
<tr><td></td><td colspan="4">Upstream area (NK1-4)=343</td><td colspan="2" rowspan="2">NB=414</td><td colspan="3" rowspan="2">SK=1,235</td></tr>
<tr><td></td><td colspan="5">NK=347</td></tr>
<tr><td></td><td colspan="7">Nam Kam River and tributary=366</td><td colspan="3" rowspan="2">Unregulated river=1,235</td></tr>
<tr><td></td><td colspan="7">Regulated river=366</td></tr>
</table>

The Nam Kam River system

Results from PERMANOVA analysis showed that the abundance of fish in the Nam Kam River system varied between sampling sites (*P*≤0.01) and between times (*P*≤0.01). Abundance of fish in the Nam Bang River was higher than the Nam Kam River (46 and 27 fish/100^{2}m/night, respectively). Average abundance of fish in the area downstream of TNNM was similar to the upstream area (each 27 fish/100^{2}m/night; Table 4.). Total number of fish caught in the Nam Kam River system continuously increased from June, August, October and February (150, 218, 226 and 322 fish/100^2/night).

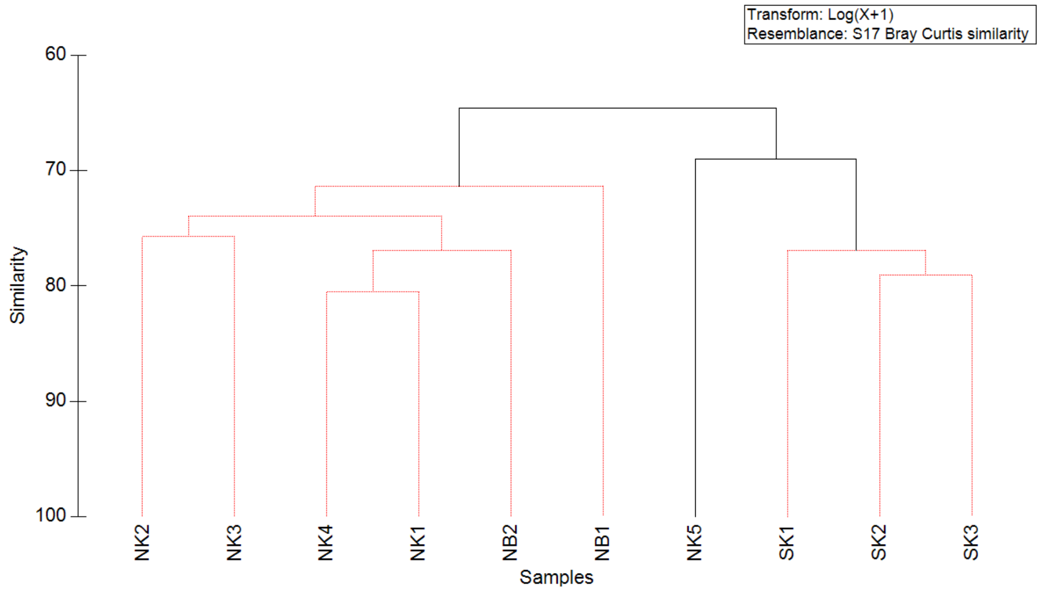
Results from PERMANOVA analysis exhibited that CPUE by weight of fish in the Nam Kam River and its tributary differed significantly between sampling sites (*P*≤0.01) and between occasions (*P*≤0.01). Average CPUE by weight of fish in the Nam Bang River was higher than in the Nam Kam River (414 and 347 g/100m^2/night, respectively). CPUE by weight of fish in the area downstream of TNNM was slightly higher than the average of the area above (362 and 343 g/100^{2}m/night; Table 4.7). Catch rate in June was significant lower than August, October, and February (232, 450, 389, and 316 g/100^{2}m/night). The highest average CPUE by weight (411 g/100m^2/night) and abundance (33 fish/100m^2/night) in the Nam Kam River was observed at the most upstream sampling site (NK1) while average CPUE by weight and abundance in the Nam Bang River was highest at NB2 (569 g/100m^2/night and 70 fish/100m^2/night; Table 4.7). Overall, a paired-samples t-test determined that abundance of fish and catches by weight in the regulated Nam Kam River system were lower than in the unregulated Songkhram River (46.00 and 215.76 fish/100m^2/night; *P*≤0.05, and 365.78 and 1,235.05 g/100m^2/night; *P*≤0.05) (Table 4.6-4.7).

4.4.4 Spatial variation of fish in the Nam Kam River system and Songkhram River

The composition of gillnet catches between sites based on weight and abundance at the species level were similar. Cluster analysis discriminated three distinct groups of study sites, Cluster A: most of the sites in the Nam Kam River system (NK1-4 and NB1-2) were group together with average similarity of 74.1%. Cluster B: the most downstream sampling site (NK5) was different from the other sampling sites at dissimilarity of 38.5% and species composition of fish in the Nam Kam River system was significantly different from the sites on the Songkhram River (SK1-3), which were group together (average similarity 77.32%) (Table 4.4). PERMANOVA analysis found river and sampling time (that represent differently watergate management) were important factors discriminating species composition ($P \leq 0.01$), but the interaction between the two factors was not significant ($P \geq 0.05$; Table 4.8).

Table 4.8 Permanova table of result calculated from abundance of fish in the Nam Kam River system and Songkhram River.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
river	2	8666.7	4333.4	3.0173	0.001	9977
month	3	9206.9	3069	2.1369	0.001	9962
river x month	6	9119	1519.8	1.0582	0.343	9987
Res	28	40213	1436.2			
Total	39	68340				



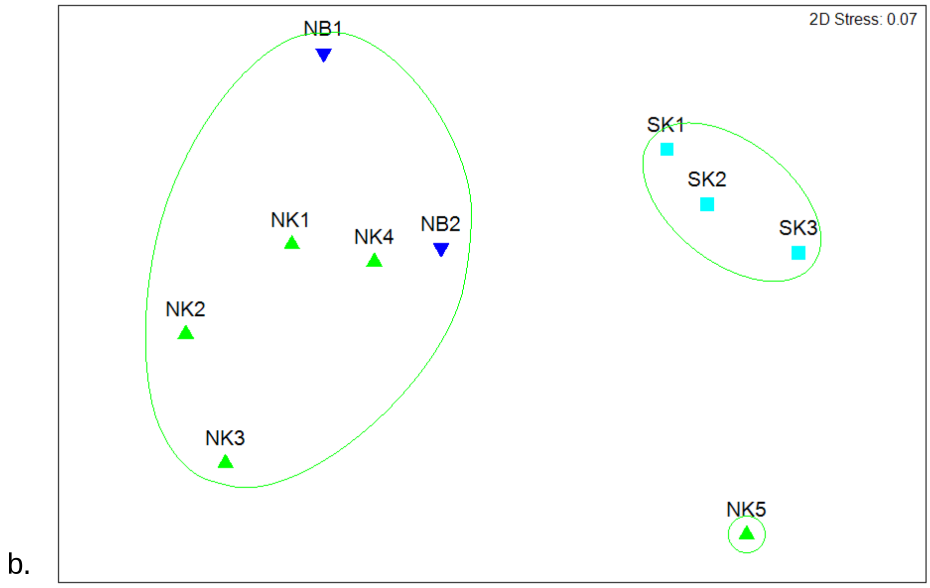


Figure 4.2 Average linkage cluster (a) and Multi-dimensional scaling (MDS) analysis of species biomass from 10 sites in the Nam Kam River, Nam Bang and Songkhram River.

The species composition of the clusters is identified below (Figure 4.2).

Cluster A: NK1-4 and NB1-2 Species composition in sampling sites above the TNNM was contributed by *Oxyeleotris marmoratus* (4.36%), *Puntioplites proctozystron* (4.25%), *Dangila lineatus* (4.21%), *Rasbora dusoensis* (4.18%), *Notopterus notopterus* (4.05%), *Osteochilus hasselti* (3.85%), *Osteochilus lini* (3.77%), *Cyclocheilichthys armatus* (3.53), *Parambassis siamensis* (3.51%) and *Hampala dispar* (3.48%). Seven out of ten species were grey fish, while two species were white fish and one black fish.

Cluster B: NK5 was assemblage comprised white fish and grey fish. The top ten most abundant fish species by weight were *Puntioplites proctozystron* (12.51%), *Barbodes gonionotus* (10.54%), *Probarbus jullieni* (6.89%), *Sikukia gudgeri* (5.72%), *Oxyeleotris marmoratus* (5.06%), *Barbodes altus* (4.62%), *Parachela siamensis* (4.07%), *Chitala ornata* (4.03%), *Thynnichthys thynnoides* (3.55%), and *C. macrocephalus x C.gariepinus* (3.34%). Six out of the ten species were white fish, plus two of grey fish and two black fish.

Cluster C: SK1-SK3 Species composition in the Songkhram River was dominated by *Sikukia stejnegeri* (3.21%), *Puntius brevis* (2.95%), *Mystus mysticetus* (2.92%), *Puntioplites proctozystron* (2.87%), *Chitala ornata* (2.84%), *Parambassis siamensis* (2.64%), *Hampala dispar* (2.40%), *Osteochilus melanopleura* (2.39%), *Pristolepis fasciata* (2.37%) and *Osteochilus hasselti* (2.36). Four out of ten species were white fish, four were grey fish and two were black fish.

The key difference species between clusters were as follows;

Cluster A and B: Average dissimilarity was 38.50%. The top five key species differences which were observed in the downstream area only were *Probarbus jullieni* (7.49%), *Morulius chrysophekadion* (6.42%), *Cyprinus carpio* (6.00%), *Pangasius larnaudii* (5.92%), and *Pseudolias pleurotaenia* (4.97%).

Cluster B and C: Average dissimilarity was 30.99%. The top five key species differences which were observed in the Songkhram River only were *Hypostomus plecostomus* (6.42%), *Channa striata* (6.33%), *Paralaubuca typus* (6.07%), while two species (*Cyprinus carpio* (6.00) and *Pseudolias pleurotaenia* (4.97%)) were only observed in the downstream area of Nam Kam River.

Cluster A and C: Average dissimilarity was 34.37%. The top five key species differences which were observed only in the Songkhram River were *Osteochilus melanopleura* (6.99%), *Hypostomus plecostomus* (6.42%), *Pangasius larnaudii* (6.01%), *Morulius chrysophekadion* (5.76%) and *Phalacronotus bleekeri* (5.11%).

4.4.5 Seasonal variation of fish

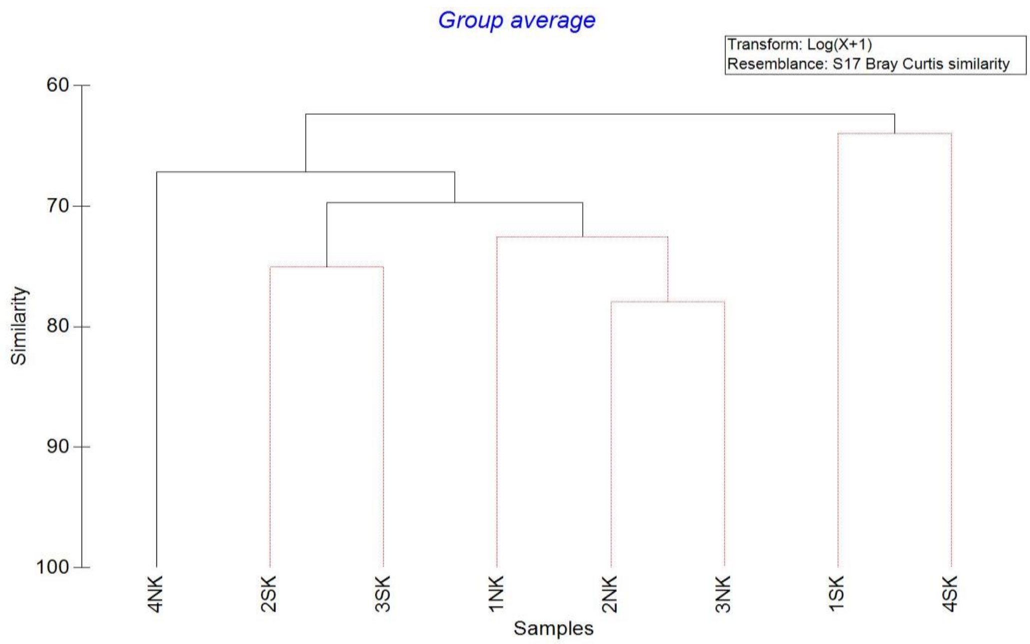
Cluster analysis discriminated two distinct groups of sampling according to the watergate operation (Figure 4.3).

Cluster A: most of the sampling in the Nam Kam River system (June, October and February) were group together with an average similarity of 64.5%. Species composition of fish observed in the Nam Kam River system in June, October and April was contributed by *Puntioplites proctozystron* (4.25%), *Rasbora argyrotaenia*

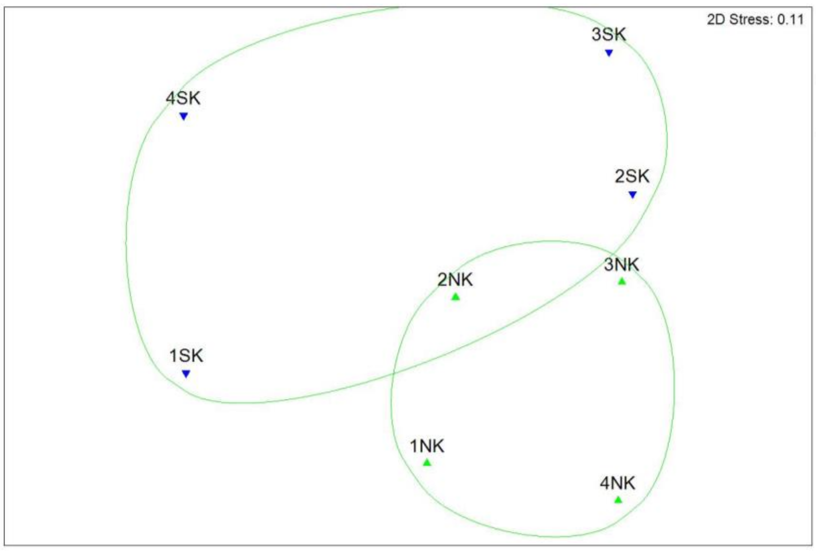
(4.05%) *Labiobarbus lineatus* (3.99%), *Oxyeleotris marmoratus* (3.81%), *Notopterus notopterus* (3.62%), *Parambassis notatus* (3.47%), *Puntius brevis* (3.38%), *Cyclocheilichthys armatus* (3.37%), *Pristolepis fasciata* (3.13%) and *Cyclocheilichthys apogon* (3.10%).

Cluster B: sampling in the period that watergates were opened to maximum capacity in the flood season (August) were group together with sampling in the unregulated Songkhram River with average similarity of 66.3%. Two clusters were different with average dissimilarity 33. 6%. The species composition of cluster B was dominated by *Sikukia stejnegeri* (4.24%), *Puntius brevis* (4.05%), *Puntioplites proctozystron* (4.02%), *Labiobarbus lineatus* (3.79%), *Cyclocheilichthys armatus* (3.65%), *Parambassis notatus* (3.43%), *Mystus mysticetus* (3.39%), *Thynnichthys thynnoides* (3.21%), *Pristolepis fasciata* (3.13%) and *Mystus singaringan* (3.07%).

The top ten different species between Cluster A and B, which were observed in only in peak of flood season of the Nam Kam and in all season of Songkhram River, were white and grey fish like *Euryglossa harmandi* (1.05%), *Syncrossus helodes* (0.92%), *Barbichthys nitidus* (0.84%) *Paraluabuca riveroi* (0.69%), which are species that normally inhabit flowing water in the flood season and are found to migrate between and within the Mekong mainstem and Mekong tributaries.



a.



b.

Figure 4.3 Average linkage cluster (a) and Multi-dimensional scaling (MDS) analysis of species biomass from 8 samplings in the Nam Kam River system and Songkhram River. 1NK, 2NK, 3NK and 4NK represents sampling in the Nam Kam River system in June 2013, August 2013, October 2013, and February 2014, while 1SK, 2SK, 3SK and 4SK represent sampling in the Songkhram River in June 2013, August 2013, October 2013, and February 2014 , respectively.

Songkhram River; unregulated river

ANOVA indicated that CPUEs by number and weight in the Songkhram River were significantly different between sampling occasions (*P*≤0.01). CPUE by number and weight in the wet season were higher than the dry season (247.82 and 119.58 fish/100^2/night, and 1,390.34 and 769.18 g/100^2/night). Also, abundance and CPUE by weight in October were significantly higher than June, August and February (466 fish/100^2/night and 163,115 and 119 fish/100^2/night) (Tables 4.3, 4.6-4.7 and 4.9). Diversity of white fish, abundance and CPUE of fish increase in the flood season (August) at the upstream floodplain (SK1-2) indicate upstream migration of fish from Mekong River, while they are increase at the end of flood season (October) at the sampling site downstream (SK2-3; Table 4.10 and Figures 4.4-4.6) suggesting downstream migration when water levels receded (Figure 3.13). In the dry season (February), the diversity of white fish, abundance, and CPUE declined, while the number and relative abundance of grey fish species was still high or showed a marginal decline at all sampling sites (Table 4.9 and Figures 4.4-4.6).

The Nam Kam River system; regulated river

Result form PERMANOVA reveal that fish species composition in the Nam Kam River system varied significantly between months ($P \leq 0.01$). Seventy three species were observed in the wet season and 51 species in the dry season. The total number of species observed in June, August, October and February were 43, 52, 49, and 41 respectively (Table 4.4)

The fish assemblage at the onset of rainy season in June represents the fish population that starts being supplemented by fish from Mekong River and the other sections with in the river. The composition of fish at the floodplains above TNNM (NK1, NK3-4 and NB1-2) was mostly grey fish (Table 4.9), while composition of fish at NK2 and NK5 were mainly contributed by white fish (Table 4.9 and Figures 4.4-4.6). NK3 exhibited the highest number of fish species and CPUE by weight in this period (56 fish/100m^2/night and 319 g/100m^2/night; Table 4.6-4.7), species that dominated in this site were grey fish like *Parambassis notatus, Rasbora argyrotaenia, Dangila lineatus*, and *Puntius brevis,* which was stimuated by water level changed at the onset of rainy season.

After all sluice gates were opened in August to release water in the flood period, of the contribution of white fish increased especially at the upstream floodplains (NK1-3 and NB1-2) (Tables 4.9-4.10 and Figures 4.4-4.6). Fish species that migrated into the upstream floodplain were white fish including *Notopterus notopterus, Gymnostomus ornatipinnis, Chitala ornata, Wallago attu*, *Puntioplites proctozystron*, *Henichorhynchus siamensis,* and *Sikukia stejnegeri,* and grey fish including *Osteochilus hasselti, Osteochilus lini, Dangila lineatus, Cyclocheilichthys armatus, Hampala macrolepidota, Hemibagrus nemurus, Thynnichthys thynnoides*, *Puntius brevis* and *Cyclocheilichthys apogon*. However, the number of species and fish assemblages at the downstream floodplains, NK4-5 was dominated by black and grey fish (Table 4.9).

Moreover, the occurrence of young of the year fish in the upstream areas in August and October suggest this area of the river is spawning habitat. Juvenile and small sized (between 14-93 mm) *Cyclocheilichthys apogon, Puntioplites proctozystron*, *Osteochilus hasselti, Barbodes altus, Barbodes gonionotus, Hampala macrolepidota*, *Barbonymus schwanenfeldii, Henichorhynchus siamensis, Hampala dispar, Thynnichthys thynnoides, Cyclocheilichthys* sp., *Labiobarbus siamensis* and *Clupeichthys aesarnensis* were recorded. Most of the juvenile fishes were the same species of adult fish that migrated through TNNM fish pass at the onset of the rainy season. Thus the Nam Kam River system is a spawning and rearing ground for fish that migrate from the Mekong River in the flood season.

When the water level in this area receded at the end of the flood season (October), the composition of fish in the upstream floodplains (NK1-3 and NB1) was dominated by grey fish white fish dominated in the downstream areas (NK4-5 and NB2). This suggests migration of white fish to the downstream floodplains when water level receded and before all watergates were completely closed in November (Figures 4.4-4.6).

Abundance and CPUE of fish in all sections in the dry season (February) were dominated by grey fish (Table 4.6-4.7 and 4.9), while white fish numbers were low (Tables 4.9) because some had already moved to the Mekong River before the watergates were closed. However, white fish were still represented in the catch by weight in the dry season at NK1, NB2 and NK4 indicating some white fish were stranded in the floodplain once the watergates were closed (Table 4.9). These were *Sikukia stejnegeri, Acanthopsis choirorhynchos, Labiobarbus lineatus*, *Notopterus notopterus* and *Puntioplites proctozystron*, and these fish needed to be adapting to these conditions during dry season. NB2 showed the highest CPUE by weight and abundance in the dry season (1,039 g/100m^2/night and 203 fish/100m^2/night) due to the high numbers of grey fish like *Parambassis notatus, Cyclocheilichthys armatus* and *Osteochilus hasselti* and some stranded white fish like *Sikukia Stejnegeri* in February (Table 4.6-4.7).

Composition of fish at the most downstream area below TNNM and connected with the Mekong River (NK5) was dominated by white fish at the onset of the rainy season suggesting white fish had free access to this section from the Mekong. White fish abundance decreases in August when all watergates were opened to maximum capacity, and fish had migrated upstream to their spawning ground in the Nam Kam River system. When water receded at the end of the flood season, the contribution of white fish to the assemblage increased due to fish migrating downstream but decreased again when fish continued to migrate to the Mekong for refuge in the dry season.

Table 4.9 Number of species, abundance (fish/100m^2/night) and biomass (g/100m^2/night) of each guild fish at different time and site sampling in the Nam Kam River system and Songkhram River from June 2014-February 2015.

Site	Month	White fish			Grey fish			Black fish		
		sp.	Abundance	Catch	sp.	Abundance	Catch	sp.	Abundance	Catch
NK1	Jun-14	2	1	5	11	10	104	8	4	102
	Aug-14	6	17	141	13	26	160	11	11	185
	Oct-14	4	1	76	11	31	172	11	9	280
	Feb-15	5	4	125	15	22	285	4	1	17
NK2	Jun-14	4	8	171	7	5	38	2	1	22
	Aug-14	8	36	417	13	10	144	5	2	57
	Oct-14	6	2	149	10	14	84	6	2	24
	Feb-15	5	2	28	11	15	212	2	1	2
NK3	Jun-14	5	2	46	15	54	220	5	2	55
	Aug-14	6	6	93	16	19	149	4	4	204
	Oct-14	4	2	126	7	7	53	8	3	84
	Feb-15	3	2	57	12	8	91	2	1	42
NK4	Jun-14	4	3	48	8	9	50	3	1	8
	Aug-14	3	2	31	13	13	118	11	8	278
	Oct-14	6	23	115	14	27	147	7	6	66
	Feb-15	7	4	143	15	26	269	5	1	13
NK5	Jun-14	15	30	251	6	6	42	1	1	5
	Aug-14	10	4	161	6	9	87	5	2	30
	Oct-14	19	25	350	11	17	131	8	5	94
	Feb-15	7	4	51	19	15	186	6	2	64
NB1	Jun-14	4	1	28	8	6	32	8	2	86
	Aug-14	9	7	236	14	27	170	10	12	142
	Oct-14	3	2	8	9	16	124	1	1	8
	Feb-15	3	3	15	11	20	186	2	1	7
NB2	Jun-14	5	7	105	10	9	86	5	2	31
	Aug-14	8	9	228	9	4	42	6	6	81
	Oct-14	10	10	415	13	30	152	7	8	101
	Feb-15	4	30	140	16	164	780	10	12	120
SK1	Jun-14	5	28	223	9	4	33	3	2	26
	Aug-14	12	59	389	10	6	66	3	1	11
	Oct-14	9	16	215	15	81	357	13	84	552
	Feb-15	7	2	22	17	35	314	4	1	24
SK2	Jun-14	8	35	378	15	265	1612	9	21	338
	Aug-14	10	66	434	13	74	376	13	14	253
	Oct-14	20	614	2915	20	243	960	13	17	241
	Feb-15	5	8	63	14	207	879	7	7	112
SK3	Jun-14	11	92	471	11	39	263	7	9	188
	Aug-14	12	68	352	15	56	188	4	6	107
	Oct-14	16	74	482	15	202	725	12	73	372
	Feb-15	5	18	111	19	40	413	5	48	375

Table 4.10 Percentage of top ten fish species by biomass and by abundance observed in difference period of operation at the areas above the Thoranit Naruemit Watergate (NK1-4 and NB1-2).

		% Catch		% Abundance
Jun-14	*Oxyeleotris marmoratus* (BF)	10.74	*Rasbora trilineata* (GF)	31.95
	Dangila lineatus (WF)	9.15	*Barbodes altus* (GF)	5.06
	Parambassis siamensis (GF)	7.65	*Leiocassis siamensis* (GF)	5.04
	Rasbora dusoensis (GF)	6.55	*Euryglossa harmandi* (GF)	4.94
	Osteochilus hasselti (GF)	6.05	*Systomus orphoides* (GF)	4.63
	Puntius brevis (GF)	5.91	*Parambassis siamensis* (GF)	4.53
	Puntioplites proctozystron (WF)	5.87	*Rasbora dusoensis* (GF)	4.23
	Pristolepis fasciata (BF)	5.43	*Sikukia gudgeri* (WF)	3.93
	Thynnichthys thynnoides (WF)	5.37	*Puntigrus tetrazona* (WF)	3.02
	Parachela siamensis (GF)	5.25	*Sikukia stejnegeri* (WF)	3.02
Aug-14	*Oxyeleotris marmoratus* (BF)	28.43	*Sikukia stejnegeri* (WF)	53.75
	Thynnichthys thynnoides (WF)	9.64	*Puntius brevis* (GF)	30.88
	Puntioplites proctozystron (WF)	9.59	*Rasbora dusoensis* (GF)	13.97
	Notopterus notopterus (WF)	5.96	*Parambassis siamensis* (GF)	13.67
	Dangila lineatus (GF)	5.20	*Oxyeleotris marmoratus* (BF)	9.59
	Puntius brevis (GF)	3.93	*Pristolepis fasciata* (BF)	8.71
	Sikukia stejnegeri (WF)	3.85	*Thynnichthys thynnoides* (WF)	8.48
	Osteochilus hasselti (GF)	3.66	*Osteochilus lini* (GF)	8.23
	Rasbora dusoensis (GF)	3.44	*Puntioplites proctozystron* (WF)	7.99
	Pristolepis fasciata (BF)	2.49	*Dangila lineatus* (GF)	7.25
Oct-14	*Puntioplites proctozystron* (WF)	19.46	*Puntius brevis* (GF)	16.88
	Notopterus notopterus (WF)	18.13	*Parambassis siamensis* (GF)	12.43
	Oxyeleotris marmoratus (BF)	11.55	*Rasbora dusoensis* (GF)	10.72
	Dangila lineatus (GF)	6.66	*Puntioplites proctozystron* (WF)	10.71
	Thynnichthys thynnoides (WF)	5.38	*Cyclocheilichthys armatus* (GF)	8.42
	Cyclocheilichthys armatus (GF)	5.16	*Dangila lineatus* (GF)	4.86
	Pristolepis fasciata (BF)	3.61	*Osteochilus lini* (GF)	4.18
	Barbodes gonionotus (WF)	3.54	*Mystus mysticetus* (BF)	4.07
	Hampala dispar (GF)	3.41	*Thynnichthys thynnoides* (WF)	3.98
	Rasbora dusoensis (GF)	3.22	*Oxyeleotris marmoratus* (BF)	2.04
Feb-15	*Osteochilus hasselti* (GF)	9.26	*Parambassis siamensis* (GF)	35.68
	Dangila lineatus (GF)	8.50	*Cyclocheilichthys armatus* (GF)	11.10
	Rasbora dusoensis (GF)	8.44	*Rasbora dusoensis* (GF)	10.55
	Cyclocheilichthys apogon (GF)	7.98	*Sikukia stejnegeri* (WF)	8.90
	Notopterus notopterus (WF)	7.70	*Dangila lineatus* (GF)	4.77
	Osteochilus lini (GF)	7.34	*Cyclocheilichthys apogon* (GF)	3.75
	Xenentodon cancila (GF)	6.51	*Osteochilus hasselti* (GF)	3.35
	Hampala dispar (GF)	6.18	*Puntius brevis* (GF)	2.97
	Puntius brevis (GF)	4.38	*Acanthopsis choirorhynchos* (GF)	2.71
	Parambassis siamensis (GF)	4.33	*Parachela siamensis* (GF)	1.98

GF:Greyfish, WF:Whitefish, and BF:Blackfish

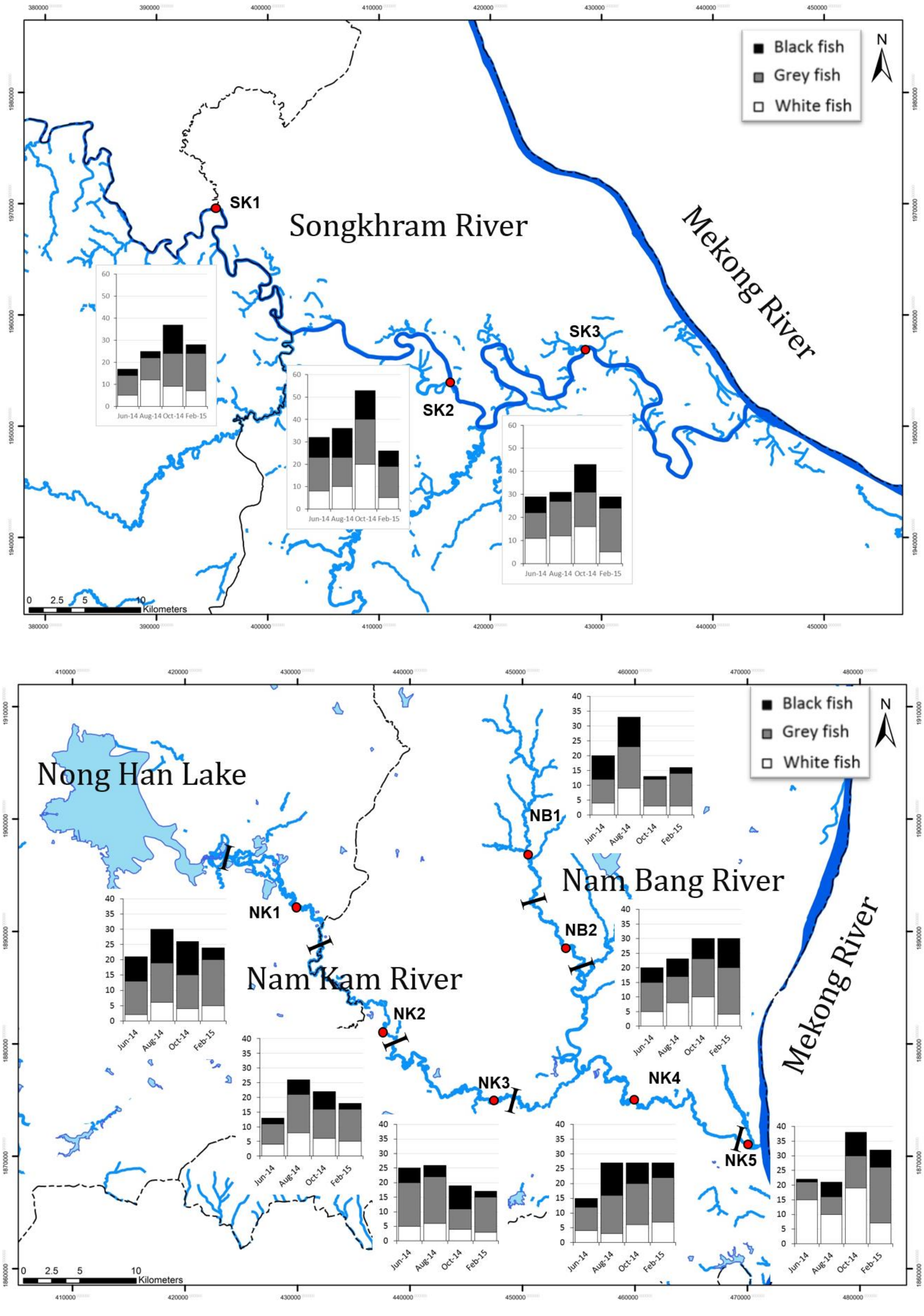
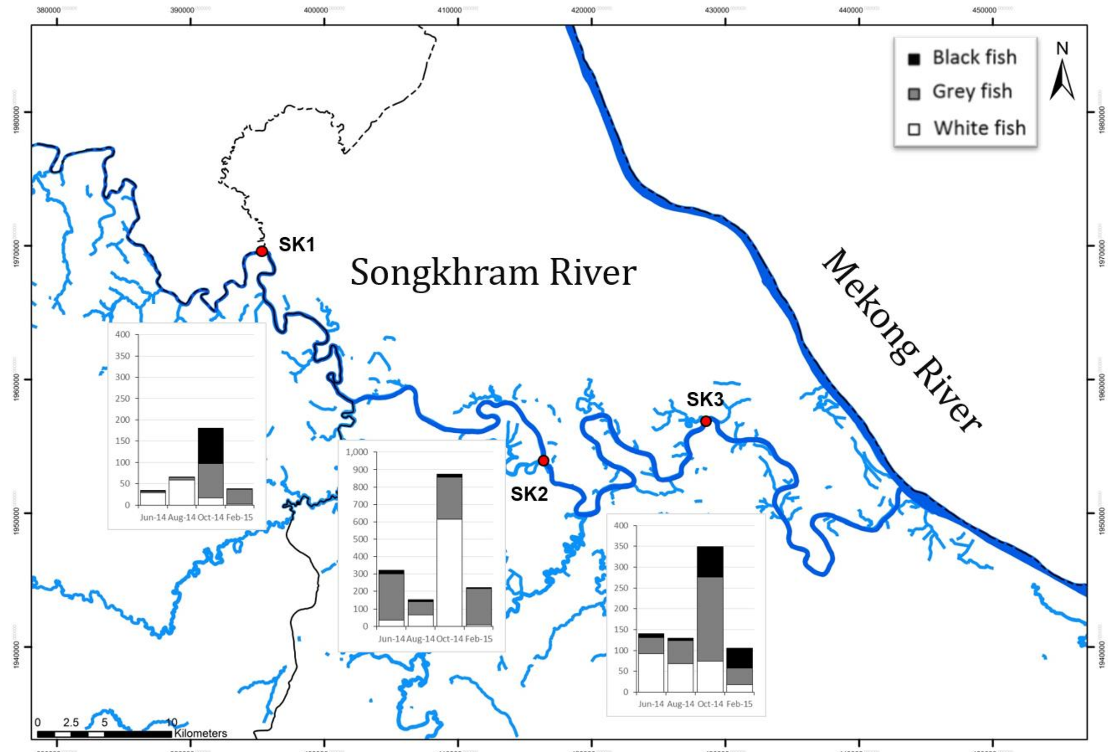


Figure 4.5 Species richness of fish in the Nam Kam River system and Songkhram River in difference operating time from June 2014 - February 2015.



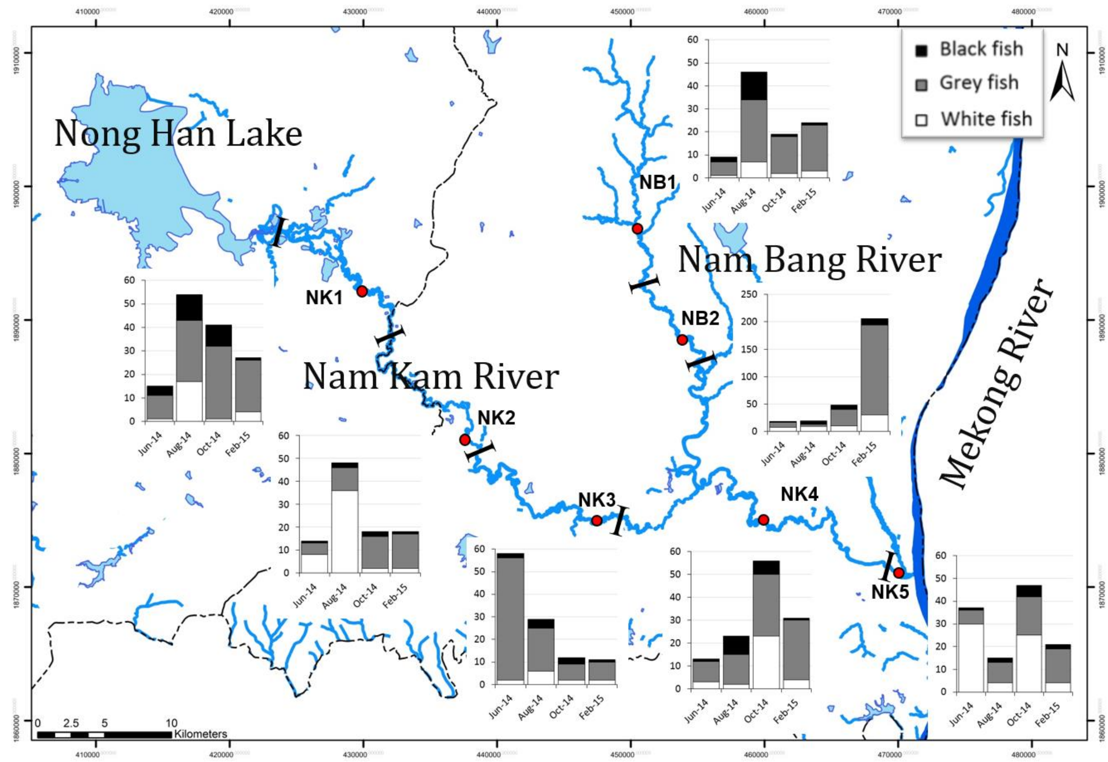


Figure 4.6 Fish abundance in the Nam Kam River system and Songkhram River in difference operating time from June 2014 – February 2015.

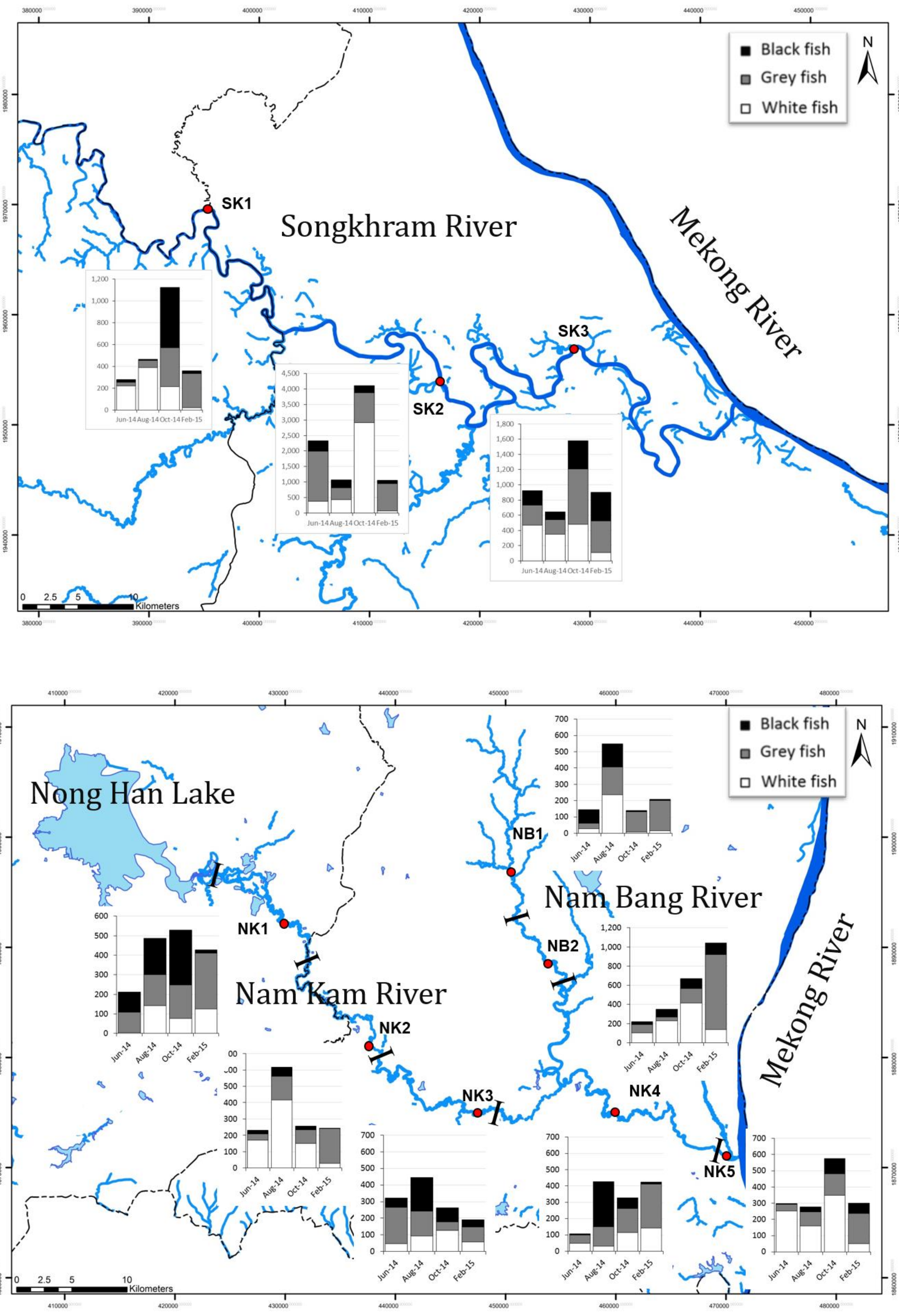


Figure 4.7 CPUE by weight of fish in the Nam Kam River system and Songkhram River in difference operating time from June 2014 – February 2015.

To conclude, fish abundance by number and weight in the Nam Kam River system was mainly dominated by grey fish on most sampling occasions. Composition of fish changed after the watergates were opened, and the fish assemblage was dominated by white fish that had migrated upstream from the Mekong and adult white fish occupied floodplain along the river. Timing of white fish migration into the Nam Kam River system is delayed compared with the free flowing Songkhram River, in which fish could migrate as soon as they are stimulated by environmental cues. When water receded, white fish already migrated to downstream refuge areas, therefore the fish assemblage was dominated by grey fish again at the end of flood season. Thereafter, larval and juvenile fish that spawned and developed in the upstream floodplain drift to downstream rearing grounds while some small fish take feeding migrations to the upstream area after the migration was observed at the downstream fish pass. Some adult white fish were stranded in the river section once the watergates were completely closed. The mainly differences in composition of fish between the regulated Nam Kam River and free flow Songkhram River was the ability of fish to migrate freely downstream to their refuge area in the Mekong River when the water receded.

4.4.6 Catches and distribution of target species

Two target species for the genetic study, *Hemibagrus nemurus and Osteochilus hasselti,* were commonly observed at all sampling sites in the Nam Kam River. The highest abundance and biomass of *Hemibagrus nemurus* were found at the most downstream sampling site, which connected to the Mekong River, NK5, in October (30 fish/100^2m/night and 346 g/100m^2/night). *Hemibagrus nemurus* was mostly observed after the watergates were opened in the flood season (August), except at NB2 where fish were observed since the onset of flood season (June). *Osteochilus hasselti* at all sampling sites showed the highest biomass at the dry season (February). The highest abundance and CPUE by weight of *Osteochilus hasselti* were observed at NB2 in February (138 fish/100^2m/night and 2,128 g/100m^2/night).

In terms of distribution of fish in Songkhram River, distribution of *Hemibagrus nemurus* was observed at in the river system (SK2) after the onset of the rainy season (June) while *Osteochilus hasselti* were also observed at the upstream sampling site (SK1-2) at the onset of rany season. The downstream migration of target species was indicated by the high catch observed after the end of flood season and in the dry season at the downstream sampling sites (SK2-3).

4.5 Discussion

Fish species diversity, abundance and fish assemblage in the Nam Kam River system was considerably modified by construction and operation of the series of watergates. The main effects were:

- Hydrological changes during the flood season caused by the watergate operation, result in intense flow and turbulence impeding the upstream migration of fish through the sluice gate.
- Timing of the flood pulse changed according to the operation schedule and is not harmonize with the spawning migration of fish from Mekong River which is triggered by water levels rise. This delayed the migration of fish into the river system at the onset of rainy season.
- Watergate operation impounded water above the watergate resulting in habitat change from a running river to lacustrine habitat. New habitats are not suitable for some groups of fish, like white and grey fishes and some habitat becomes disconnected from the mainstem resulting in habitat loss.
- The watergate structure obstructed both upstream and downstream migration of fish, especially when it was closed to store water in dry season.

All of these factors impact on the migration of fish which is key impact on diversity and population structure of fish in the river system.

4.5.1 Do watergate and fish pass operations impact on fish species diversity and population structure in the Nam Kam River system?

In total, 136 species of fish were recognised as having the ability to migrate upstream through the fish passage facilities (Pongsri *et al.,* 2008; Ngoichansri *et al.,* 2013, unpublished and this study), but just 78 species were observed at the upstream area of the river system in 2014, and some were rare. The diversity of fish in the area above TNNM from this study (60 species) was higher than Phomikong *et al.* (2014), probably because the current study sampled a greater area and included the Nam Bang, the main tributary of the Nam Kam and used a different sampling method. It should also be noted that overall diversity in the Nam Kam River system (54 and 112) was lower than the Songkhram River (Phomikong *et al.,* 2014). It is lower than diversity of fish in the Middle Mekong Migratory zone, which is about 386 species from 42 families and the other nearby tributaries including Songkhram River (216 sp. 40 families), Xe Bang Fai (157 sp. 31 families), and Xe Bang Hieng (180 sp. 33 families; ICEM, 2010).

The flooded area above TNNM had a less diverse fish fauna than in the downstream area and also less than the unregulated Songkhram River (Table 4.3). The relative abundance of white fish was significantly different between the floodplain above and below TNNM during the study period (Table 4.9 and Figures 4.4-4.5). For example, 15 white fish species were not observed in the area above TNNM (Table 4.4), especially main channel resident fish such as *Probarbus jullieni, Pangasius larnaudii,* and *Cyclocheilichthys enoplos*, main channel spawning species such as *Phalacronotus bleekeri, Pangasius macronema, Labeo chrysophekadion, Hemibagrus wyckioides, Pseudolais pleurotaenia, Tenualosa thibaudeaui, Kryptopterus macrocephalus* and *Osteochilus melanopleura*, the floodplain spawner *Mystus bocourti* and rithron resident *Raiamas guttatus.*

The lower abundance or absence of these common white fishes and any migrating species, especially main channel resident fish and main channel spawning species in the upstream area most likely resulted from alterations to the natural hydrological regime by the watergate operation, although effective fish passage facilities were installed at each watergate. Main channel resident and main channel spawning species are the most likely groups to be impacted by the watergate operation because they undertake longitudinal migrations from refuge habitat downstream to their specific upstream spawning habitats during the rising flood period before returning with the young of the year to downstream feeding, nursery and refuge habitats in the dry season (Welcomme *et al.,* 2006; Halls & Kshatriya, 2009). However, the number of fish species, and catches by number and weight, increased at almost all upstream sampling sites above TNNM when the watergates were opened to their maximum capacity in August (Figures 4.4-4.6, Table 4.9). This was caused by the occurrence of cyprinid white fish and some grey fish species that migrate upstream to spawn in the wet season.

In addition, it should be noted that young of the year fish that recruited in the 2013-2014 spawning season also contributed to the fish assemblage in the floodplain above the upstream watergate. These species included *Puntioplites proctozystron, Barbodes gonionotus Cyclocheilichthys apogon, Labiobarbus siamensis, Mystus mysticetus, Osteochilus hasselti,* and *Hampala macrolepidota*. It is important to note that this increase in number and abundance of species are the same species that have been reported to undertake upstream migration from the Mekong River through the most downstream fish pass at the onset of rainy season in 2012 and 2013; species that were mature and ready to spawn (Ngoichansri *et al*., 2013, unpublished). Results from this study suggest that opening the watergates in the migration period of the majority of Mekong fish could maintain species diversity and increase fish population size in the Nam Kam River system. However, this situation will need to be repeated year on year, as recruitment of fish will depend on watergate operation in each particular year relative to the flooding cycle.

Similar declines in species distribution and abundance were reported after Pak Mun Dam was constructed on the largest tributary of the Mekong in Thailand. Roberts (1993) found that the number of fish species in the Mun River decreased from 121 species in 1967 to 66 species in 1981 and 31 species in 1990, and fishing yield also declined. Amornsakchai *et al.* (2000) found at least 50 species of fish disappeared. The declining and disappearance of migratory fish in the river to Pak Mun Dam operation and, importantly, the reservoir fisheries created did not compensate the losses caused by dam construction. The dam also had negative impacts on the ecology and fisheries in the middle and lower Mekong basin not just in the Mun River and its tributaries.

4.5.2 Do watergate and fish pass operations impact on fish distribution?

Although the diversity of fish in the upstream area increased after the watergates were opened, 16 key species were not found in the area above the TNNM that were found below the watergate. These were mostly white fish (15 species) which normally migrate in and out of the tributaries of the Mekong River (Table 4.4). Furthermore, 13 key species that were reported to migrate as mature fish through the most downstream fish pass at TNNM to spawn in the Nam Kam River at the onset of rainy season (Ngoichansri *et al.,* unpublished) were rarely reported upstream. Among these, *Labeo chrysophekadion*, *Phalacronotus bleekeri, Pangasius larnaudii* and *Cyprinus carpio* were rarely observed in upstream floodplains, while nine white fish species (*Probarbus jullieni, Pangasius macronema, Cyclocheilichthys enoplos, Hemibagrus wyckioides, Pseudolais pleurotaenia, Tenualosa thibaudeaui, Osteochilus melanopleura, Mystus bocourti,* and *Raiamas guttatus*) had not been observed in the upstream area of the Nam Kam system between 2012 and 2015 (Ngoichansri *et al.,* 2013*,* unpublished; Phomikong *et al.,* 2014 and this study), despite fish being able to migrate upstream via the fish pass. Seven of nine of these species have, however, been found in other nearby Mekong tributaries such as the Songkhram and Mun Rivers (Phomikong *et al.,* 2014). This suggests that upstream migration of nine white fish species from the Mekong into the Nam Kam River system might, to some extent, be affected by the watergate operation although fish passage facilities are provided. Similarly, two key pangasids typically found in this region (*Pangasius larnaudii* and *Pangasius macronema*) have been rarely observed upstream of TNNM since it became operational in 2012 (Pongsri *et al.,* 2008; Ngoichansri *et al.,* 2013*,* unpublished; Phomikong *et al.,* 2014 and this study). Similarly, pangasids were also rarely observed above the lowest dam in the Mun River (Jutagate *et al*., 2002) but were common in the unregulated Songkhram River (Phomikong *et al.* 2014) and mainstem Mekong River (Poulsen *et al.,* 2004). Migration of pangasid species in the Mekong River basin is normally triggered by water level rise and flow changes and usually dominate the catches at this time (Jutagate *et al.,* 2002, Jutagate *et al.,* 2012; Cowx *et al.,* 2015). Absence or rare occurrences of pangasids species above the TNNM, which are economically and biologically important in the Mekong River Basin (Dugan, 2008) indicated that upstream spawning migrations of this group are disrupted by watergate operation.

This was supported by loss in fish species diversity with increasing number of barriers in the river (Table 4.3), with the most upstream section that was obstructed by more barriers exhibiting lower species diversity than the downstream area of TNNM. Phomikong *et al.* (2014) found that species diversity in the Mun River with only one dam was higher than in rivers with a series of obstructions (the Nam Kam River). Similarly, Amornsakchai *et al.* (2000) found fish diversity in the upstream area of the regulated Mun River lower than the downstream area.

Perhaps one benefit of the barrier effect is control of introduced species like *Cyprinus carpio, Clarias gareipinnus,* and *Clarias macrocephalus x Clarias gareipinnus.* These were rarely found above TNNM, and only in the wet season. These structures may act as a barrier that limit their dispersion and thus protect the endemic species from competition with alien species. Flow regulation might impact alien species like *Clarias gareipinnus,* and *Clarias macrocephalus x Clarias gareipinnus* as they need flooded areas for their spawning ground (IUCN, 2010) and the modified systems restrict access to this type of habitat and the free flowing system in the wet season means the impoundment is possibly not conducive to breeding. Although some species like *Cyprinus carpio* exists into two forms, lacustrine and riverine strains, and benefits from their plasticity (migratory/sedentary capacity) to adap with the changed environment, high discharge caused by watergate operation might flush out these introduce species at the peak of flood season. Regardless, the spread of alien species in the impounded areas is cause for concern, especially in the dry season.

Despite the Nam Kam River being apparently unobstructed for free migration of fish during the nominal migration period at the start of the flood season, species are clearly unable migrate throughout the system. This may arise because fish can only use the fish passage facilities when the sluice gates were closed or partially opened in the wet season. Upstream migration of fish was only totally unobstructed when the watergates are fully open in the wet season. However, Warren *et al.* (1998); Poulsen *et al.* (2004) and Jutagate *et al.* (2005) suggested that upstream migration of fish from the Mekong River into the tributaries also occurs outside the wet season. There is evidence from the species richness and CPUE that fish migrate at other times of the year (Warren *et al.,* 1998; Poulsen *et al.* 2002), albeit it in lesser abundance and the duration of migration is also less than at the onset of rainy season. The species that migrate at this time include the same species that migrate at the onset of the wet season (Chapter 7: Migration).

Although most fish species in Mekong River Basin spawn in the wet season, there is some variation related to trophic/dispersal patterns of migratory species; for example, *Probarbus jullieni* and *Hypsibarbus malcomi* usually spawn in the dry season and juvenile fish migrate into the Mekong tributaries for feeding in the flood season (Warren *et al.,* 1998; Poulsen *et al.,* 2002). Ngoichansri *et al.* (unpublished) also reported that migration of fish from the Mekong River occurred during the flood season but another peak of migration has been found at the end of flood season in October. In this study, juvenile *Probarbus jullieni* between 88-182 mm were only observed in the downstream area while *Hypsibarbus malcomi* was successful in migrating upstream to their feeding grounds in the upper Nam Kam River System. It appears that some species are able to complete their feeding migrations whilst others are obstructed. The variability may arise because some species such as *Hypsibarbus malcomi* are able to use the fish pass facilities whilst others not. For example, both species have been observed at the TNNM fish pass in both 2012 and 2013, but only *Hypsibarbus malcomi* was observed in the upstream area in 2014. However, *Hypsibarbus malcomi* need to adapt to the modified habitat during the dry season due to the watergates being closed around October-November.

Similarly, *Pangasius larnaudii, Pangasius macronema, Mystus bocourti,* and *Phalacronotus bleekeri* (white fish species) have never been observed in the Nam Kam River system before the end of the flood season and in this study were only observed in the most downstream area connected with the Mekong River, suggesting they are late migrating species and their size, ranging between 115 to 223 mm, suggests they are mature fish. Upstream migration of these species was likely obstructed by TNNM sluice gate operation because two of the four sluice gates were already closed at the end of the wet season and the others were only partially open with a narrow gap of about 0.2-0.5 m, which would restrict migration because of the intense flow velocity (4.4-197.11 m/s). Ngoichansri *et al.* (unpublished) also did not find *Probarbus jullieni, Pangasius macronema* and *Mystus bocourti* in the area upstream of TNNM while mature *Pangasius larnaudii* (size ranging between 550-760 mm) were observed just once at the end of flood season in the area upstream of TNNM, although the species was able to migrate via the fish pass in 2012 and 2013 and had a chance to migrate through the opened watergate in the flood season. This is supported by the absence of larval and juvenile pangasids above the TNNM in the same year (see Chapter 5). Additionally, *Pangasius macronema, Pangasius larnaudii* and others pangasids species were not observed above the regulated lower head dam in the Mun River but they were observed in the Songkhram River, an unregulated Mekong tributary (Phomikong *et al.,* 2014), and also in the mainstem Mekong (Poulsen *et al.,* 2004).

In addition to upstream migration being impacted by watergates, downstream migration of adult and juvenile fish is also obstructed, especially at the end of the rainy season. Adult white and grey fish can become stranded in the section above each watergate when all sluice gates are completely closed. Species that spawn late around October to November have no opportunity to migrate back downstream and their larvae cannot drift downstream due to all the watergates being closed; eggs and larvae are stranded in each section and have to develop in that area until the next rainy season. Therefore, fish need to adapt to the new static water conditions and occupy that particular area as rearing and refuge habitat during the dry season or be lost from the system. The ability of fish to adapt to and tolerate the new habitat depends on the quality of feeding and reproductive habit for each species and their ability to exploit the new conditions, as well as tolerate the fishing pressure in the area.

A further problem arises because *Pangasius larnaudii, Pangasius macronema* and *Probarbus jullieni* spawn on gravel habitats in rapid flowing areas; therefore this group of species is at risk after the watergate construction on the Nam Kam River because of inundation of spawning habitats due to closure of the watergates. A similar demise was observed following closure of Pak Mun Dam, where a 50-100% decline in fish catches of these species was recorded and catches of many other fish species also declined both downstream and upstream of the watergates (Amornsakchai *et al.,* 2000). Roberts (2001) concluded that dams obstruct fish migration and can lead to stock depletion and local extinction. Consequently there is concern about conservation of the stocks of these four white fish species because of the damming of the Mekong tributaries, especially *Mystus bocourti,* which is a floodplain spawner and needs to migrate into the Mekong tributaries to spawn in floodplain habitat to complete its life cycle (Halls *et al.,* 1998).

4.5.3 Seasonal variation in fish population structure and watergate operation

Abundance and catches of migratory fish species, especially white fishes, fluctuated during the year. After the Nam Kam River system was regulated by a series of watergates, the hydrological regime in Nam Kam River has become dependent on watergate operation. Timing of the flood has been delayed, short duration, high flood pulses are more frequent, water is impounded in the river system longer and water level is higher than under natural conditions (see Chapter 3). These changes have had an impact on the distribution of fish in this river system.

Watergate operation has impounded water at the onset of the rainy season for flood control purposes, which impacts on the upstream migration of fish. During this period, the relatively high abundances of white fish species were observed in the area below TNNM and also on the floodplains in the unregulated Songkhram River, supporting the observation that fish migrate into the tributaries when the Mekong water level rises. Most fish species in the Mekong basin are flood spawners that migrate to the tributaries as the water level increases at the onset of rainy season (Bao *et al.,* 2001; Poulsen & Valbo-Jørgensen, 2000; Poulsen *et al.,* 2004; Hortle, 2009) and any impediment to migration will potentially disrupt this migration cycle. The relatively low abundance of fish in the floodplain above of TNNM at the onset of the rainy season associated with this natural spawning migration period indicates that fish cannot migrate into the Nam Kam River system because TNNM is not fully open. Furthermore, under natural conditions most pangasids and silurids in the Mekong River Basin migrate in the wet season (June to July) (Poulsen *et al.,* 2004; Jutagate *et al.,* 2005). However, during the present study, some fish species in these groups, for example *Hemisilurus mekongensis*, *Wallago attu* and *Micronema cheveyi*, were caught at the onset of the rainy season in the Mekong tributaries, but in the Nam Kam system they were mostly caught between August and October after the watergates were opened. This suggests that the upstream migration was obstructed by watergate operation and timing of upstream migration into the regulated river was delayed. Fish are, however, able to migrate upstream through the fish pass when operational and consideration should be given to opening the fish pass early to accommodate migration of fish until the watergates are fully open.

A good example is the upstream migration of the main channel spawning species, *Micronema cheveyi*. The species is a main channel spawner that has been observed migrating from the Mekong River to its floodplain/tributaries for spawning in the rainy season (Poulsen & Valbo-Jørgensen, 2000). *Micronema cheveyi* was observed in the Songkhram River and at the area below TNNM in June, but it was only observed in the upstream floodplain after the sluice gates were opened (August). This represents a two-month delay to the area above the TNNM compared with the unregulated Songkhram River, despite the two rivers having the same rainfall patterns and natural hydrological regimes. The Songkhram River is free flowing with no obstacles on the mainstem , therefore Mekong fish can migrate into the river as soon as any migration cue, for example rainfall causing an increase in water level or flow changes, triggers their migration. It should be noted that even when the watergates were opened a little (0.05-0.10 m), it would create high discharge between 10.86-41-57 m^3/s, migration of fish through the sluice gate was impeded because the high and fluctuating flows created by the watergate operation were not suitable for fish to migrate through.

The white fish assemblage increased in the flood season at the upstream floodplains (SK1-2) due to upstream migration of fish stimulated by rainfall and water level changes. When water level receded at the end of flood season, fish return from the floodplain to the mainstem increasing the abundance of white fish in the downstream floodplains (NK2-3; Table 4.9). In the dry season (February), a diversity of white fish, abundance, and CPUE declined due to fish already migrating down to refuge areas in the Mekong River, while the number and relative abundance of grey fish species was still high at all sampling sites (Table 4.9 and Figures 4.4-4.6). However, fish assemblage of the regulation river is differs from the free-flowing river. At the onset of rainy season, the composition of fish at the floodplains above TNNM (NK1, NK3-4 and NB1-2) was mostly grey fish that was stimulated by water discharge changes from watergate operation and take early lateral migration to the floodplain to occupy habitat and spawn as soon as rainfall, flows and water level changes triggered migration (Table 4.9). Composition of fish at NK2 was mainly contributed by white fish that probably migrated early through the fish pass at the onset of the rainy season (Table 4.9 and Figures 4.4-4.6). However, the number of species and fish assemblages at the downstream floodplains, NK4-5 was dominated by black and grey fish (Table 4.9). This suggests that white fish move to optimal floodplain spawning habitat further upstream (NK1-3 and NB1-2) instead of occupying the lower floodplains (Figures 4.4-4.6) at the onset of rainy season.

After the watergates were opened in the flood season, the fish assemblage in the regulated Nam Kam River became similar to the unregulated Songkhram River. The relative abundance of fish, especially migratory white fish, increased in the upstream floodplains, such as from below SRWD to above NAKO (NK1-3) and above BATA

(NB1), while the relative abundance of white fish in the downstream habitats, such as above NABU and from below NAKO to the area downstream of TNNM (NB2 and NK4-5) increased when the water receded at the end of the flood season (Figures 4.4-4.6). This was similar to the seasonal variation in fish assemblages in the Songkhram River; high catches were observed in the upstream floodplain at the onset of rainy season indicating upstream migration of fish and then relative abundance was higher in the downstream floodplain at the end of flood season indicating downstream dispersal of some adult fish (Table 4.6).

Relative abundance of white fish in the Songkhram River floodplains declined in the dry season suggesting fish had migrated from the floodplains as the water level recedes. However, this was not the case in the Nam Kam River system because downstream migration was obstructed by watergate operation. Relative abundance of white fish in the Nam Kam River system declined in some sampling sites (NK2-3 and NB1), indicating some white fish migrating downstream to the Mekong River before the most downstream sluice gate was closed, but some were stranded in the permanent floodplains or sections above the watergates, for example in the NK1, NK4 and NB2 floodplains. One advantage of the watergates being closed in the dry season is that water levels remain high and the floodplain habitats are maintained for prolonged periods (Figure 3.13) therefore fish can use these areas in the dry season. Fish species composition in dry season in the Nam Kam River still included some white fish, although the top ten fish species by abundance and catches were dominated by grey fish (Table 4.10). Phomikong *et al*. (2014) also found that the contribution of whitefish in dry season in the Songkhram River was replaced by grey and black fish. Rapid fluctuations in water level and flow caused by the watergate operation could, however, disrupt fish recruitment processes and lead to stranding of fish on the floodplain (Petts, 1984), and potentially account for the lower abundances of whitefish and other fish species in the Nam Kam system.

4.5.4 Adaptation of fish to hydrological changes and modified habitat in the Nam Kam River system

Signs of fish adapting to the hydrological and habitat changes were observed during the watergate closure period. After the sluice gates were closed at the end of the flood season, black fish and some grey fish were able to remain in each floodplain due to the impounded water. These groups of fish are more tolerant to the hydrological and habitat changes than white fish (Welcomme *et al.,* 2006). Grey fish typically move from the floodplain to the main river and spend their dry season in the main river or the river margins while black fish are resident in the remaining floodplain habitat or sometimes inhabit the main river channel when the wetlands dry up. However, some species of white and grey fish were stranded in the floodplains above the watergates and show tendencies to adapt to occupy the floodplain as refuge and rearing habitat during dry season. For example *Cirrhinus moritorella* and *Notopterus notopterus* were observed in NK1, *Thynnichthys thynnoides, Puntioplites proctozystron, Cyclocheilichthys apogon,* and *Hampala macrolepidota* in NK2 and *Dangila lineatus* in NK3, *Puntioplites proctozystron, Sikukia stejnegeri, Dangila lineatus* and *Osteochilus hasselti* in NK4, and all were able to survive the new lacustrine conditions.

Small white and grey fish (1+ year fish), like *Puntioplites proctozystron, Sikukia stejnegeri, Thynnichthys thynnoides, Dangila lineatus, Cyclocheilichthys apogon, Kryptopterus cheveyi, Hampala macrolepidota, Hampala dispar,* and *Osteochilus lini* were also observed in the three floodplains above TNNM (especially NK1-3) in June before the watergate was open. These are generalist fishes, floodplain and main channel spawners that use the floodplain as feeding and nursery habitats. Their presence suggests that larvae and juvenile of resident species can breed and survive in each section while the watergates are still closed in the dry season. Moreover, it is likely that the longer the floodplains are inundated because of the closure of the watergates the greater the benefits for larval development and fish feeding (Baran *et al*., 2006).

In addition, juvenile and small fishes of many species were observed in the NK1, NK3, and NK4 in October and November. These included white fish (*Puntioplites proctozystron, Sikukia stejnegeri, Henichorhynchus siamensis, Cyclocheilichthys armatus, Dangila lineatus*) and grey fish (*Osteochilus lini, Hampala macrolepidota, Barbonymus schwanenfeldii* and *Puntius brevis*) and larvae and juveniles of multiple spawning and continuous spawning fishes, for example, *Osteochilus hasselti, Barbodes gonionotus, Crossocheilus siamensis, Cyclocheilichthys apogon, and Mystacoleucus marginatus.* These fish species probably spawned in the late flood season and the larvae could not drift downstream to the Mekong River because the TNNM gates were already closed in mid-October, although the other upstream watergates were still open until the end of November, thus these larvae and juvenile fishes still have the possibility to drift or move down to the big floodplain above TNNM (Kud La-A: NK4). However, these small fish need to adapt to occupy this floodplain as nursery and rearing habitat during the dry season. This was supported by growth of fish, and bigger fish were also observed at the same area in February 2015. The quality of the stock that develops in the inundated floodplain area may, however, not be as good as the stocks in the unregulated river because the river system has changed characteristics to a lacustrine system. Stranded adult fish in each section also might not be good broodstock in terms of genetic integrity and might lead to a bottleneck and small genetic population size (see Chapter 6 for further details on genetic diversity, population size and population structure). Water quality in the impounded area during the closed period also needs to be monitored as deterioration in the dry season because of high temperatures, evaporation, algal blooms and degradation of organic materials may impact on larval development and fish survival.

Finally, late migrating species that migrate upstream at the end of flood season might adapt by returning to the Mekong River or find alternative spawning habitat, although this is likely to be low quality habitat. Unfortunately, no mature fish or eggs and larvae of the four main species; *Pangasius larnaudii, Pangasius macronema, Mystus bocourti,* and *Phalacronotus bleekeri,* were found in the downstream area during the period of study.

4.6 Summary

Species composition of the fish assemblage in the regulated Nam Kam River was different from the unregulated Songkhram River. Relative abundance of fish caught in the area above the Thoranit Naruemit watergate was lower than the downstream area which connects to Mekong River and also lower than the Songkhram River. The presence of barriers in the Nam Kam River system has affected the distribution and diversity of fish in the river, and most of the sections obstructed by watergates had low species diversity. White fish diversity and abundance was significantly different between above and below the Thoranit Naruemit Watergate in the flood season.

Fish species composition was modified by watergate operation, and was dominated by the occurrence of cyprinid white fish and some grey fish species that migrate upstream to spawn in wet season so the fish assemblage in the Nam Kam River system became similar to that of an unregulated river. However, the abundance of white fish declined at the end of the flood season as a result of downstream migration of white fish when the water level receded. Upstream and downstream migration of fish in dry season was blocked by the closure of the sluice gates. Larval and juvenile fish that could not drift downstream to the refuge area were stranded in the river section above the watergate and show tendencies to adapt to occupy the impound habitat.

It can be concluded that the lower abundance or absence of other migrating species in the upstream area mostly likely resulted from watergate management that altered the natural hydrological regime and restricted fish migration, which is the main factor for discriminating species composition in the river system. Although fish passage facilities are provided at all watergates and most fish species are able to migrated through the fish pass and the opened sluice gate, upstream migration of nine white fish species (*Probarbus jullieni, Pangasius macronema, Cyclocheilichthys enoplos, Hemibagrus wyckioides, Pseudolais pleurotaenia, Tenualosa thibaudeaui, Osteochilus melanopleura, Mystus bocourti,* and *Raiamas guttatus*) from the Mekong into the Nam Kam River system appear, to some extent, to be affected by the watergate operation. These species have not been observed in the upstream area of the Nam Kam system between 2012 and 2015. Upstream migration of late migrating species; *Pangasius larnaudii, Pangasius macronema, Mystus bocourti,* and *Phalacronotus bleekeri*, was obstructed by the watergate closing at the end of flood season. Upstream migration of some pangasids and silurids was delayed by watergate and fish pass operation.

The upstream migration of fish is supported by fish passage facilities and the opening of the sluice gates in the wet season. Timing of sluice gate operation is very important to support upstream migration of fish from the Mekong River. Opening should be associated with the main spawning migration of fish from the Mekong River to support accessibility into the river system. Relative abundance of fish in most of the floodplain increased when the watergates were opened to the maximum capacity in the wet season. This suggests that if the watergates are opened in the spawning season of most Mekong fish species migration is possible, thus supporting recruitment and maintaining population abundance in the river system.

Chapter 5: Spawning and nursery grounds in the Nam Kam River system

5.1 Introduction

In tropical river systems, many fish species (typically referred to as white fish species) migrate upstream and spawn in the upstream reaches and tributaries, with the eggs and larvae drifting back downstream to feed and grow in the main river and floodplains (Poulsen *et al.* 2002, 2004,). Some groups of fish (grey fish) also migrated laterally for breeding and feeding; generally moving from the mainstem to the highly productive floodplains at the onset of the rainy season. This movement is undertaken by adult fish for breeding (grey fish guild) and young fish and adult fish that move downstream from upstream breeding areas (white fish guild). In addition, there is a group of fish that inhabit the floodplain water bodies but exploit the flooded area in the wet season for feeding and breeding, typically known as black fish (Poulsen *et al*. 2002; Welcomme 1985, 2001; Welcomme *et al.,* 2006).

Dam construction on mainstem rivers can cause disruption of ecosystem functioning, altering river hydrology in upstream and downstream areas, affecting water quality and quantity and aquatic ecology by flooding spawning and nursing grounds, thus disturbing fish recruitment. Moreover, dams block fish migration routes (Hellan-Hansen *et al.*, 1995; Postel, 1997; Barlow *et al.,* 2008; Baran & Myschowoda, 2008; Larinier, 2012), disrupting fish species composition, abundance and diversity as well as size structure of the community (Starr, 2009). This is particularly the case in the Mekong River system, where most fish catch is based on long distance migratory species that migrate along the mainstem and the tributaries. Most Mekong fish are flood spawners: adult fish migrate into the Mekong tributaries or upstream reaches for their spawning when flood waters rise and fish larvae grow in the free-flowing tributaries after hatcing and before drifting downstream from those habitats (Hortle, 2009), so this mechanism will be potentially lost, and the recruitment processes distrupted. Thus these stocks are vulnerable to dam construction on the Mekong mainstem and tributaries (Barlow *et al.,* 2008; Baran & Myschowoda, 2008).

Several authors have investigated fish stocks and migration of fish through fish passes along the Nam Kam River (Srisatit *et al.*, 1981; Pongsri *et al.,* 2008). Ngoichansri *et al.* (2013) found that mature fishes migrated from the Mekong River into the Nam Kam River system at the onset of the rainy season and migrated further upstream into both the Nam Kam and Nam Bang, while juveniles of a number of species were also been observed migrating upstream through the most upstream fish pass to Nong Han Lake a few months after the onset of upstream migration of mature adults. However, little attention has been given to the distribution of larvae in the river system, Phomikong *et al.* (2014) studied fish diversity and assemblages and found the high proportion of larvae in flood season in this river system, Rukeawma and Nachaipram (2013) revealed that there were 42 species of larval and juvenile fish in the Nam Kam River in 2012 and the greatest abundance of early life stage was found at the upstream area of the river but none have mentioned spawning areas, rearing grounds and distribution of fish larvae in the whole Nam Kam system, or the impacts of watergate operation on spawning migration and these key habitats the Nam Kam River system.

Therefore, to gain an understanding of fish production and recruitment in the Nam Kam and its tributary, it is important to identify spawning and rearing grounds along the rivers and investigate the temporal aspect of spawning (timing, duration and frequency in relation to environmental variability), juvenile recruitment processes throughout the river, as well as assess the effects that watergate operation could have on recruitment. The relative abundance of fish larvae and juvenile fish at the different locations would provide a measure of the importance of different stretches of the river for fisheries production.

5.2 Aims and Objectives

The aim was to determine the key spawning areas, rearing grounds and recruitment processes through assessment of the distribution and relative abundance of larval and juvenile fishes in the Nam Kam River system and the likely impacts that watergate operation may have on these key recruitment features.

The objectives of the study are:

1. Assess larval and juvenile fish distribution throughout the study area and monitor shifts in community structure, especially in the spawning period.
2. Identify spawning and nursery ground in the Nam Kam River system based on the distribution of larval and juvenile life stage.
3. Determine the characteristics of spawning migrations in the river in relation to fish production by determining the proportion of fish migrating via the most downstream fish pass and each identified main rearing habitat along the river that contributes to fish stock migrating to the upstream Nong Han swamp.
4. Assess likely impact of watergate and fish passage operation, and environmental variables on diversity and recruitment of fish in spawning and nursery grounds in the Nam Kam River and its tributary.

5.3 Methodology

5.3.1 Sampling and data collection for larval and juvenile fish

Fish larvae sampling sites were chosen to represent four floodplains in different sections of the Nam Kam and Nam Bang Rivers that have the potential to be spawning or rearing grounds (Table 5.1 and Figure 5.1). All these sites were located in mainstem of river for conical net drift sampling and/or floodplains between watergates for seine net sampling. Three sampling sites in the unregulated Songkhram River were included for comparison.

Table 5.1 Locations of seine net sampling sites and conical net sampling site for fish larvae and juvenile along the Nam Kam River system.

Sampling sites		Locations	
Seine net sampling sites			
DK	Ban Dan Muang Kham Village	431272.23 E	1891104.64 N
NK	Na Koo Village	449212.00 E	1875313.00 N
KA	Kud La-A	459722.68 E	1873848.22 N
NB	Na Bua Village	455101.00 E	1887000.00 N
TH	Ban Tha Pan Hong village	395689.01 E	1969528.40 N
KS	Kud Sing	416237.00 E	1953827.00 N
HA	Huay Auan	427868.21 E	1956797.07 N
Conical net sampling sites			
B1	Ban Dan Muang Kham Bridge	431272.23 E	1891104.64 N
B2	Na Bua Watergate	455182.00 E	1886792.00 N
B3	Na Koo Watergate	449492.00 E	1875405.00 N
B4	Tha Lad - Pak Bang Bridge	456493.80 E	1878802.46 N
B5	Ban Tong - Fang Dang Bridge	466419.57 E	1872043.41 N
B6	Ban Tha Pan Hong	395689.01 E	1969528.40 N
B7	Kud Sing	416237.00 E	1953827.00 N
B8	Huay Auan	427868.21 E	1956797.07 N

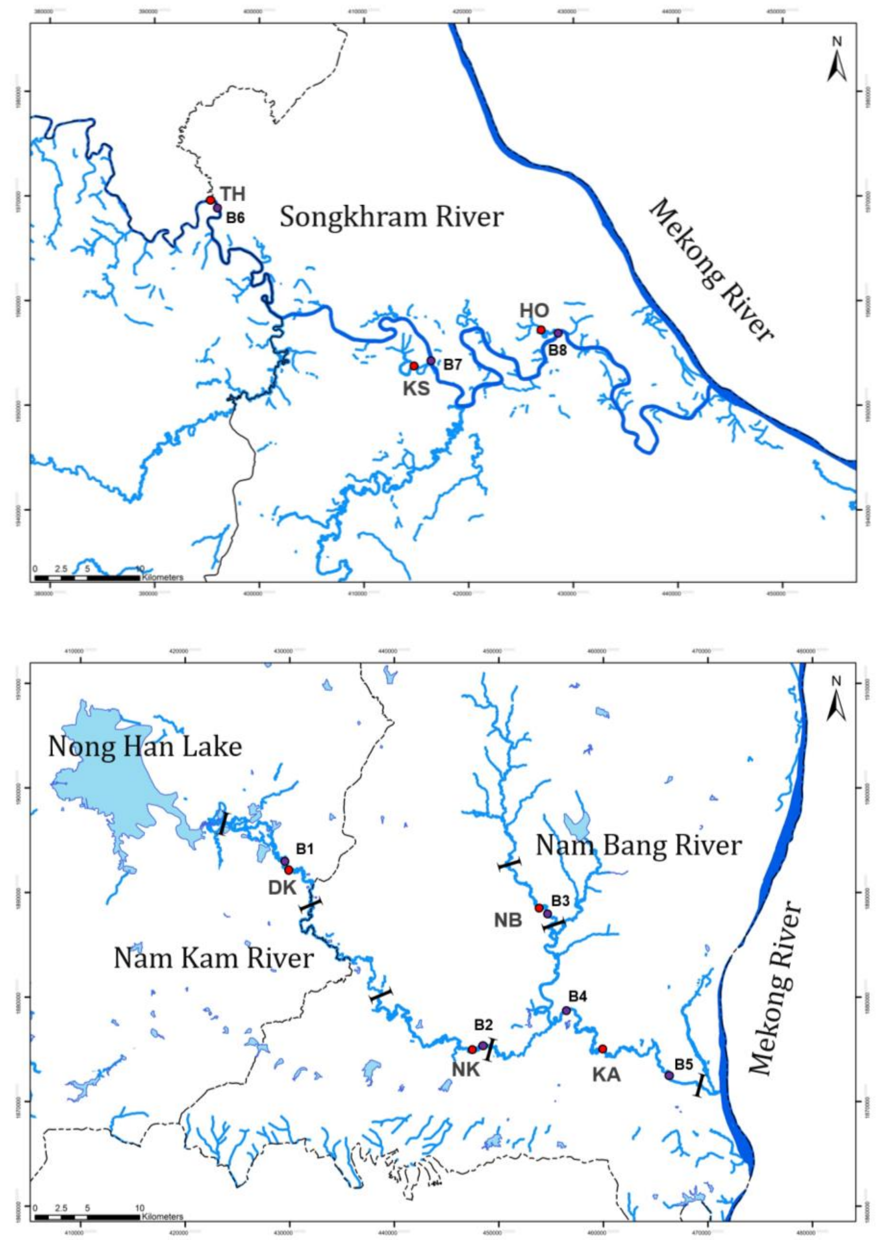


Figure 5.1 Location of larval and juvenile sampling sites in the Nam Kam River system (red dots represent seine net sampling sites; purple dots represent the conical net sampling sites).

Sampling was undertaken monthly during the peak period of recruitment associated with the flood period (July to November 2014). This was associated with the hatching period, drifting of eggs and larvae, and dispersion of juvenile to understand recruitment dynamics and contribution of juveniles to adult stock, and to account for seasonal hydrological events.

Fish larvae and juvenile samples were collected using micromesh seine netting and conical nets (Figure 5.2). Micromesh seine netting was carried out in the flooded area on each occasion. The conical net which target early life stage larvae and drifting eggs was set 30 cm below the surface (30 min x 2 replications) in open water at each sampling site. For comparative purposes, a flow meter was placed in the mouth of the conical net to quantify filtered water volume. The samples were preserved in 40% formalin for a week and then transferred to 70% ethanol. In addition, juvenile fish and small fish data collected from the smallest mesh size of gill net sampling (20 mm) in Chapter 4 were used to indicate potential rearing grounds.

All fishes were identified to highest taxonomic level (preferable species) using field guides (Rainboth, 1996; Termvidchakorn, 2003a, b; Termvidchakorn & Hortle, 2013). Size and number of larval and juvenile fish catches in each site were recorded. The relative abundance of fish species was defined as the number of individuals per unit area of seine net (individual/100 m^2) or unit volume of conical net (individual/100 m^3). Seine netting sampled juvenile fishes more effectively and provided greater information about the growth and recruitment processes in different sections of the river in relation to habitat variability.

Figure 5.2 Photos of conical net (upper) and seine net (lower) sampling.

5.3.2 Data analysis

Diversity and distribution of fish

Differences in larval and juvenile fish population composition at multiple sites and shifts in population structure throughout the spawning season using seine netting were explored using the following tests.

1. The Shannon-Wiener (H') diversity index and Margalef's species richness index (d) and Pielou's measure of evenness (J) were applied to investigate spatial variations in diversity and evenness of larval and juvenile fish catches.
2. Similarity in larval and juvenile fish species composition between sites based on mean number of each larval and juvenile species (based on aggregation of catches in multiple samples taken at a site at each time) was investigated using a Bray-Curtis similarity matrix (Bray & Curtis, 1957), grouped and presented as a dendrogram using hierarchical agglomerative clustering (complete linkage). Overall similarity between each pair of samples was calculated and presented as Bray-Curtis similarity index (Cz) based on the occurrence of all species. Species compositions of each group were computed using SIMPER analysis performed in PRIMER, version 6.
3. Multi-dimensional scaling (MDS) analyses were used to determine population structure and the relationship between abundance of larval and juvenile fishes at the different sites and sampling occasions. MDS was also used to identify similarities between catches at different sites and occasions, which were tested as factors for discriminating the difference observed using PRIMER, version 6.

Spawning season, spawning ground and nursery ground

Mean length of the larval and juvenile fishes collected by conical net and seine net sampling in the 2014 flood season and some samples caught from the 20 mm gillnet panels from Chapter4 were used to estimate age and life stage of fish using the length for age (in days) keys (Termvidchakorn, 2003a, b; Poungcharean, 2008; Termvidchakorn & Hortle, 2013).

The spawning period of fish was back calculated from the sampling date or the date that fish was sampling and the ages of fish (approximately in days, weeks or months) estimated from the mean length of age as:

Julian date of spawning period = Julian date of sampling day – age of fish

Unfortunately, no drifting eggs and early life stage (york-sac larva and pre-larva) were collected in the conical net sampling, thus the spawning period of each species in this study were based on estimated age of post-larval and juvenile samples in the flood season, which is the peak spawning season of fish in the Mekong River Basin.

The spawning and nursery grounds in the Nam Kam River system were identified from the occurrence, abundance and changes in size distribution of larval and juvenile fish at each sampling sites and times were used to determine the spawning periods and spawning habitats of each species. The spawning ground was indicated from the presence of eggs or early larval stages although it was noted that later larval stages may have been dispersed from spawning sites by water currents, thus a simple drift model based on flow velocity was used to approximate spawning sites in the Nam Kam River system. The nursery grounds were identified as area where large numbers of post larval stage and juvenile fishes were observed from conical net, seine netting and 20-mm gill net. Key differences between each spawning and nursery ground in terms of contribution to the fish larvae drift and hence recruitment were identified from hydrological and habitat characteristics.

5.4 Results

5.4.1 Spatial distribution of larvae and juvenile fish

Diversity and abundance of fish larvae and juvenile fish caught by seine netting varied considerably between sampling sites. Most larvae and juveniles found in both the Nam Kam River system and Songkhram River were of the Family Cyprinidae (more than 40 species) follow by Cobitidae and Gobiidae (6 and 5 species). Larvae and juvenile fish of the Family Pangasiidae were not caught in the Nam Kam River system by seine or conical netting while individuals of the Family Siluridae and Bagridae were rarely observed. In total, 59 larval and juvenile species were observed in the Nam Kam River (54 species) and its tributary (24 species), while 61 species observed in the Songkhram River. The largest number of species was found at KA, the most downstream floodplain, (45 species) follow by NK (31 species), DK (27 species), which is located upstream in the Nam Kam River, and NB which is located in the Nam Bang River (24 species) (Table 5.2).

Common species found in all sampling sites were larval and juvenile black and grey fish species, including the main channel spawner *Clupeichthys aesarnensis,* floodplain spawners *Parambassis siamensis, Parachela oxygastroides,* and *Rasbora borapetensis* and generalist species; *Hampala dispar*. These fish were resident species in each section before the watergates opened in 2014. Abundance of larval and juvenile white fish, for example *Barbonymus gonionotus, Henichorhynchus siamensis, Labiobarbus lineatus, Puntioplites proctozystron* and *Mystacoleucus atridorsalis,* increased after the watergates were opened. Few economically important juvenile species were observed in the area above the TNNM: the main species were *Micronema micronema, Oxyeleotris marmoratus, Channa striata, Henichorhynchus siamensis, Hemibagrus nemurus, Osteochilus hasselti, Pristolepis fasciata, Hampala dispar* and *Hampala macrolepidota*. Most of them were black and grey fishes that normally migrate between the mainstem and floodplain and are well adapted to the impounded habitat.

Table 5.2 Number of species of larvae and juvenile fishes at 7 sites in the Nam Kam River system and Songkhram River in 2014.

Month	DK	NK	KA	NB	TH	KS	HO
Jul-14	8	15	20	12	6	17	5
Aug-14	14	15	28	6	19	28	23
Sep-14	10	10	14	11	18	13	11
Oct-14	5	13	17	12	10	12	5
Nov-14	12	13	15	3	5	7	4
total	27	31	45	24	36	49	29
	NK=59				SK=61		

PERMANOVA results revealed significant differences in species composition were found between each sampling location in the Nam Kam River ($P \leq 0.05$). Diversity of fish in the upstream floodplains of the Nam Kam River system (DK NK and NB) were lower than downstream (KA) in each sampling month and overall (Table 5.2). Moreover, the average number of species found in the Nam Kam River was less than in the Songkhram River (32 and 38). Similar to species richness, the highest average abundance of larvae and juvenile fishes was observed in KA (130 individual/100 m^2) follow by NB, DK and NK, respectively (112, 49 and 47 individual/100 m^2). Average abundance of larvae and juvenile fishes of the Nam Kam River was also lower than the Songkhram River (Table 5.3).

Table 5.3 Abundance of larvae and juvenile fishes (individual/100m^2) in the Nam Kam, Nam Bang and Songkhram rivers.

Month	DK	NK	KA	NB	TH	KS	HO
Jul-14	12	28	70	20	6	31	1,524
Aug-14	20	66	150	8	91	68	56
Sep-14	48	45	65	486	40	31	64
Oct-14	127	43	255	19	11	12	11
Nov-14	37	54	111	29	5	104	40
average	49	47	130	112	31	49	339
	NK=87				SK=140		

This was particularly true for larvae and juvenile white fish which showed higher diversity and average abundance in the most downstream floodplain compared with upstream floodplains (Table 5.4). The declining of diversity and abundance of fish were observed at sampling site that obstructed by many barriers.

Species diversity (Shannon-Wiener diversity Index) in the different sampling sites based on relative abundance at the species level was low, partly due to the low abundance and number of species in each sample, and ranged from 1.71-2.21 in the Nam Kam River system, and 1.16-2.68 in the Songkhram River (Table 5.5). Additionally, diversity indices for the upstream populations (DK, NK and NB) were less than that of the population in the downstream reach of the river; KA (1.57-2.01 and 2.39).

Table 5.4 Number of species, abundance (fish/100m^2) of each migratory guild fish larvae and juvenile fish in Nam Kam River, its tributary and Songkhram River in flood period (July 2014-November 2014).

		White fish		Grey fish		Black fish	
Site	Month	Sp.	abundance	Sp.	abundance	Sp.	abundance
DK	Jul-14	0	0	7	11	1	1
	Aug-14	2	2	9	14	3	4
	Sep-14	3	10	5	36	2	2
	Oct-14	0	0	4	126	1	1
	Nov-14	0	0	8	25	4	12
NK	Jul-14	1	1	9	22	5	5
	Aug-14	3	7	11	58	1	1
	Sep-14	2	2	7	41	1	2
	Oct-14	1	1	6	35	6	7
	Nov-14	1	1	8	49	4	4
KA	Jul-14	6	11	7	46	7	13
	Aug-14	5	24	17	106	6	20
	Sep-14	2	2	8	53	4	10
	Oct-14	6	7	7	244	4	4
	Nov-14	3	29	7	72	5	10
NB	Jul-14	5	7	7	13	0	0
	Aug-14	0	0	6	8	0	0
	Sep-14	1	10	8	474	2	2
	Oct-14	1	1	8	14	3	4
	Nov-14	0	0	3	29	0	0
TH	Jul-14	2	2	3	3	1	1
	Aug-14	5	5	9	47	5	39
	Sep-14	5	14	9	22	4	4
	Oct-14	4	4	6	7	0	0
	Nov-14	0	0	5	5	0	0
KS	Jul-14	3	6	9	18	5	7
	Aug-14	7	8	10	26	11	34
	Sep-14	1	1	7	14	5	16
	Oct-14	3	3	8	8	1	1
	Nov-14	2	2	5	102	0	0
HO	Jul-14	0	0	4	1,523	1	1
	Aug-14	7	7	13	43	3	6
	Sep-14	3	5	7	56	1	3
	Oct-14	4	10	1	1	0	0
	Nov-14	2	2	2	38	0	0

Table 5.5 Diversity index of larval and juvenile fishes in 7 sampling sites on 5 sampling occasions.

	Species richness		Diversity index; H'(loge)	
	Nam Kam	Songkhram	Nam Kam	Songkhram
Jul-14	14±8 (32)	10±7 (20)	2.12±1.00	1.72±0.63
Aug-14	16±9 (36)	23±5 (46)	2.21v0.56	2.68±0.29
Sep-14	12±2 (24)	14±4 (27)	1.71±0.21	2.18±0.30
Oct-14	12±7 (27)	9±4 (34)	1.89±0.94	1.90±0.57
Nov-14	11±5 (26)	6±2 (26)	1.77±0.72	1.16±0.22

5.4.2 Species composition of larval and juvenile fishes-spatial variation

T-test analysis revealed that species composition of larval and juvenile fishes between sampling sites was similar (Figure 5.3); and fish larvae and juvenile composition in Nam Kam system was not different from the Songkhram River ($P \geq 0.05$). Although there were different flooding patterns between the regulated Nam Kam and unregulated Songkhram rivers (see Chapter 3 and Table 5.6), it did not have a significant effect on diversity based on relative abundance of larval and juvenile fishes.

Table 5.6 Minimum, maximum and average discharge in the Nam Kam River system during the sampling period (July to November 2014).

Site	Month	Discharge		
		Min	Max	Ave.
DK	Jul-14	59.78	265.13	159.08
	Aug-14	22.5	224.17	157.47
	Sep-14	11.4	93.78	61.18
	Oct-14	11.58	85.78	44.76
	Nov-14	2.85	27.66	8.26
NK	Jul-14	67.24	157.18	96.03
	Aug-14	18.87	140.9	80.17
	Sep-14	13.67	127.72	76.02
	Oct-14	5.13	105.66	49.31
	Nov-14	2.46	6.95	4.63
KA	Jul-14	88.93	525.85	292.99
	Aug-14	37.42	343.5	214.82
	Sep-14	17.49	305.92	118.97
	Oct-14	36.59	147.04	73.86
	Nov-14	19.79	20.4	20.02
NB	Jul-14	21.1	128.36	58.95
	Aug-14	4.38	101.58	26.6
	Sep-14	2.61	80.72	20.83
	Oct-14	2.62	24.58	8.52
	Nov-14	2.58	2.58	2.58

The key species similar between sampling sites were *Clupeichthys aesarnensis*, *Parambassis siamensis, Rasbora borapetensis, Rasbora spilocerca, Parachela oxygastroides* and *Rasbora dusoensis,* which have been categorized as generalist, main channel spawning and floodplain spawning species.

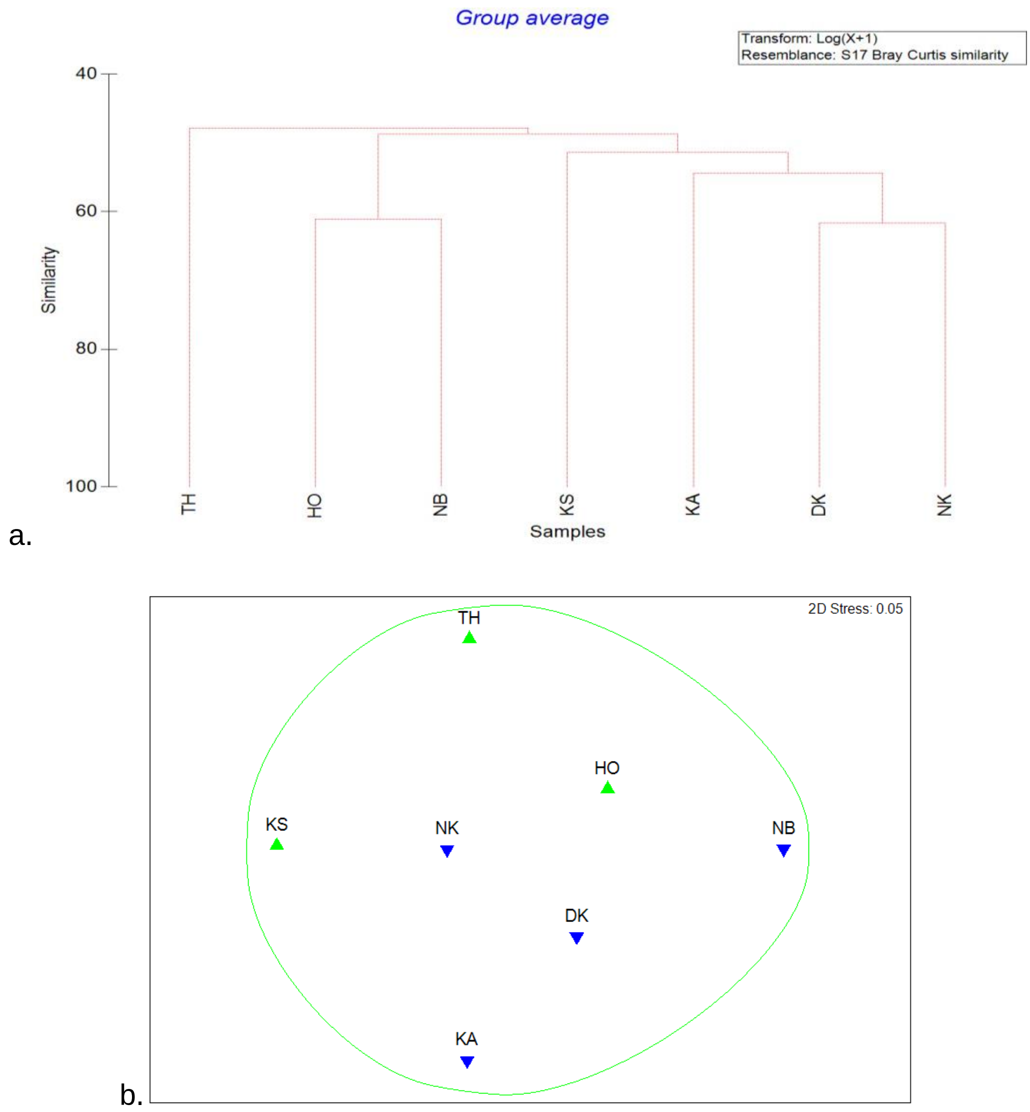


Figure 5.3 Average linkage cluster (a) and Multi-dimensional scaling (MDS) analysis (b) of fish larvae and juvenile fish from 7 sites in the Nam Kam River system and Songkhram River in 2014.

5.4.3 Seasonal variation of larval and juvenile fishes

The greatest number of species and hence highest diversity index in the Nam Kam River system was generally found in the flood period from July to November, although analysis of variance indicated no statistical difference between sampling times ($P \geq 0.05$). This was caused by an increase in the number and abundance of larval and juvenile white fish species after the upstream migration of adult fish through the most downstream watergate and fish pass at the onset of the rainy season.

At the beginning of the rainy season (July), diversity and abundance of larval and juvenile of white fish observed in the downstream floodplain of the Nam Kam (KA) and floodplain on the Nam Bang (NB) (Tables 5.2-5.3). The main species found in this period were *Labiobarbus lineatus* and *Puntioplites proctozystron*. Diversity and abundance of larval and juvenile white fish in the upstream area of the Songkhram River was higher than in the Nam Kam River. This was related to greater abundance of adult white fish that are able to reach the upstream area of the unregulated Songkhram River at the onset of rainy season whilst the most downstream watergate on the Nam Kam was still closed or opened marginally causing high discharge, which prevented upstream migration of adult fish (Table 4.9).

Species diversity of larvae and juvenile fishes in the Nam Kam River system and Songkhram River increased during the high flood period at the end of August (Table 5.5). White fish larvae captured in the Nam Kam system in this period were *Puntioplites proctozystron* observed at NK and *Barbonymus gonionotus* and *Mystacoleucus atridorsalis* at KA. The highest fish abundance was found in September, particularly in the seasonal floodplain NB (486 fish/100 m^2; Table 5.3) because of a schooling of *Sundasalanx mekongensis* and *Clupeichthys aesarnensis.* Average number of juvenile white fish was also high in October (Table 5.3) as a result of increased abundance of *Barbonymus schwanenfeldii* at NB, and *Henichorhynchus siamensis, Barbonymus schwanenfeldii, Systomus aurotaeniatus* and *Crossocheilus atrilimes* at KA.

Species richness and abundance of fish larvae and juveniles caught in the Songkhram River declined at the end of the flood season (October and November) associated with larval drift downstream to dry season feeding and refuge habitats in the Mekong River as water recedes (Table 5.5) . By contrast, species richness and abundance of all groups of fish in each section of the Nam Kam River system remained high probably because downstream drift of fish larvae and juvenile fish was obstructed by watergate operation at the end of flood season.

5.4.4 Spawning period of fish in the Nam Kam River system

Spawning period of fish in the Nam Kam River system was based on estimated age of larval and juvenile samples collected by conical net and seine net sampling in the 2014 flood season, which is the peak spawning season of fish in the Mekong River Basin.

Length and estimated age of juvenile *Hampala dispar* at NK and NB in July (51-93 mm)*, Hemibagrus nemurus* at DK (75-96 mm), and *Puntioplites proctozystron* at KA in August (40-41 mm), suggested that these fish had spawned around May 2014 (Table 5.7), which was the period when the watergates were still closed.

When all watergates started to released water in June, changes in rainfall and associated flow were the important factors that stimulated the reproductive migration of white and grey fish from the main river to the floodplain. Migration of fish from the Mekong River through both the TNNM sluice gate and the fish pass at the onset of rainy season together with larvae of *Hampala dispar, Parambassis siamensis, Brachygobius xanthomelas*, *and Labiobarbus siamensis* at KA also support the observation that fish spawned in June in the Nam Kam River. The size of juvenile white and grey fish observed above TNNM, such as *Hampala dispar* observed at every sampling site, *Barbonymus gonionotus* at NK and NB, *Osteochilus hasselti* at KA, *Puntioplites proctozystron* at KA, *Hemibagrus nemurus* at DK and KA, indicate that they probably spawned in June and July, and could be offspring of adults that migrated upstream from the Mekong River (Table 5.7), whilst juvenile *Barbonymus altus Barbonymus schwanenfeldii*, *Puntioplites proctozystron*, *Osteochilus hasselti, Hampala dispar* and *Henichorhynchus siamensis* at NB and KA, were of a size to suggest they spawned in August (Table 5.7). The size of juvenile *B. schwanenfeldii* at NB, *Puntioplites proctozystron* at KA, *Hampala dispar* and *Osteochilus hasselti* at DK and NK suggest they had spawned in September (Table 5.7). Some repeat breeding and protracted spawning species that spawned late around October to November, like *Hampala dispar, Barbonymus gonionotus* and *Crossocheilus siamensis* at NK and *Mystacoleucus marginatus* at KA, were not able to drift downstream because the watergates were closed at the end of October.

Additional data from small mesh gillnets showed that some small white and grey fish (sized 57-80 mm) like *Sikukia stejnegeri, Labiobarbus lineatus, Cyclocheilichthys apogon, Hampala macrolepidota, Hampala dispar,* and *Osteochilus lini* were found in the upstream floodplains (NK1-3) in June, and were probably 1+ fish that were stranded and used the Nam Kam as nursery and rearing habitat since the previous year (2013). This indicated that larvae and juveniles of these species can develop in this area, although the watergates have been closed since the previous dry season.

Table 5.7 Estimated spawning periods of fishes in the Nam Kam River system and Songkhram River based on estimated age of larvae and juvenile samples collected by conical net and seine net sampling in 2014. Numbers represent number of juvenile fish and illustrate the likely spawning period. Numbers in green represent the number of post larvae (size <30 mm) and likely spawning period.

Species	Sites	May	Jun	Jul	Aug	Sep	Oct	Nov
Barbodes gonionotus (WF)	NK		1				1	
	NB		6					
	KS	2						
	HO		2	1	1			3
Barbonymus altus (WF)	NK			6				
	KA			2	2			
	NB				2			
	KS			44				
Barbonymus schwanenfeldi (WF)	NB				1	1		
	TH			1	1			
	KS			2	2			
	HO			4	9	1		
Puntioplites proctozystron (WF)	KA	3	19		2	1		
Labiobarbus siamensis (WF)	KA			2				
Mystacoleucus marginatus (WF)	KA							10
Henichorhynchus siamensis (WF)	KA			2				
	NB			1	1			
Cyclocheilichthys sp. (WF)	TH				5		5	
	KS			3				
Labiobarbus sp. (WF)	KS			1				
Hampala dispar (GF)	DK		2	1		1		
	NK	7	5	1		1	1	
	KA			1	1			
	NB	1		2	1	1		
	TH		2	11				
	KS		1	3	1			
	HO	1	6	4				
Hemibagrus nemurus (GF)	DK	2	1					
	KA		2					
	TH		2	23	8			
	KS		11					
Osteochilus hasselti (GF)	DK					8		
	NK			1		1		
	KA		9	5	2			
	TH	4	14	5				
	KS	1	2	5	3	2		
	HO	2	5					
Crossocheilus siamensis (GF)	NK							2
Trichopsis vittatus (GF)	NK						1	
Brachygobius xanthomelas (GF)	KA			1				
Parambassis siamensis (GF)	DK						1	
	NK						1	
	KA			2				
	KS						158	
Rasbora sp. (GF)	DK						1	
Oxyeleotris marmoratus (BF)	KS			3				
Laides longibarbis (BF)	KS			2				
Brachygobius zoa (BF)	DK						3	

The size distribution and age of larvae and juvenile collected from the Songkhram River indicated that fish mostly spawn from May-September while some repeat breeders spawned in October-November (Table 5.7). The number of species declined when water level started to recede at the end of September (Tables 5.5-5.6): larvae of many species moved or drifted downstream to the Mekong River while others occupied the remaining floodplain as nursery habitat during the dry period.

Juvenile *Barbonymus gonionotus*, and *Osteochilus hasselti* were caught in the upstream floodplain of the unregulated Songkhram River (TH and KS) in May onwards but were not caught in the Nam Kam system until June (Table 5.7). Moreover, the spawning period of *Barbonymus schwanenfeldii* in the Nam Kam River system also started around one month later than in the Songkhram River suggesting a delay in migration and possible spawning in the Nam Kam caused by watergate operation.

5.4.5 Distribution of target species

The entire target species samples collected from the Nam Kam River system is juvenile stage. Juvenile of *Hemibagrus nemurus* collected at KA and DK in August with abundance 1 individual/100m^2 sized between 44-96 mm indicated fish spawned in May and June. While abundance of juvenile fish in Songkhram River was observed at KS with abundance 16 individual/100m^2 and size between 19-65 mm indicated that fish spawned from June to August.

Juvenile of *Osteochilus hasselti* were observed at KA in August with abundance 2 individual/100m^2 and NK in August and October with abundance 2 and 1 individual/100m^2. Size distribution of these samples ranged between 18-43 mm indicated fish spawned in June-August. Juvenile fish observed at NK and DK in November with abundance 8 and 8 individual/100m^2 and sized between 22-52 mm indicated fish spawned in September and October. Size distribution of juvenile fish in Songkhram River ranged between 26-79 mm indicated fish spawned from June to Septermber.

5.4.6 Spawning and nursery areas

Generally, the habitat where ichthyoplankton was most abundant is likely to be in the vicinity of the spawning ground. Although the spawning period could be determined from the size of larval stages, it proved difficult to isolate the spawning area in the river because no early life stages- eggs and yolk sac stages- were observed in this study. It was also difficult to determine spawning habitat using a flow model because the flow was not continuous throughout the whole river. Flows at the watergates were usually high, but slower nearer the bank or floodplain or stagnant when the watergates were closed. Therefore drifting of early life stages only provided an approximation of spawning area. However, it was possible to provide some indication of the nursery and rearing grounds of this river system based on presence of young of the year, which were typically caught in the 20 mm gillnet panels.

Spawning ground

In the Nam Kam River system, larval and post larval life stages (size less than 10 mm) of some white and grey fish species were caught by conical and seine netting at KA, NK and DK. The most likely spawning periods for particular species based on larval presence were: grey fish like *Hampala dispar, Parambassis siamensis, Brachygobius xanthomelas*, and *Labiobarbus siamensis* in July (one month after the beginning of wet season) at KA, *Trichopsis vittatus* and *Parambassis siamensis* in October, and *Mystacoleucus marginatus* at the same site in November. *Barbonymus gonionotus* larvae at NK in October, while *Parambassis siamensis* was in October and *Crossocheilus siamensis* at the same site in November (Table 5.7). Some repeat spawners larvae, for example *Brachygobius zoa, Parambassis siamensis* and *Rasbora* sp., were again observed in November at DK.

Some larval and post larval life stages of white and grey fish species were also observed at different times in the Songkhram River: *Labiobarbus* spp., *Laides longibarbis, Labiobarbus siamensis*, *Barbonymus altus* and *Cyclocheilichthys* spp. were found at KS in July, while *Cyclocheilichthys* was observed again at the same site in October and *Parambassis siamensis* was found at this site in November. Other white and grey fish species found in November were *Barbonymus gonionotus* at HO and *Cyclocheilichthys* sp. at TH (Table 5.7). The high number of fish species and abundance of larval fishes in KS suggests the area is a spawning ground for many white and grey fish, especially when the water level in the Songkhram River increased in July.

Nursery ground and rearing ground

Nursery grounds were identified as sites where larval, juvenile and small size fishes were found in the highest densities. The highest densities of fish larvae and juveniles in the Nam Kam River (130 fish/100m^2) were at KA, which is connected to a large impounded area resulting from the downstream watergate. This habitat is suitable for the feeding and larval development of many species of fish because the flow is not too high and is lacustrine habitat when the gates are closed. Dominant species observed in this area were floodplain spawners *Parachela oxygastroides* and

Parambassis siamensis, and the generalist species *Labiobarbus siamensis* that take lateral migration in and out the floodplain during flooding. Main channel spawners like *Clupeichthys aesarnensis* probably drifted downstream and occupied this floodplain as nursery grounds. High densities of small white fish species (50-90 mm) like *Henichorhynchus siamensis, Puntioplites proctozystron, Sikukia* sp., and some grey fish like *Barbonymus altus*, *Cirrhinus macrosemion*, *Osteochilus hasselti, Osteochilus lini, Labiobarbus lineatus,* and *Puntius brevis* were also observed at this site from October to February indicating young of the year cyprinids were stranded in this section and have adapted to the modified habitat during the dry season.

Although juvenile fish like *Labiobarbus lineatus, Barbonymus altus, Hampala dispar*, and *Osteochilus hasselti* were observed in the flood season at NK, their densities were low. Small individuals (40-95 mm) of floodplain spawners (*Cyclocheilichthys apogon, Cyclocheilichthys armatus* and *Parambassis siamensis*) and generalist species (*Labiobarbus lineatus, Osteochilus lini and Hampala macrolepidota*), floodplain residents (*Puntius brevis*) and main channel spawners (*Hemibagrus nemurus*) were caught at NK in the flood season indicating this area is probably a rearing ground for many groups of fish in the flood season. NB seems to be the another nursery ground in the Nam Bang River but the fish community in this area was dominated by schooling *Clupeichthys aesarnensis* in September (104 fish/100m^2). However, many small white fish species (50-90 mm) like *Puntioplites proctozystron, Sikukia stejnegeri, Larbiobarbus lineatus, Henichorhynchus siamensis* and *Thynnichthys thynnoides* were observed in high densities from October to February. Juvenile *Osteochilus hasselti* (23-52 mm) were observed at DK in November. Many small (50-90 mm) white and grey fishes like *Cirrhinus macrosemion, Labiobarbus lineatus, Osteochilus hasselti, Cyclocheilichthys apogon, Hampala macrolepidota, Mystus singaringan, Osteochilus lini, Puntioplites proctozystron, Puntius brevis*, *and Parambassis siamensis* were observed at the same site from October to February indicating DK is a rearing ground for young of the year. Review of the distribution and abundance of juvenile and small fishes at the sampling sites suggests NB, DK and KA are likely rearing grounds in the Nam Kam River system.

The highest abundance of juvenile fishes (339 fish/100 m^2) in the Songkhram River was at HO and resulted mainly from the contribution of schooling *Clupeichthys aesarnensis* in July and many species of small white fish (45-80 mm) from October to February, such as *Osteochilus melanopleura, Labiobarbus lineatus, Sikukia stejnegeri, Thynnichthys thynnoides, Puntioplites proctozystron, Euryglossa* *harmandi, Barbonymus altus, Crossocheilus siamensis, Cyclocheilichthys armatus, Mystus atrifasciatus, Mystus singaringan, Pristolepis fasciata* and *Sikukia stejnegeri.* High densities of larval stages of resident fish like *Parambassis siamensis, Clupeichthys aesarnensis, Barbonymus schwanenfeldii, Labiobarbus lineatus* and *Parachela oxygastroides* at KS in November suggests this could be another rearing area. In addition small white fish (60-90 mm) of the species *Barbonymus altus, Cyclocheilichthys armatus, Labiobarbus lineatus, Puntioplites proctozystron, Osteochilus melanopleura, Mystus atrifasciatus, Puntioplites proctozystron, Labeo chrysophekadion, Sikukia stejnegeri, Sikukia gudgeri,* and *Thynnichthys thynnoides* were observed at this site in October and November. Juvenile *Mystacoleucus atridorsalis* were observed at TH from July to October with a peak in September (Table 5.7). It appears that many species use these sites as nursery grounds in the flood season before the flood water recedes.

5.4.7 Habitat characteristic of spawning and nursery ground

Most fish larvae and juvenile fish observed in the Nam Kam River system (see Section 5.4.1) were main channel spawners, main channel residents that mostly spawn in the main channel and generalist species. These groups of fishes usually spawn in the mainstem Nam Kam River, and eggs and larvae drift downstream to the floodplains. Thus the spawning areas are likely located upstream of or associated with DK, NK and KA as these areas appear to be floodplain nursery areas in the Nam Kam River system, together with NB in the Nam Bang (Figures 3.2 and 5.1).

The habitat characteristics of the floodplain nursery grounds along the Nam Kam River system are typically grasslands with a diverse vegetation of trees, plants, shrubs and aquatic plants on the shoreline, which is good shelter for fish larvae. Also, the adjacent flooded paddy fields are good habitat for feeding. Some floodplain sizes were big, e.g. KA and DK, while others, NB and NK, are areas located above the NABU and NAKO watergates resulting from impoundment. These areas flood when the river overbanks in the flood season and offer suitable spawning and nursery habitat. KA, NK and NB are connected with the main river throughout the year since TNNM was closed, while DK is a seasonal floodplain that disconnects from the mainstem in the dry season, but lots of water is still retained in temporary man-made ponds in this section of river. Diversity and abundance of larval and juvenile fishes, mainly grey fishes, were observed in the Nam Kam River system when water level receded indicated that fish are stranded in each area in dry season (Table 5.4).

The three large seasonal floodplains in the Songkhram River (TH, KS and HO), are characterized by diverse vegetation of trees, plants and aquatic plants on the shoreline as well as plenty of grassland, paddy fields, shrubs and flooded forest, which are suitable habitat for refuge and feeding. High densities of fish larvae were observed in the flood season, but when the water started to recede at the end of September, the number of fish larvae and juvenile declined gradually indicating downstream drift or active dispersal to suitable dry season habitat. The floodplains mostly disconnect from the mainstem around December but some water is retained in each floodplain and they still function as rearing grounds.

5.5 Discussion

5.5.1 Distribution of larvae and juvenile fish

Several studies found migration of fish from the Mekong River into its tributaries at the beginning of the rainy season, and then eggs and larvae drift and juvenile fish spread onto the nursery and feeding grounds in the marginal floodplains while adult fish migrate downstream to refuge areas when the water recedes (Poulsen *et al.*, 2002; 2004). In the Nam Kam River system, the appearance of larvae, post larvae, juvenile and small fish in the flood season (May to November) indicated fish had probably migrated upstream and spawned in the upper reaches after the TNNM opened and the main migration triggers were discharge and water level changes, possibly helped by watergate operation. Their appearance suggests many Mekong fish species use this tributary to complete their life cycle and occupy the floodplains as nursery and feeding habitats.

Most larvae and juvenile fishes observed in this study were semi-lotic and lentic grey and black fishes. The diversity and abundance of larvae and juvenile whitefish increased in the area above the TNNM in the flood season (Table 5.4) suggesting adults have migrated from the Mekong River to spawn and may have been attracted by flow and discharge changes caused by watergate operation. Larvae and juvenile whitefish in the free-flowing Songkhram River were found to drift downstream when water receded at the end of flood season, and thus their diversity and abundance declined in the dry season (Table 5.4). However, white fish were trapped in the regulated Nam Kam River when the watergates were closed to store water before the start of the dry season. A similar situation was found by Phomikong *et al*. (2014) in the Pak Mun River: the fish community behaved like a free flowing river when the watergates were open in the wet season but the whitefish assemblage was replaced by grey and black fish when the watergates were closed.

In terms of diversity, most of the early life stages observed in this study were cyprinids followed by bagrids, osphronemids and silurids, respectively, but pangasids were not caught. The same pattern was found by Rukeawma and Nachaipram (2013) before TNNM was completely constructed in 2009, but the abundance of fish caught in this study was lower than the previous study, which was characterized by catches of schooling fish larvae. The species composition of the larvae and juvenile fish is not different from the composition of adult fish from Chapter 4 and the previous studies by Ngoichansri *et al.* (2013) and Phomikong *et al.* (2014); the composition was dominated by grey fish follow by black fish and white fish.

5.5.2 Recruitment to fish populations in the cascade river system

To help establish operating rules for the watergates to support fisheries management, it is critical to understand the fish stock characteristics of the river. Appearance of larvae and juvenile fish indicated that recruitment occurs in the river system from May to November, associated with the flood season (May to September). This is typically the spawning period of fish from the other rivers and reservoir in Thailand (Jutagate *et al.,* 2002; Boonyung & Dumrongtripob, 2008; Chunchom & Nachaipherm, 2008, Poungcharean, 2008; Nuaengsit & Chansri, 2008; Keawrit & Keawsrithong, 2014).

Unfortunately, the abundance of larvae and juvenile fish catches in this study were quite low and might not provide clear evidence of recruitment processes, consequently, genetic analysis of two common fish species was used to determine the role of migration to the contribution of different stocks in the Nam Kam River system. Recruitment of the two target species varied according to differences in their reproductive biology. The size of fish larvae and juvenile fish observed from this study suggests that *Hemibagrus nemurus* spawned at the onset of the rainy season, around May and June, in both the upstream and downstream areas of Nam Kam River. Migration of this species is triggered by flow and water level changes caused by releasing water from the upstream area (see Chapter 7). This spawning period is associated with the flood season (April to September) with adults actively migrating downstream and larvae drifting downstream to feed in the floodplains around the end of flood season was compatible with other studies in the region (Jutagate *et al.*, 2002; Boonyung & Dumrongtripob, 2008; Keawrit & Keawsrithong, 2014). *Hemibagrus nemurus* is a main channel spawner; spawning in the main channel, tributaries or marginal areas upstream before moving to downstream floodplain areas for feeding and nursery habitat (Halls & Kshatriya, 2009). Therefore, recruitment of this species is likely to be impacted if watergate operation does not support the spawning migration between the Mekong River and Nong Han Lake.

Osteochilus hasselti is a repeat breeder that spawns all year round, but peaks during the flood season. This is similar timing to other studies in the region: August to October in Tapi River (Keawrit & Keawsrithong, 2014) and April to September in two reservoirs in Northeast Thailand (Nuaengsit & Chansri, 2008; Chunchom & Nachaipherm, 2008). Migration of this midwater living species is also triggered by the lunar cycle (see Chapter 6) therefore any opportunity to migrate upstream needs to be linked to this cue as well as changes in hydrology in the river. This species seems well adapted to inhabiting impounded areas (Vidthayanon, 2012) as young of the year were found above the watergates when they were closed in 2014 (Chapter 3) and could benefit from increased water levels in each floodplain when the water gates are closed. *Osteochilus hasselti* is categorized in the generalist guild that usually migrates along the mainstem but take lateral movements on to the floodplain in the flood season, therefore dam construction or watergate operation probably has little or no impact on recruitment of this species (Halls & Kshartriya, 2009).

5.5.3 Impact of watergate operation on recruitment to fish populations in the cascade river system

When considering the impact of watergate operation on distribution of early life stages of fish, two main impacts are prevalent: 1) modified flow regime and changes in spawning/rearing habitats; and 2) obstruction to migration of mature adult fish from the Mekong River.

The main groups of fish that contributed to the fish community in this river are grey and black fishes, which migrate laterally onto the floodplain and thus are potentially not seriously affected by the watergate operation. Larval and juvenile white fish were less commonly observed because of the modified flow regime and modified habitat caused by watergate operation (Humphries *et al.,* 1999; Pepin, 2002). This group of fish needs a relatively smooth flood regime (curve) for larval drift to the main channels of the river where they can complete their migration and development; smooth flood curve avoiding repeated releases or withdrawals of the water that strand and desiccated eggs adhering to marginal vegetation and nets should be avoided (Welcomme, 2008). The diversity and abundance of fish larvae and juvenile fishes observed in the Nam Kam River suggests upstream migration of adult fish in the river system is to some extent impacted by watergate operation (see Chapters 4 and 7).

Diversity of fish in the downstream floodplains was higher than the upstream floodplain, especially white fishes, and overall diversity and abundance of fish larvae and juvenile fishes was lower than in the unregulated Songkram River. Recruitment of white fish is regulated by upstream spawning migration of adult fishes which is depended on watergate operation (see Chapter 4). Watergate operation at the onset of the rainy season delays migration of some adult fish until the watergates were fully opened, despite fish passage facilities being installed in this river system. Fish are probably forced to seek new spawning habitat in the Mekong River or nearby floodplains and this might lead to declining productivity. For example, no early life stage of pangasids was caught in this study, which was associated with adult pangasids being rarely caught in the upstream area of this river (see Chapter 4). The absence of pangasids and many other white fish species in the Nam Kam system suggests watergate operation disrupts migration and thus recruitment (see Chapter 4). Similar outcomes were observed on other regulated rivers such the Mun River (Jutagate *et al.,* 2005; Amornsakchai *et al.,* 2000).

The migration of fish into the Nam Kam River system appears to be regulated by the opening times of the watergates. In the drought year of 2014, the sluice gates at TNNM were opened a little later than the previous two years (2012 and 2013) therefore migration of fish from the Mekong River into the Nam Kam River system was delayed. By contrast, migration into the unregulated Songkhram River started was triggered as soon as the rainfall and flows increased, and fish reached the upstream spawning grounds by the onset of rainy season (May-June). Late spawning was also observed in some cyprinids in the Nam Kam River system, such as *B. gonionotus*, *B. schwanenfeldii* and *Osteochilus hasselti.* This occurred around one month later than the spawning migration of the same species in the unregulated Songkhram River. To summarize, fish recruitment in the Nan Kam River system occurred later than free flow rivers due to the watergate operation delaying upstream migration at the beginning of the flood season, and thus the distribution of fish in regulated rivers is different from free-flowing river systems. Furthermore, upstream migration of some late spawning migratory fish from Mekong River was also obstructed by watergates closing early at the end of flood season.

Estimated age of juvenile fish observed in flood season indicated that fish spawned in the period when the watergates were still closed, therefore they could be larvae and juveniles of resident fish, fish that had occupied or stranded the floodplains since the end of 2013 flood season which were triggered to reproduce at the onset of rainy season by the rainfall and water level changes and moved to the floodplain to spawn. Most larvae that observed in this study were of generalist species belonging to the Family Cyprinidae, which are not obligatory migrators and can easily adapt to the stagnant water. Normally this group of fishes prefers to lay eggs in the mainstem Nam Kam River and the water currents transport their eggs and larvae to the floodplains. Thus, the precise spawning grounds should be located further upstream of those sites.

Downstream drift of larval and juvenile fishes of some repeat breeding and protracted spawning species was also obstructed by the watergates closing at the end of the flood season. Some juvenile and small fishes were stranded above the watergates in the dry season and needed to use the floodplain areas between the watergates as nursery grounds during the dry season (see Chapter 4). This group of fish has adapted to the modified habitat and used upstream floodplains as nursery grounds during the dry season. In the long-term, however, juvenile life stage trapped in the impounded areas will likely compromise fisheries recruitment in the river (Poulsen *et al.,* 2002) because fish that normally inhabit in Mekong floodplains are characterized by short lifespans and early sexual maturation (Lowe-McConnell, 1987). This strategy increases resilience for species when conditions for reproduction are variable (e.g. flood with suitable duration, magnitude frequency and timing) (Bayley, 1995). This is important because fish with longer reproductive cycles generally benefit from longer flood periods allowing greater opportunity for fish larval development and fish feeding, resulting in higher fish production (Baran & Myschowoda, 2009; Jutagate, 2014). In the Nam Kam system, however, watergate operation will increase the duration of flooding by holding back water in the dry season and this could create fish habitats, which will act as nursery and feeding habitats for fish larvae and juvenile in the dry season or also act as spawning and feeding habitat for repeat and protracted spawning species in dry season.

One other aspect that has been rarely studied is the ecological processes that occur during inundation after closure of the watergates, e.g. deterioration in water quality and ecosystem functioning (Amornsakchai *et al.,* 2000; Scharf, 2002; Jutagate *et al.,* 2002; Wei *et al.*, 2009). In the Nam Kam system water levels in the floodplain are higher and for a longer period in the dry season than previously, which could result in stagnant water for longer periods. This could lead to deterioration of habitat quality, through de-oxygenation caused by decomposition of submerged plants in the river and die back caused by longer flood duration. It is unsure what the impact will be on the development of fish larvae and juveniles. As the dry season progresses there may be serious deterioration in water quality with adverse impact on fish, for example white and grey fish, although black fish could tolerate with this situation (Dugan, 2008). This situation was not observed in the Nam Kam probably because the vegetation is adapted to seasonal flooding and the watergates are open for around 5 months per year, which reconnects the river system. Nevertheless, water quality in the impounded area and floodplains needs to be monitored to be able to respond to any negative impact on the development of fish populations (Humphries *et al.,* 1999). In addition, floodplain habitat below the watergates is also lost after closing at the end of the flood season and in the dry season, which might lead to a decline in productivity of the river as a whole.

5.6 Summary

The appearance of larvae, post larvae, juveniles and small fish in the flood season (May to November) suggests that fish from the Mekong River enter the Nam Kam River system to complete their life cycle and occupy the floodplains as nursery and feeding grounds. Most larvae and juvenile fishes were semi-lotic and lentic grey and black fishes which migrate laterally onto the floodplain and thus are not potentially seriously affected by the watergate operation. The diversity and abundance of larvae and juvenile whitefish increased in the upstream area after the watergate opened at Thoranit Naruemit watergate at the onset of rainy season suggesting adults have migrated from the Mekong River to spawn and may have been attracted by flow and discharge changes possibly assisted by watergate operation. However, white fish were less frequently observed in this river system because of the modified flow regime and modified habitat affected by watergate operation. Moreover, watergate operation at the beginning of the rainy season delays migration of some adults, especially pangasids, until the watergates were fully opened despite fish passage facilities being attached with all watergates. Seasonal distribution of fish in the Nam Kam River system is different from the free-flowing river. Downstream drifting of larval and juvenile fish was obstructed by watergate closure at the beginning of the dry season. Larvae and juvenile whitefish in the free-flowing Songkhram River drifted downstream when water receded at the end of flood season, and thus their diversity and abundance declined in the dry season. However, larval and juvenile whitefish were trapped in the regulated Nam Kam River when the watergates were closed to store water for the dry season.

Chapter 6: Population structure and genetic diversity of fish in the Nam Kam River system

6.1 Introduction

Habitat fragmentation is a fundamental issue in conservation biology and one of the top threats to biodiversity (Hanski, 1999; Fahrig, 2003; Henle *et al.,* 2004). Watergate construction on mainstem river brings many changes to the river ecosystem and fish habitats. In particular, regulated flow regimes will impact on the functioning of the ecosystem by degrading feeding and breeding habitats along the river and disturbing fish recruitment processes. In addition to environmental changes, the physical barrier of the watergate also blocks fish migration routes and thus contributes to changes in fish species composition, abundance and diversity as well as size structure of communities. This can genetically isolate and degrade upstream populations, since population fragmentation can reduce within-population genetic polymorphism and increase genetic differentiation within the area (Knaepkens *et al.,* 2000).

The Nam Kam River has been fragmented since 2011 after all of the watergates had been constructed. At least 103 species have been recorded migrating via through this river. Several investigations have reported on the fish stocks and migration of fish through fish passes at watergates on the Nam Kam River (Srisatit *et al.,* 1981; Pongsri *et al.,* 2008). Ngoichansri *et al.* (2013) found 95 species were able to pass from the Mekong River through the Nam Kam fish passes and most were mature and ready to spawn. Juveniles of several species have also been observed at the upstream fish pass a few months after upstream migration of mature adults. However, there is no information that confirms these juveniles are offspring of migratory fish from the Mekong River or if they are resident in the floodplains along the river.

Others have explored the impact of weir operation and environmental factors on migration patterns of fish (Ngoichansri *et al.,* unpublished). However, little is known about the impacts of habitat fragmentation on genetic diversity and population structure of fish in this river. Fish tagging and recapture have been used to investigate the migration of fish in the Nam Kam River system (Chapter 7) and concluded that fishes from the Mekong River can migrate upstream through both the Nam Kam and Nam Bang rivers. Although migratory fish have been observed bypassing the watergates, it does not guarantee that the species are not at risk in term of genetic integrity or confirm that gene flow is maintained. Migration of fish has limited value if fish do not occupy, reproduce and transfer genetic material to the next generation

(Miko & Le Jeune, 2009). There is a need to maintain the genetic integrity of the population and population size which can be impacted by barriers.

In this study, microsatellite DNA was used as biological markers to characterize the level of genetic diversity and population structure of two economically important fish species (*Hemibagrus nemurus* and *Osteochilus hasselti*) in the study area. In addition, microsatellite DNA was used to evaluate any impact of water resources management and hydrological changes on migration pattern and subsequent impact on genetic diversity and population structure along the longitudinal profiles of the Nam Kam River and its tributary. It is hypothesized that operation and hydrological regime changes caused by a series of watergates in the Nam Kam River and its tributary make the river effectively impassable to fishes. Consequently (1) the fish populations, especially the groups isolated upstream in the drought season, should have reduced genetic diversity compared with the larger groups downstream; and (2) significant genetic differentiation should be detected between each part of the river. Although the series of watergates in the Nam Kam River system have been operated for just 5 years, it is long enough to see if genetic isolation has occurred. Results from this study should improve understanding of habitat fragmentation effects on population structure and genetic diversity of fishes and may be useful for effective management to mitigate the effects of weir operation on two economically important species and fish populations that have the same migratory guild.

6.2 Objectives

The aims were to elucidate the molecular genetic diversity and the genetic relationships among the populations, particularly:

1. To assess the population structure and genetic diversity of two economically important fish species (*Hemibagrus nemurus* and *Osteochilus hasselti*) in the Nam Kam River and its tributary;
2. To test the hypothesis that if a series of watergates is effectively impassable to fishes in the river:
    - 2.1 the fish populations isolated in the upstream reaches of the Nam Kam River and its tributary have deteriorated genetically compared with the downstream groups.
    - 2.2 there is highly significant genetic differentiation (high Fst value) between each part of the river.
3. To evaluate any likely impact of watergate operation and hydrological management on connectivity and their impact on genetic diversity and

population structure of the fish populations in the Nam Kam River and its tributary.

6.3 Methods

6.3.1 Sampling method and DNA extraction

Two economically important fish species, *Hemibagrus nemurus and Osteochilus hasselti*, were used to estimate the contribution of fish from the Mekong River and floodplains along the Nam Kam River to the mixed populations: fish that recruit to Nong Han Lake at the end of the migratory season.

A total of 942 individuals comprise of adult fish samples from fishing by fisherman, gill netting at 9 sampling sites (Table 6.1 and Figure 6.1) in the floodplain areas between each watergate along the Nam Kam and Nam Bang rivers, adult fish and sub-adult fish samples from seine net sampling at the fish passes (TNNM and SRWD fish pass). Sample from S (Table 6.1 and Figure 6.1) represents the mixed population or recruited population in Nong Han Lake collected from Suraswadi fish pass 3 months after the migration of mature fish at TNNM at the onset of rainy season. Sample from T represents the baseline mature fish from the Mekong River that migrated through the TNNM fish pass at the onset of the rainy season (May-July 2013). Samples of *Hemibagrus nemurus* from Zone A were collected after all watergates were completely closed at the end of flood season (October-December 2013), which is the period of greatest abundance Samples of the two target species were collected from each floodplain along the Nam Kam River system (B, D, E, F and G), and *Osteochilus hasselti* from Site A during the migration period from the onset of the rainy season until the end of wet season (May-December 2013). Some sample were not included in the analysis due to low numbers caught (Zone C) and no sample of *H. nemurus* collected by fisherman in zone E (Table 6.1).

One piece of fin was cutted from each fish and specimens were then returned to the stream. Fin samples were preserved in 99.9% absolute alcohol then DNA extracted following the method of Sambrook *et al.* (1989). DNA was precipitated out using isopropanol precipitation, air dried, and then re-suspended in sterile double-distilled water and stored at 5°C. The concentration of DNA in the samples was determined by spectrophotometric measurement at 260 nm.

Table 6.1 Detail of samples and location of genetic sampling sites.

Name	Samples/Locations			No of samples HN	No of samples OH	period of sampling
zone A	Adult fish from area below Thoranit Naruemit Watergate to the area confluence with the Mekong River.			48		Oct-Dec 2013
					48	May-Dec 2013
zone B	Adult fish from impoundment area and floodplain between Thoranit Naruemit Watergate and Na Bua Watergate, and Na Koo Watergate.			39	72	May-Dec 2013
zone C	Adult fish from floodplain between Na Bua Watergate and Ban Tab Tao Watergate.			7	5	May-Dec 2013
zone D	Adult fish from floodplain above Ban Tab Tao Watergate.			48	48	May-Dec 2013
zone E	Adult fish from floodplain between Na Koo Watergate and Na Karm Watergate.			-	28	May-Dec 2013
zone F	Adult fish from floodplain between Na Karm Watergate and Nong Bueng Watergate.			19	16	May-Dec 2013
zone G	Adult fish from floodplain between Nong Bueng Watergate and Suraswadi Watergate.			48	48	May-Jul 2013
S	Small fish from seine net sampling at Suraswadi fish pass	423747.32 E	1896648.90 N	192	192	Oct-Dec 2013
T	Adult fish from seine net sampling at Thoranit Naruemit fish pass	469796.23 E	1870994.73 N	48	48	May-Jul 2013

HN; *Hemibagrus nemurus*, OH; *Osteochilus hasselti*

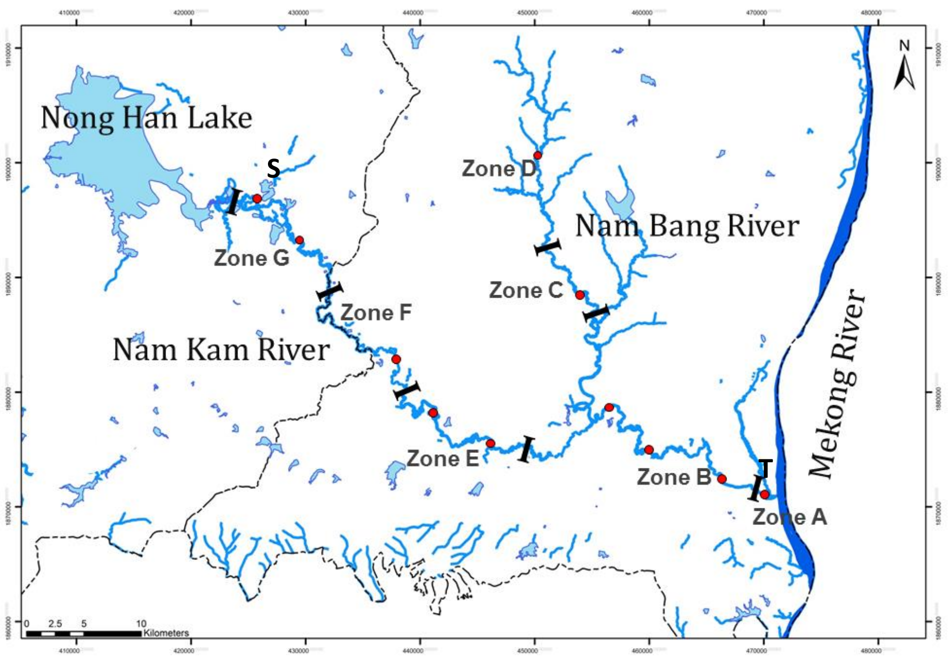


Figure 6.1 Location of genetic sampling sites in the Nam Kam River system.

6.3.2 Microsatellite DNA Analysis

Microsatellite DNA markers were used to genotype the fish sampled and assess genetic variation of fish populations in Nam Kam River and tributary (Sambrook & Russell, 2001).

Cross species amplification

Instead of developing of new primers of two target species, 70 existing microsatellite primers isolated from 15 related species were screened for possible cross-species amplification. Using loci that have already been developed in a related species provides a cost-effective alternative, saving considerable investment of time. Six primers (Table 6.2) gave polymorphic results and suitable to use for each species (*Hemibagrus nemurus:* BgOn75, Ns16 Hmo34, Ost03, Ost05 and Ost07 and *Osteochilus hasselti:* Hw04, Hw08, Hw25, Hw26, Hw32 and Hw35), and were used in this study.

Table 6.2 Microsatellite primers used for *Hemibagrus nemurus* and *Osteochilus hasselti.*

Locus	Repeat motif	Primer sequence (5'-3')	Annealing Temperature (°C)	Allele sizes (bp)
Hemibagrus nemurus				
Hw04	$(TG)_{14}$	F: AAGTCGTCTCTCGTAATGGCGCT R: CGTGTCACCTAAGCTTGCGGAA	52	106-160
Hw08	$(CA)_{9}$	F: GAGGGAAGTTAGCCCCAAAT R: TCATTCTTCCGGCTGTTCTT	52	174-212
Hw25	$(GT)_{11}$	F: CGTTGATACAAAGAGAGGAT R: CTCACATGTGTTATTTCTGC	52	110-128
Hw26	$(TG)_{16}$	F: CCATGGTTCGCCCAAACGTG R: TAGCGTGTCCAATCACCCTGC	52	140-178
Hw32	$(CA)_{11}$	F: CCACATTGAGTTCCTCCAGCATGA R: CTTAACACGCTCCACACGGA	52	186-224
Hw35	$(GT)_{11}$	F: TTTTCCCAGCACCACTTTTC R: TTGCTTGCCTTCTCACACAC	52	110-128
Osteochilus hasselti				
Bgon75	$(AC)_{10}$	F: CTGGTAAAGACTTCAGATGC R: GCATGCAAAATGAGAAAGGCT	49	84-108
Ns16	$(TG)_{18}$	F: CGCGGGAATTCGATTATCAGGTGC R: GCGCATTCGTTCTCACCGCAAGGA	52	162-250
Hmo34	$(GT)_{19}$	F: GTTCCCTGAGGCTTTACAA R: GGGTCATTATCCTCTCACTTT	59	92-156
Ost03	$(TG)_{5}TT(TG)_{17}$	F: ATGGTGTCAGATTCCT R: GCATTTATCATCCTTC	49.5	144-188
Ost05	$(GT)_{12}(GA)_{5}$	F: CTGTAGTAAATCTTGACG R: TAACTCCCAGGAATGTG	53.5	126-206
Ost07	$(TG)_{25}$	F: CACCTTCAACACTCTT R: ACACACATCATCCTTC	51	184-206

DNA Genotyping

For PCR amplification (Figure 6.2), the DNA concentration was adjusted to 20 mM by dilution with sterile double-distilled water. The PCR reaction was performed using a Taq PCR Core Kit (Qiagen) consisting of 1X PCR buffer, 1.5 mM Mg 2Cl, 200 µM of each dNTP, 0.25 µM of each primer, 20 ng of genomic DNA, and 0.1 unit of taq DNA polymerase (Qiagen) in a total volume of 5 µL. The PCR amplification of DNA was performed on a PTC-200 thermal cycler (MJ research), set for 5 min at 95°C follow by 30 cycles of 30 s at 95°C (denaturation), 30 s at the specific annealing temperature (Table 6.2), and 1 min at 72°C (extension), and followed by incubation at 72°C for 5 min as a final extension step. The PCR products were stored at -20°C until used for gel electrophoresis. The PCR products were size fractionated by electrophoresis for 2 h 30 min in 6% denaturing polyacrylamide gel with 8M urea and 1X TBE buffer (tris-borate-EDTA) at 50 W constant powers. Prior to loading, 5 µL of loading buffer (10 mM NaOH, 99% formamide, 0.1% bromophenol blue, 0.1% xylene cyanol) was added to the PCR product followed by denaturing at 95°C for 15 min whilst kept on ice. After electrophoresis, gels were stained with SYBR®Gold (Molecular Probe) following the manufacture's protocol (1:10,000 in TE buffer pH 8.0). The gels were photographed with FluorChem 8000 (Alpha Innotech Corp.). DNA fragments were scored relative to the 25 bp ladder (Invitrogen) using Universal software (American Applied Biotechnology).

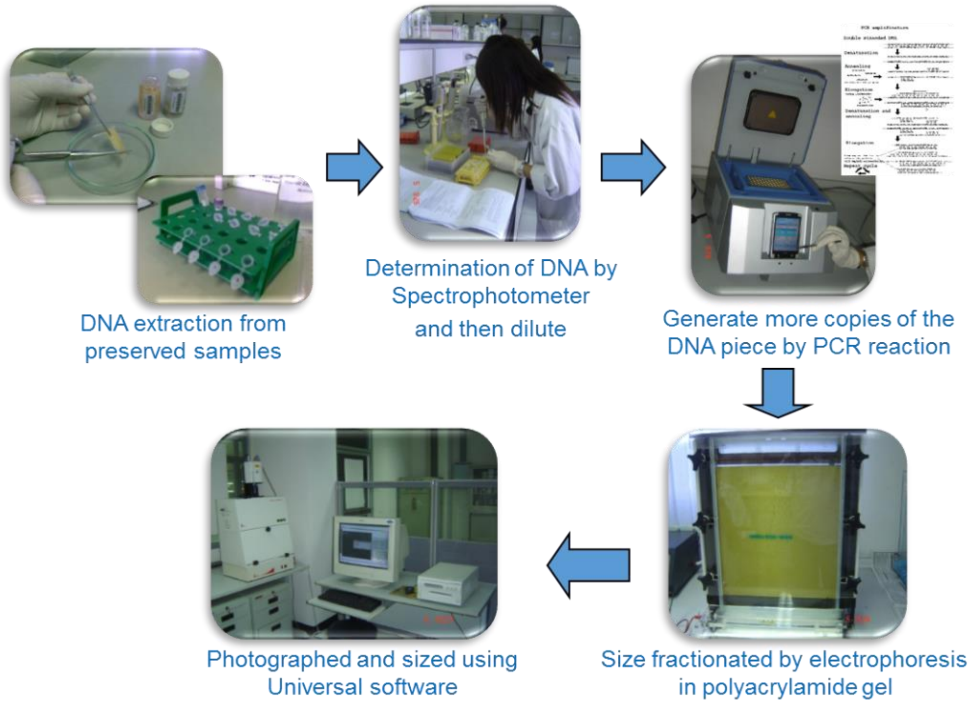


Figure 6.2 Microsatellite DNA analysis.

The Micro-Checker program (Van Oosterhout *et al.,* 2004), freeware download from http://www.norwichresearchpark.com/research1/researchgroups/elsa/software/microchecker.aspx, was used to identify and correct microsatellite scoring errors from null alleles, large allele and stuttering. It also provides null allele estimates, and adjusts allele and genotypes frequencies.

6.3.3 Data analysis

Genetic diversity

Genetic diversity for each population was investigated through average number of alleles per locus (MNA) and allelic richness (AR) using FSTAT version 1.2 (Goudet, 1995). The proportion of individuals sampled that are heterozygous (observed heterozygosity; Ho) and the unbiased estimate of Heterozygosity (He) were estimated (Nei, 1978). Allele frequencies of each locus for each population were calculated using the TFPGA (Tools for Population Genetic Analyses) program (Miller, 1997).

As described by Guo & Thompson (1992), the Markov chain “approximation to exact test” was used to test for conformity to Hardy-Weinberg equilibrium (HWE) of each locus in each population using Genepop Version 3.4. HWE indictaes that the amount of genetic variation, allele frequencies and genotype frequencies in the population remain constant from generation to generation in the absence of evolutionary influences, including mate choice, mutation, selection, genetic drift, gene flow and meiotic drive (Guo & Thomson, 1992). HWE is used to test for population stratification; populations that distorted from HWE indicated the distrubtion by a number of forces, in this study the gene flow caused by spawning migration of fish. Statistical significance was assessed after 100,000 iterations. Results of the multiple tests were corrected using the Bonferroni sequential method to adjust *P* values when several dependent or independent statistical tests are performed simultaneously on a single data set (Lessios, 1992). If genotype frequencies were not consistent with HWE, evidence of genotyping error due to stuttering, large allele drop-out and/or null alleles were interrogated using Micro-Checker 2.2.3 (Van Oosterhout *et al*., 2004).

The number of spawning parents or size of idealize population that could contribute offspring to the next generation (Effective population size, (*Ne*) was estimated for each population using the linkage/gametic disequilibrium method (Hill *et al.,* 1981) and performed using the NeEstimator program (Peel *et al.,* 2004). *Ne* is extremely important in evaluating conservation priorities for a species. It is a direct measure of the rate of loss of diversity and the rate of increase in inbreeding with in a population (Wright, 1969). Assessing the Ne of a species provides an indication of both the breeding population size and of population genetic health (Frankham, 1995), making it a potentially invaluable stock evaluation tool for conservation and fisheries management (Luikart *et al.*, 1998).

Population structure

The differentiation between population due to genetic structure was investigated using the F_{ST} statistical test. Unbiased estimates of Wright's F statistics (Weir & Cockerham, 1984) were calculated for all populations and the probability that each statistic was greater than zero was tested by permuting the data set 1,000 times using FSTAT, version1.2 (Goudet, 1995).

Genetic differentiation tests and pairwise F_{ST} test of differentiation were used to determine allele frequency differentiation between pairs of populations. The analyses were performed in GENEPOP, version 3.4 (Raymond & Rousset, 1995). Bonferroni correction was used to adjust significant levels for multiple tests (Dunn, 1961). Roger's modified unbiased test (Wright, 1978) was used to compute genetic distances between populations using the TFPGA program (Miller, 1997). Genetic distances between populations were computed and cluster analysis using the unweighted pair-group method with arithmetic mean (UPGMA) was performed using the Tool for Population Genetic Analysis or TFPGA program (Miller, 1997). Genetic distance is used to measure the genetic divergence between populations; populations that have similar alleles will exhibit small genetic distance while populations that are different will exhibit greater genetic distance (Nei, 1987).

Effect of fragmentation on genetic diversity and genetic structure

Generalized linear models (GLM) with genetic diversity (allelic richness) as the dependent variables, and the geographic distance as a continuous predictor were used to determine the effect of fragmentation. Geographic distance between pairs of sampling sites were expressed in two ways 1) distance between sampling site in km and 2) number of obstracles limiting upstream dispersion (Epps *et al.,* 2005; Dehais *et al.,* 2010).The best correlation was then identified on the basis of the Coefficient of Determination; R^2 (after Epps *et al.,* 2005 and Dehais *et al.,* 2010).

The spatial genetic structure was investigated using the isolation by distance (IBD) framework (Hutchison & Templeton, 1999; Templeton *et al.,* 2001). The IBD describes the linear relationship between genetic differentiation between pairs of sampling sites from the confluence of Mekong River (in km) and number of barriers that obstructed upstream migration of fish. Identifying IBD is important to determine ability and extent to which gene flow may fill neighbouring area in the event of localized extinction. Linear relationships between the matrix of genetic distances expressed as F_{ST}/ 1-F_{ST} between pairs of sampling sites were graphically inspected using the Mantel test followed by a permutation procedure (9999 permutations) with Spearman Rank correlation coefficients as statistical test (Mantel, 1967). The effect of fragmentation on the slope of the linear relationship were compared between species or compared with the continuous landscape. If gene flow is reduced between subpopulations, the fragmented area would expected to show a higher slope than the continuous landscape (Blanchet *et al.,* 2010)

The effects of weir operation and eco-hydrological change on population structure and genetic diversity and migration pattern were evaluated from (1) genetic diversity of the fish population in the isolated upstream groups compared with the larger group downstream; and (2) population structure and genetic differentiation between each part of the Nam Kam River and its tributary. If the watergates are obstacles to spawning migration of some fish species in the river and whether watergate operation and flow modification impacted on fish larvae and juvenile population recruitment, two hypotheses were tested: (1) species diversity in the isolated upstream population should be less than those of the populations in the lower spawning areas and (2) significant differentiation between populations in each spawning area should be observed.

Mixed stock analysis

The stock composition of fish was estimated using the ONCOR program for genetic stock identification (Kalinowski *et al.,* 2007) using the conditional maximum likelihood (CML) method (Millar, 1987). Percent contribution of fish from each spawning and nursery grounds along the river were use to evaluate the importance of each rearing habitats for production in the river system and also identify the source of fish that recruit to Nong Han Lake. The ONCOR program is free to download from http://www.montana.edu/kalinowski/Software/ONCOR.htm. Mixed stock analysis of known origin mixtures was used to estimate relative contribution of the '*baseline populations*' in the '*mixed population' or recruited population* which is S: sub-adult fish samples collected during mixed stock period of fish migrating via the most upstream fish passage to Nong Han Lake at the end of flood season (October 2013). The components assessed as 'baseline populations' included T, which is fish migrating via the most downstream fish passage at the onset of rainy season (June-July 2013) and A, B, D, F and G, which are fishes from each rearing ground along the river. These baseline populations might contain both resident fish in that particular area and fish immigrated via TNNM fish pass in the rainy season (Table 6.1 and Figure 6.1).

Therefore ‘Individual assignments’ were used to identified origin of each fish in B, D, E, F and G samples and fish that migrated from TNNM were then eliminated from the residence group before undertaking the mixed stock analysis. Thus, samples used as base populations were resident populations only. The “known-origin mixture analysis”, for which population of origin is known, was used in this study. Random samples were removed from the baseline population of the population of known origin and used as a mixture independent of baseline. The known origin mixture was assembled to range in regional proportion from 0% to 100%. The aim was to determine whether observed genetic divergence was sufficient to apportion population mixtures to different sources. Results of the known-origin mixture analysis were used to check the accuracy of the analysis.

6.4 Results

6.4.1 Genetic diversity of target species in the Nam Kam River system

Genetic diversity of *Hemibagrus nemurus*

Genetic diversity of samples from the Nam Kam River system were relatively high. No null alleles or stuttering were detected with Micro-Checker. The number of alleles per locus and allelic richness ranged from 8.67±3.08 to 13.50±8.96 and 8.19 to 9.57, respectively. Observed heterozygosities were moderate, ranging from 0.575 to 0.714 and did not show any significant difference among all samples (Table 6.3). Samples from the downstream area of the river system (A and B) exhibited higher genetic variation than those of upstream area samples (E, F, G and D), as reflected by greater number of alleles and allelic richness. However, fish that migrated into Nong Han Lake (S) located in the upstream area a few months after passing the downstream reaches showed the highest number of alleles sampled, and higher than fish that migrated from the Mekong into the Nam Kam River at Thoranit Naruemit fish pass (T) (Table 6.3). Multi loci probability tests showed that three subpopulations (S, T and A) were departure from Hardy-Weinberg Equilibrium (HWE) expectation, while the rest conformed to HWE, after sequential Bonferroni correction for most microsatellite loci examined, except HW04 (Table 6.4).

Table 6.3 Genetic diversity (average number of alleles per locus (MNA) ±SD, Allelic richness (AR), Unbiased expected heterozygosity (He), observed heterozygosity (Ho), and Effective population number (*Ne*)) of *Hemibagrus nemurus* for each collection across all loci.

Samples	N	MNA±SD	AR	He	Ho	Ne	Approx. 95% CI.
A	48	11.83 ± 3.49	9.57	0.841	0.616	79.8	52.8-149.8
B	38	11.33 ± 4.97	9.67	0.780	0.714	35.5	25.6-53.7
D	48	9.83 ± 3.97	8.21	0.714	0.644	46.3	32.0-77.2
F	19	8.67 ± 3.08	8.50	0.795	0.694	44.4	23.4-212.5
G	48	10.50 ± 5.17	8.64	0.765	0.672	23.6	17.9-33.3
T	48	10.50 ± 6.38	8.19	0.717	0.575	70.9	44.0-158.4
S	192	13.50 ± 8.96	8.68	0.703	0.629	240.5	171.3-382.6

Table 6.4 Hardy-Weinberg equilibrium test for *Hemibagrus nemurus* samples. P-values marked with asterisks are those that were significantly different after Bonferroni adjustment for multiple tests.

	Hw04	Hw08	Hw25	Hw26	Hw32	Hw35
A	0.0000*	0.0000*	0.0182	0.0000*	0.0000*	0.0019*
B	0.0003*	0.0264	0.0526	0.1665	1.0000	0.0791
D	0.0000*	0.3389	0.2024	0.0667	1.0000	0.1563
F	0.0000*	0.6039	0.1662	0.0938	1.0000	0.4171
G	0.0000*	0.3343	0.1652	0.2918	0.0323	0.0146
T	0.0000*	0.9693	0.0129	0.0000*	1.0000	0.0000*
S	0.0083	0.1039	0.0124	0.0000*	1.0000	0.2607

The estimated effective population size (Ne) for the Nam Kam River system ranged from 23.6 to 240.5 (Table 6.3). Fish that migrated from the Mekong River via the downstream fish pass and the area that connected to Mekong River (T and A) had a higher effective population size than fish from the area above TNNM (B, D, F and G). Young of the year of *Hemibagrus nemurus* that migrated to the Nong Han Lake in the late rainy season (S) exhibited a relative big population size (240.5). Distortion from the HWE in subpopulation S also supported sub-adult fish had migrated to Nong Han at the end of flood season and was a mixed population.

Relatively higher genetic diversity and greater population size of migratory fish collected from the SRWD and TNNM fish pass (S and T) suggest that huge numbers of migrating *Hemibagrus nemurus* continuously passed from the Mekong River in the 2013 spawning season (Table 6.3).

Genetic diversity of *Osteochilus hasselti*

Genetic diversity of *Osteochilus hasselti* in the Nam Kam River system was relatively high and varied. The number of alleles per locus and allelic richness ranged from

7.00±3.46 to 15.00±8.51 and 6.61 to 8.37, respectively. Observed heterozygosity was relatively high and ranged from 0.591 to 0.705 (Table 6.5). Fish that migrated from the Mekong River via the TNNM fish pass (T), fish in the area that connects to the Mekong (A) and migratory fish that migrated to Nong Han through the SRWD fish pass (S) exhibited high genetic variation, while other samples along the river exhibited lower diversity.

Table 6.5 Genetic diversity (number of alleles sampled±SD, Allelic richness (A_R), Unbiased expected heterozygosity (H_e), observed heterozygosity (H_o), and Effective population number (N_e)) for *Osteochilus hasselti* for each collection across all loci.

Samples	N	MNA±SD	A_R	H_e	H_o	N_e	Approx. 95% CI.
A	48	12.33 ± 5.05	8.20	0.781	0.665	74.8	48.5-148.7
B	72	11.00 ± 4.86	7.98	0.774	0.638	82.2	55.6-145.1
D	48	11.17 ± 6.24	7.78	0.763	0.705	106.6	62.4-297.2
E	28	10.17 ± 5.19	7.87	0.758	0.630	16.1	12.7-21.3
F	15	7.00 ± 3.46	6.61	0.651	0.600	8.4	6.1-12.4
G	28	11.17 ± 7.33	7.43	0.701	0.598	80.5	47.4-217.5
T	48	11.67 ± 6.02	8.02	0.815	0.676	inf.	301.3-inf.
S	192	15.00 ± 8.51	8.37	0.789	0.591	376.9	228.8-944.2

The estimated effective population sizes (*Ne*) for all samples ranged from 8.4 to 376.9. Site D exhibited the highest population size among the river suggesting it may be a key resident area for *Osteochilus hasselti* population (Table 6.5). Heterozygosity observed was lower than expected ($Ho<He$) indicating that this population was mixed from contributions from more than one population (Table 6.5) resulting in the distortion from HWE (Table 6.6).

Osteochilus hasselti migrated in many batches rather than aggregated in a single pulse in the spawning season and showed relatively high genetic diversity and greater population size of migratory fish at the TNNM (T) and SRWS fish passes (S). Most subpopulations were significantly distorted from HWE after Bonferroni correction, suggesting they were mixed populations**,** except E and F, which are small floodplains above NAKA and NAKO (Table 6.6). Subpopulations E and F had low genetic diversity and exhibited smaller effective population sizes (Table 6.5), indicating low gene flow in these two sections.

Table 6.6 Hardy-Weinberg equilibrium test for *Osteochilus hasselti* samples. P-values marked with asterisks are those that were significantly different after Bonferroni adjustment for multiple tests.

	Hmo34	BgOn75	NS16	Ost3	Ost5	Ost7
A	0.0256	0.3993	0.0000*	0.0000*	0.1250	0.1761
B	0.0052*	0.0000*	0.0000*	0.0004	0.0000*	0.1247
D	0.0551	0.0001*	0.0000*	0.0426	0.4697	0.7747
E	0.0000*	0.1100	0.0000*	0.2954	0.1740	0.3417
F	0.0196	0.1721	0.0143	0.4037	0.4483	0.0683
G	0.0000*	0.0496	0.0000*	0.0000*	0.1476	0.1773
T	0.0000*	0.1160	0.0000*	0.0000*	0.0055	0.1206
S	0.0000*	0.0000*	0.0000*	0.0000*	0.0568	0.0000*

6.4.2 Population structure of target species in the Nam Kam River System

Population structure of *Hemibagrus nemurus*

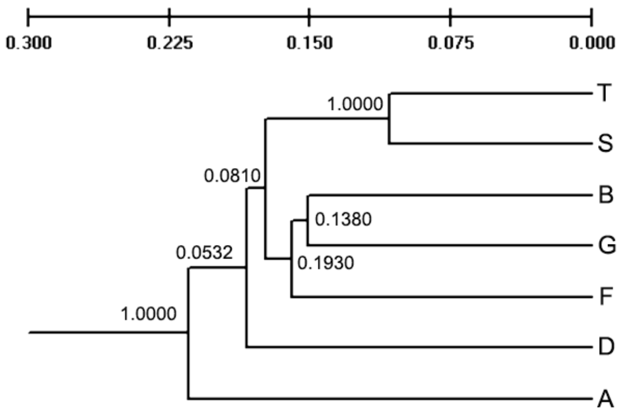
Among-sample variation indicated structuring, although weak, across all samples, (θ=0.0286±0.008; 95%CI: 0.0169-0.0523). Pair-wise estimates of F_{ST} of fish in the Nam Kam River system ranged from 0.0056-0.0580, indicating little to moderate genetic differentiation (Table 6.7). Similar small genetic distance results were found with the genetic differentiation test between pairs of samples based on microsatellite frequencies; they ranged between 0.1077-0.2395 (Table 6.7)

High bootstrapping values (1.0000) from UPGMA analysis also supported genetic differentiation between samples, with sample A isolated from the other samples (Figure 6.3 and Table 6.8). However, small genetic distance between each pair of samples indicated that the downstream sample (A) was similar to the upstream samples (B, F, G and D; Table 6.7). Migratory fish collected from TNNM fish pass at the onset of rainy season (T) and fish that migrate to Nong Han via SRWD fish pass at the end of rainy season (S) were grouped. This two sampling sites exhibited low genetic differentiation and small genetic distance between samples (Tables 6.7-6.8). This output suggests ongoing gene flow along of Nam Kam River system, caused by moderate levels of migration.

Table 6.7 Pairwise estimates of F_{ST} based on polymorphism of 6 microsatellite DNA loci and genetic distance of *Hemibagrus nemurus* sample in the Nam Kam River system.

	A	B	D	F	G	T	S
A	*****	0.0211^{ns}	0.0550*	0.0216*	0.0348*	0.0527*	0.0580*
B	0.1778	*****	0.0243*	0.0078^{ns}	0.0110^{ns}	0.0193*	0.0246*
D	0.2395	0.1757	*****	0.0260^{ns}	0.0337*	0.0305*	0.0304*
F	0.1988	0.162	0.1936	*****	0.0056^{ns}	0.0249^{ns}	0.0350^{ns}
G	0.2072	0.1509	0.1952	0.1568	*****	0.0148^{ns}	0.0260*
T	0.2367	0.1666	0.184	0.1946	0.1557	*****	0.0067^{ns}
S	0.2274	0.1617	0.1696	0.1973	0.1644	0.1077	*****

Above diagonal; Pairwise estimates of F_{ST} based on polymorphism of 6 microsatellite DNA loci. Statistical significant ($p<0.05$) indicated by superscript * and ^{ns} for non-significant ($p> 0.05$). Below diagonal; Roger's modified unbiased genetic distance (Wright, 1978) of *Hemibagrus nemurus* sample in the Nam Kam River system.



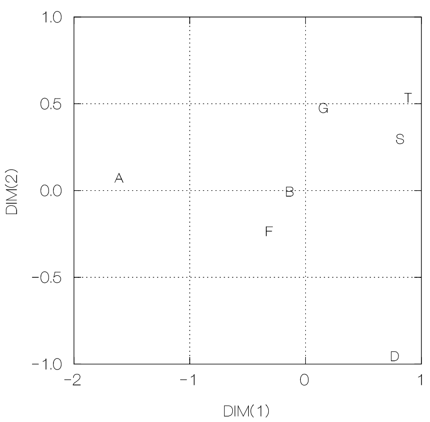


Figure 6.3 The unweighted pair-group method with arithmetic mean analysis (UPGMA) and Multidimension Scale analysis (MDS) of *Hemibagrus nemurus* samples from Nam Kam River system.

Table 6.8 Estimated genetic differentiation among *Hemibagrus nemurus* samples in the Nam Kam River system. P-values marked with asterisks are those that were significantly different after Bonferroni adjustment for multiple tests.

	Hw04	Hw08	Hw25	Hw26	Hw32	Hw35
A & B	0.0010*	0.0241	0.4772	0.0018*	0.0000*	0.3304
A & D	0.0000*	0.0000*	0.0150	0.0008*	0.0000*	0.0003*
A & F	0.0000*	0.0005*	0.2177	0.0116	0.0000*	0.7083
A & G	0.0000*	0.0000*	0.0086	0.0114	0.0002*	0.3495
A & T	0.0001*	0.0000*	0.0131	0.0002*	0.0000*	0.0000*
A & S	0.0002*	0.0000*	0.0086	0.0000*	0.0000*	0.0000*
B & D	0.0005*	0.1651	0.0131	0.0191	0.0087	0.0086
B & F	0.4096	0.8311	0.0760	0.0001*	0.0006*	0.7095
B & G	0.0434	0.1022	0.0082*	0.0316	0.0017*	0.0986
B & T	0.4262	0.0000*	0.0009*	0.0050*	0.0313	0.0041*
B & S	0.0600	0.0005*	0.0030*	0.0223	0.0000*	0.0000*
D & F	0.1840	0.8147	0.0115	0.0000*	0.0006*	0.0346
D & G	0.0011*	0.0000*	0.0015*	0.0417	0.2481	0.0005*
D & T	0.0107	0.0000*	0.0233	0.0507	0.0812	0.0040*
D & S	0.0000*	0.0000*	0.0038*	0.0022*	0.0000*	0.0016*
F & G	0.2078	0.0654	0.3868	0.0030*	0.1816	0.8598
F & T	0.5153	0.0000*	0.4257	0.0004*	0.0002*	0.0177
F & S	0.0364	0.0074*	0.0012*	0.0020*	0.0000*	0.0008*
G & T	0.0932	0.0354	0.0086	0.0227	0.0081*	0.0001*
G & S	0.0001*	0.6829	0.0000*	0.0000*	0.0000*	0.0000*
T & S	0.4059	0.3636	0.0083	0.0242	0.0534	0.0158

Population structure of *Osteochilus hasselti*

There were indications of weak genetic structuring of the *Osteochilus hasselti* population in the Nam Kam River system. Genetic differentiation between samples was relatively low but significant (θ=0.0317±0.0085, %95CI: 0.016-0.0456) indicating little genetic differentiation between samples in the Nam Kam River system and likely low level of migration.

Permutation testing indicated that some pair-wise estimates of F_{ST} were significantly different, except samples A E F and S (Table 6.9). The genetic differentiation test between pairs of samples based on microsatellite frequencies (Table 6.9) indicated small genetic distance between each pair of samples; ranging between 0.1547-0.2637. UPGMA analysis and genetic distance showed that population G exhibited higher genetic distance than other sampling sites (0.2158-0.2637), indicating that samples from G were different from the other samples (A, B, E, F and D).

Table 6.9 Pairwise estimates of F_{ST} based on polymorphism of 6 microsatellite DNA loci and genetic distance of *Osteochilus hasselti* samples in the Nam Kam River system.

	A	B	D	E	F	G	T	S
A	*****	0.0173*	0.0463*	0.0106^{ns}	0.0236^{ns}	0.0450*	0.0198*	0.0144^{ns}
B	0.1547	*****	0.0388*	0.0172*	0.0167^{ns}	0.0605*	0.0321*	0.0155*
D	0.2205	0.2008	*****	0.0361*	0.0469*	0.0683*	0.0508*	0.0226*
E	0.1517	0.1665	0.2076	*****	0.0049^{ns}	0.0645*	0.0330*	0.0174*
F	0.1989	0.1806	0.2357	0.1657	*****	0.0670*	0.0550*	0.0309^{ns}
G	0.2158	0.2416	0.2545	0.2567	0.2637	*****	0.0677*	0.0497*
T	0.1673	0.1894	0.2296	0.2078	0.2582	0.2579	*****	0.0276*
S	0.1425	0.1374	0.1618	0.1645	0.2113	0.2234	0.1757	*****

Above diagonal; Pairwise estimates of F_{ST} based on polymorphism of 6 microsatellite DNA loci. Statistical significant ($p<0.05$) indicated by superscript * and ^{ns} for non-significant ($p> 0.05$). Below diagonal; Roger's modified unbiased genetic distance (Wright, 1978) of *Osteochilus hasselti* sample in the Nam Kam River system.

Low bootstrap value indicated migratory fish migrated upstream to Nong Han (S) were not different from fish that migrated from Mekong River via the TNNM fish pass (T) and group of fish from further downstream (E, F, B and A), but genetically different from the fish sampled in the area downstream of the SRWD (G) (Figure 6.4 and Tables 6.9-6.10).

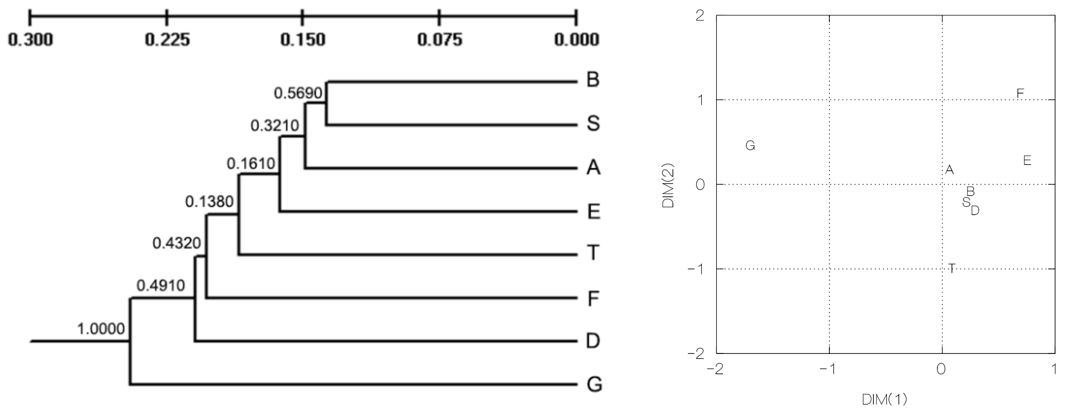


Figure 6.4 The unweighted pair-group method with arithmetic mean analysis (UPGMA) and Multidimention Scale analysis (MDS) of *Osteochilus hasselti* samples from Nam Kam River system.

Table 6.10 Estimated genetic differentiation among *Osteochilus hasselti* samples in the Nam Kam River system. P-values marked with asterisks are those that were significantly different after Bonferroni adjustment for multiple tests.

	Hmo34	BgOn75	NS16	Ost3	Ost5	Ost7
A & B	0.0022*	0.0018*	0.0000*	0.4211	0.0644	0.0018*
A & D	0.0000*	0.0000*	0.0000*	0.0003*	0.9976	0.035
A & E	0.0258	0.4223	0.0227	0.0019*	0.7413	0.8328
A & F	0.6684	0.4608	0.2190	0.0022*	0.7594	0.6867
A & G	0.0000*	0.0692	0.0000*	0.5734	0.8455	0.5960
A & T	0.0000*	0.7034	0.0000*	0.0000*	0.0427	0.6452
A & S	0.0049*	0.0000*	0.0024*	0.1232	0.7271	0.0000*
B & D	0.0010*	0.0000*	0.0000*	0.0002*	0.2726	0.4942
B & E	0.0000*	0.0092	0.0102	0.0040*	0.3957	0.0848
B & F	0.3806	0.3562	0.1709	0.0753	0.1000	0.1689
B & G	0.0000*	0.0000*	0.0000*	0.1766	0.3032	0.0632
B & T	0.0062*	0.0006*	0.0000*	0.0000*	0.0017*	0.0026*
B & S	0.1351	0.0001*	0.0034*	0.1928	0.6801	0.0000*
D & E	0.0000*	0.0000*	0.0000*	0.7416	0.8821	0.1342
D & F	0.0438	0.0000*	0.0001*	0.1172	0.9521	0.3809
D & G	0.0000*	0.0000*	0.0000*	0.0002*	0.9496	0.2596
D & T	0.0000*	0.0000*	0.0000*	0.0000*	0.1502	0.0511
D & S	0.0000*	0.0000*	0.0000*	0.0366	0.9299	0.0000*
E & F	0.0768	0.6572	0.5008	0.2203	0.5540	0.5906
E & G	0.0000*	0.0006*	0.0000*	0.0003*	0.8119	0.9300
E & T	0.0000*	0.0583	0.0379	0.0000*	0.4986	0.8723
E & S	0.0000*	0.0000*	0.2665	0.0931	0.6296	0.0381
F & G	0.0001*	0.0265	0.0000*	0.0000*	0.9008	0.5776
F & T	0.0402	0.3436	0.3648	0.0027*	0.2222	0.6706
F & S	0.9428	0.0208	0.3224	0.1514	0.3565	0.0404
G & T	0.0000*	0.0012*	0.0000*	0.0000*	0.2875	0.894
G & S	0.0000*	0.0000*	0.0000*	0.4692	0.3459	0.0019*
T & S	0.0000*	0.0000*	0.0003*	0.0000*	0.0150	0.0026*

6.4.3 Effect of fragmentation on genetic diversity and genetic structure

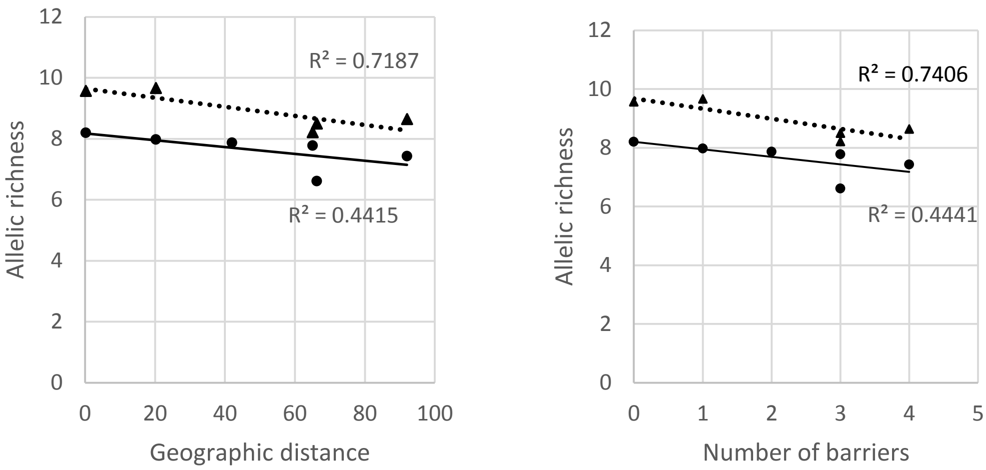
Low genetic diversity was observed in the upstream areas above many watergates. The present barrier arrangement in the Nam Kam is associated with declining genetic diversity. Allelic richness of two target species exhibited negative correlation with geographic distance (distance to the confluence of the Mekong River and number of barrier that limit upstream migration of fish) but it was different between the two target species (Table 6.11 and Figure 6.5). *Hemibagrus nemurus* shows higher correlation between allelic richness and geographic distance; distance from the confluence of Mekong River (r=-0.8477; Figure 6.5a) and between allelic richness and number of barriers (r=-0.8606; Figure 6.5b), while *Osteochilus hasselti* exhibited lower correlation between allelic richness and geographic distance; distance from the confluence of Mekong River (r=-0.6645; Figure 6.5a) and between allelic richness and number of barrier (r=-0.6664; Figure 6.5b).

Genetic differentiation tends to increase with the distance from the confluence of Mekong River and number of barrier that limited the upstream migration of fish.The lowcorrelation between genetic differentiation ($F_{ST}/(1-F_{ST})$ and geographic distance (distance from the confluence of the Mekong River and number of barriers) indicated slightly effect on population differentiation and migration of target species (Table 6.11 and Figure 6.6) and gene flow for these target species was restricted by watergate operation although it was not significant (Table 6.11).

Table 6.11 Result of generalized linear models aimed at testing the effects of fragmentation and the distance from the confluence of the Mekong River and number of barrier limiting upstream migration between samples.

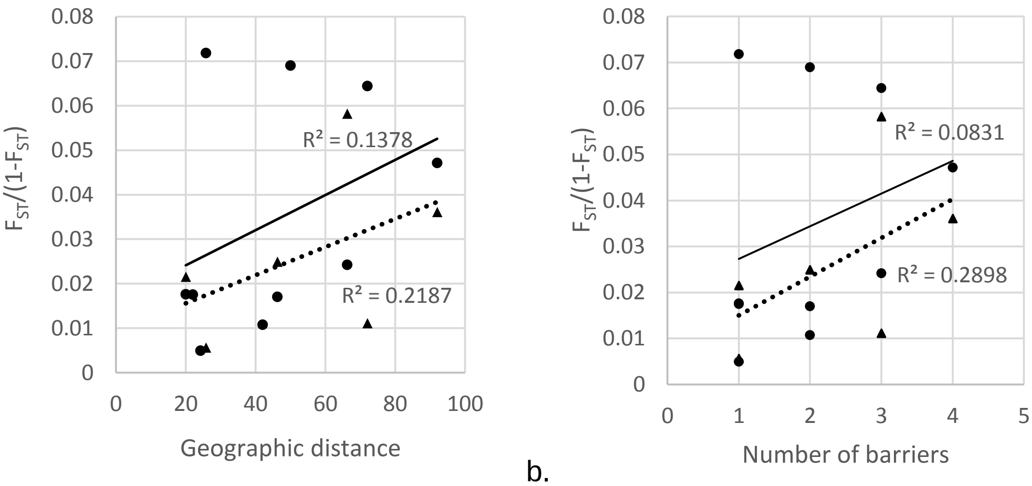
Geographic distance	Genetic diversity		Genetic structure	
	Allelic richness		FST(1-FST)	
	r	P value	r	P value
Hemibagrus nemurus				
Distance from the confluence of Mekong River (km)	-0.8477	**0.0001**	0.4676	0.6294
No. of barriers	-0.8606	**0.0001**	0.2883	0.3094
Osteochilus hasselti				
Distance from the confluence of Mekong River (km)	-0.6645	***P*****≤0.01**	0.3712	0.3923
No. of barriers	-0.6664	***P*****≤0.01**	0.5383	0.7181

Bold P-value is significant P≤0.05



a. b.

Figure 6.5 Univariate plots showing the upstream variation in genetic diversity. Correlation between genetic diversity (allelic richness (A_R) and geographic distance using generalized linear models (GLM). a. shows allelic richness variation in distance from the confluence of Mekong River for *Hemibagrus nemurus (*triangles; r=-0.8477, *P*≤0.01) and *Osteochilus hasselti* (dots; r=-0.6645, *P*≤0.01). b. shows allelic richness variation in number of barriers that limit upstream migration for *Hemibagrus nemurus (*triangles; r=-0.8606, *P*≤0.01) and *Osteochilus hasselti* (dots; r=-0.6664, *P*≤0.01).



a. b.

Figure 6.6 Univariate plots showing relationship between genetic differentiation ((F_{ST}/(1-F_{ST}) and geographic distance. a. shows F_{ST}/(1-F_{ST}) variation in distance from the confluence of Mekong River for *Hemibagrus nemurus (*triangles; r=0.4676, *P*≥0.05) and *Osteochilus hasselti* (dots; r=0.3712, *P*≥0.05). b. shows F_{ST}/(1-F_{ST}) variation in number of barriers that limit upstream migration between population for *Hemibagrus nemurus (*triangles; r=0.2883, *P*≥0.05) and *Osteochilus hasselti* (dots; r=0.5383, *P*≥0.05).

6.4.4 Estimating the contribution of fish for two target species (*Hemibagrus nemurus* and *Osteochilus hasselti*) that migrate into the river system on fish population upstream

Mixed stock analysis was used to estimate the contribution of two target species (*Hemibagrus nemurus* and *Osteochilus hasselti*) that recruit at the most upstream lake, Nong Han, at the end of flood season 2013. Recruitment of fish that migrated through SRWD fish pass to Nong Han was contributed by both the migratory fish from the Mekong River and subpopulations from along the river system.

Hemibagrus nemurus

The known-origin mixture analysis for *Hemibagrus nemurus* shows the expected and the estimated percent contribution (Table 6.12) for the species at each location. Results from the mixed stock analysis (Table 6.13) showed that sub-adult *Hemibagrus nemurus* that migrated through the SRWD fish pass to the Nong Han Lake in the late rainy season were mostly mature fish that migrated from the Mekong River via TNNM fish pass at the onset of rainy season (T; 73.0%). The contribution by fish from the downstream floodplain above the TNNM fish pass (B) was estimated at 10.0%. The remaining proportion were contributed by fish from each floodplain along the Nam Kam River (F and G: 8.1%) and the upstream sample of Nam Bang River (D: 7.6%). Most recruitment of fish in Nong Han Lake was contributed by fish that migrate from the Mekong River (73.0%) while the resident population in the Nam Kam River system contributed 25.3% (Table 6.13). This suggests a preferential migration flow in an upstream direction.

Table 6.12 Mixture results from *Hemibagrus nemurus* sample of known origin. Contribution indicates the proportion of the 100 *Hemibagrus nemurus* samples removed from each sample. Number in parentheses indicated 95% bootstrap confident interval based on 9999 permutations.

Population	Contribution	Estimates (w/ 95% ci)	
A	20	0.1674	(0.069 - 0.334)
B	20	0.2344	(0.057 - 0.366)
D	20	0.1736	(0.072 - 0.358)
F and G	30	0.3064	(0.082 - 0.471)
T	10	0.1183	(0.044 - 0.285)

Table 6.13 Proportion of sub-adult *Hemibagrus nemurus* caught at the Suraswadi fish pass (n= 194). Numbers in parentheses indicate 95% bootstrap confidence interval based on 9999 permutations.

Population	Estimates (w/ 95% ci)	
A	0.017	(0.000 - 0.110)
B	0.0969	(0.020 - 0.274)
D	0.0759	(0.022 - 0.223)
F and G	0.0806	(0.014 - 0.259)
T	0.7296	(0.436 - 0.785)

Osteochilus hasselti

The known-origin mixture analysis for *Osteochilus hasselti* (Table 6.14) proved that the observed genetic divergence was sufficient to apportion population mixtures to different sources. Results from the mixed stock analysis indicated that the population of *Osteochilus hasselti* that migrated to Nong Han Lake via the SRWD fish pass comprised of fish from Kudla-A floodplain (B; 34.8%) followed by resident fish from each floodplain along the Nam Kam River (E, F and G; 21.2%), Nam Bang River (D; 16.9%) and some early migrating fish sampled from the TNNM fish pass in the late migration period (T; 16.0%). The contribution from the most downstream sub-population at TNNM was small (A; 11.1%). Recruitment in Nong Han Lake was, therefore, mostly contributed by resident populations from the Nam Kam River system (73.0%) while recruitment added from the Mekong River was around 16.0% (Table 6.15).

Table 6.14 Mixture results from *Osteochilus hasselti* sample of known origin. Contribution indicates the proportion of the 100 *Osteochilus hasselti* samples removed from each sample. Number in parentheses indicated 95% bootstrap confident interval based on 9999 permutations.

Population	Contribution	Estimates (w/ 95% ci)	
A	15	0.1419	(0.042 - 0.298)
B	20	0.2045	(0.078 - 0.361)
D	20	0.1889	(0.066 - 0.291)
E, F and G	25	0.2492	(0.112 - 0.401)
T	20	0.2155	(0.094 - 0.348)

Table 6.15 Proportion of sub-adult *Osteochilus hasselti* caught at the Suraswadi fish pass (n= 194). Numbers in parentheses indicate 95% bootstrap confidence interval based on 9999 permutations.

Population	Estimates w/ 95% ci	
A	0.1108	(0.022, 0.288)
B	0.3482	(0.179, 0.485)
D	0.1692	(0.057, 0.288)
E, F and G	0.2123	(0.092, 0.354)
T	0.1595	(0.058, 0.292)

6.5 Discussion

Watergate construction and watergate operation in river systems can have serious consequences for fish and other aquatic organisms, especially migratory species that depend on connectivity between habitats to maintain population viability (Morita & Yamamoto, 2002). They may not only obstruct the migration of fish between habitat, especially species that depend on specific function habitat, but also genetically isolate and degrade the upstream populations. In the Nam Kam system, they possibly reduce connectivity among population of fish between the Mekong River and Nam Kam River and also within the Nam Kam River system. However, the results suggest these effects are minor in the Nam Kam system.

6.5.1 Does the watergate operation damaging the genetic diversity of fish in the Nam Kam River system?

Watergate design and operation are likely to have affected genetic diversity of fish in the Nam Kam River system. Weakly reduced genetic diversity in both target species, expressed as the number of alleles (A_R) and heterozygosities, was observed in areas upstream of the many watergates. Habitat fragmentation is the most important factor that impacts on species diversity loss; similar declines in genetic diversity have been reported in several studies that investigated the possible impact of isolation by distance+barriers and habitat fragmentation in isolated rivers (Hernandez-Martich & Smith, 1997; Yamamoto *et al*., 2004, 2016; Epps *et al*., 2005; Dixo *et al*., 2009; Blanchet *et al*., 2010; Dehais *et al*., 2010; Crookes & Shaw, 2016). The genetic diversity (both allelic richness and heterozygosities) decreased from downstream to upstream (Hernandez-Martich & Smith, 1997; Yamamoto *et al*., 2004; Blanchet *et al*., 2010; Dehais *et al.,* 2010), especially in small isolated populations (Dixo *et al.,* 2009). Significant genetic differentiation among populations was observed, especially for the isolated upstream area, the habitat where duration of isolation or number of years the watergates have been operating for longest. This site also exhibited higher genetic diversity loss (Yamamoto *et al.,* 2004, 2013; Kubota *et al.,* 2007; Blanchet *et al*., 2010). However, rate of decline in other studies were significantly greater than found in the present study because the Nam Kam River system is a partially fragmented river system, with all sluice gates open in the flood season but closed in the dry season; and this cycle is repeat every year. Therefore gene flow in this river was limited only in the dry season, which is just a short period. Gene flow is maintained in the flood season because the watergates are open and this enables spawning migration of most fish from Mekong River. Such an outcome was not found in other studies because they were conducted in areas isolated by a dam and fragmentation has occurred over many years.

Not all species of fish respond equally to river fragmentation; some species show species-specific sensitivity to fragmentation while others do not. Also the impact of migration barriers on the genetic integrity of a species depends on its biology, generation time and physical characteristics (e.g. size, and dispersal capacity) and genetic properties such as effective population size (Ne) (Hanfling & Weetman, 2006). *Hemibagrus nemurus,* which undertakes long distance longitudinal migration to its spawning area, shows the higher correlation between genetic diversity and number of barriers; diversity of this species tends to declined more rapid than *Osteochilus hasselti* in the area that is obstructed by many watergates. This suggests migration of *Hemibagrus nemurus* was more sensitive and possibly limited by the effects of barrier operations, it is more likely to be impacted by watergate operation than *Osteochilus hasselti* (Figure 6.5). Declining genetic diversity could be caused by the watergate and fish pass operation not being linked to the spawning migration; for example, the late opening of the watergates and fish passes at the onset of the rainy season limits the spawning migration of longitudinal migratory fish like *Hemibagrus nemurus,* while lateral migrating species like *Osteochilus hasselti* has less impacted.

Fortunately, most of the subpopulations of *Hemibagrus nemurus* from the floodplains along the river did not depart significantly from HWE; allele and genotype frequencies still remained constant (Table 6.4) except S. The distortion of allele frequency of S from the HWE indicated S is a mixed population. This was supported by the result from mixed stock analysis (Table 6.12) that sub-adult fish that migrate to Nong Han Lake at the end of the flood season were mostly contributed by fish from the Mekong River (T) and some fish populations from floodplains along the river system (B D F and G). This suggests that *Hemibagrus nemurus* migrated into the river system to spawn and most of the sub-adults did not occupy the river system to grow but migrated upstream to Nong Han or migrated downstream to the Mekong River instead. The Nam Kam River system is just a natural fish migratory pathway and not rearing and refuge habitats for this species.

However, *Osteochilus hasselti* behaves differently; most subpopulations along the river were significantly distorted from HWE after Bonferroni correction, suggesting they were mixed populations**,** except E and F, which are small floodplains above NAKA and NAKO (Table 6.6). Thus fish that migrate to spawn in this river system can utilize the floodplains for nursery grounds and adapt to contribute to the populations in the impoundment area of each section, except E and F that just discharge water to the downstream area in the flood season. This species has adapted and can breed in the impoundment areas (Vidthayanon, 2012). Floodplain E and F exhibited low genetic diversity and small effective population size when compared with the other sites, they mainly act as a channel for passing water to downstream areas; it thus might not be suitable for this species to inhabit because there was little floodplain habitat for fish to occupy. Samples from this area represent fish that are probably stranded when the watergates were completely closed in the dry season. High genetic diversity and big population size of migratory fish observed at the fish passes were supported by the mixed stock analysis (Table 6.14); young of the year fish at SRWD fish pass were mixed stock mostly contributed by fish from downstream fish passes (T) and floodplains along the river (B, D, E, F and G). Further information about rate of migration and rate of gene flow and migration pattern of the target species will be presented in Chapter 7.

The effective population sizes (Ne) of two target fish species from the Nam Kam River system were relative high (8.4 to 376.9), except for some sections that effectively only pass water to the downstream sections during the flood period. (Tables 6.3 and 6.5). Generally, if fish are only migrating through the section and not using it for spawning or breeding, they would not generate gene flow in that part of the river system. Dispersal of organism impacts on population size, with populations that exhibit free movement normally exhibiting higher effective population sizes while isolated populations usually show small Ne sizes (Blanchet, 2010; Dubreuil *et al*., 2010; Yamamoto *et al.,* 2015; Crookes & Shaw, 2016). Overall population size of *Osteochilus hasselti* is still high, compared with population sizes of cyprinids with a long history of inhabiting fragmented landscapes (Yamamoto *et al,* 2004). Genetic differentiation of *Hemibagrus nemurus* from this study is slightly higher than that observed in a river with non-functional fish passage facilities, i.e. Pak Mun River (13.2-30.9 Approx. 95% CI 8-58.6) (Hanpongkittikul *et al.,* unpublished). This suggests that effective fish passage management could mitigate the impacts of watergates on genetic differentiation in river systems.

The small Ne observed at some floodplains along the river support the argument that these sections of the Nam Kam River are fish ways and not refuge or residential areas for *Hemibagrus nemurus*. Similarly, the floodplains above NAKA and NAKO watergates have small Ne population size, again suggesting they are not rearing grounds or refuge areas for *Osteochilus hasselti*. Ne values for migratory fish observed at the Thoranit Naruemit fish pass and in the downstream area connected with Mekong River were bigger than those at floodplains above upstream watergates, suggesting that upstream migration of fish is partially limited by watergate operation. Anomalies were found with individuals that migrate at the end of flood season but were blocked in the upstream floodplain areas due to the watergates already being closed. Fortunately, the population size of fish migrating through the fish passes at Thoranit Naruemit and Suraswadi watergates, in the migration period were quite big. Also the watergates are fully open in the flood season so the Nam Kam River is only seasonally fragmented and not a permanently isolated system. At the same time, migration of fish is also supported by fish pass operation at the onset and the end of the rainy season. It suggests that fish passage facilities in the Nam Kam River system are effective in supporting the migration of fish and could mitigate the impact of weir operation on genetic diversity loss.

The use of *Ne* plays an important role in the conservation management of fishes. It is a direct measure of the rate of loss of diversity and the rate of increase in inbreeding within a population (Wright, 1969; Frankham, 1995: Frankham *et al.,* 2002). A minimum *Ne* of 500 is proposed for the long-term preservation of genetic diversity and adaptability of a population (FAO, 1981; Franklin, 1980; Nelson & Soulé, 1987). This study showed that although all sample sites have quite big effective population sizes they are still smaller than recommended for natural populations and may indicate bottlenecks in the recruitment of the populations.

6.5.2 Does population structure of fish indicate any impact from watergate operation?

Watergates, dams or any construction in the river that might partially impede the dispersal between areas above and downstream of the structure may result in higher levels of genetic structure (higher F_{ST} values) or highly significant genetic differentiation because of the fragmented landscape (Yamamoto *et al,* 2004; Blanchet *et al.,* 2010). The presence of barriers between sampling sites tends to increase genetic differentiation between subpopulations in fragmented rivers (Yamamoto *et al,* 2004; Epps *et al*., 2005 Raeymaeker *et al.*, 2008; Blanchet *et al.,* 2010), but Mantel's test suggested this was not the case for *Hemibagrus nemurus* and *Osteochilus hasselti* populations in the Nam Kam River system. Fortunately, most pairwise F_{ST} comparisons in the Nam Kam exhibited relatively low, but significant, genetic differentiation among populations. Thus fish in the Nam Kam River system appear to comprise many subpopulations with little genetic differentiation between samples when following the qualitative guidelines to interpreted F_{ST} values by Wright (1978). This is also supported by the moderate levels of migration that can be interpreted from the F_{ST} values (Hartl & Clark, 1997). Small genetic distance and genetic differentiations between subpopulations support the occurrence of gene flow in this river, although there is the series of watergates in the river system (Table 6.5-6.8). Maintaining gene flow between two populations can lead to the combination of two gene pools and thus reduce genetic differentiation between populations (Nei, 1978). Results from this study revealed that genetic diversity is maintained by gene flow from the downstream populations and nearby populations when the watergates are opened, especially in the flood season, which is the spawning season for most species in this river system. Therefore fully opening the watergate sluices in the flood season and installing effective fish passage facilities can mitigate impact on fish migration, which is the key factor affecting the diversity and population structure of fish in river systems.

Migratory *Hemibagrus nemurus* from TNNM fish pass (T) and SRWD fish pass (S) were closely related indicated that there was gene flow occurance between two area. Moreover, results from the mixed stock analysis indicated subpopulation S was mostly contributed by subpopulation T (72.96%; Table 6.13). Size distribution of migratory sub-adult fish migrated through SRWD fish pass to Nong Han (S) were smaller than size of fish from TNNM (T; Figure 7.5). Therefore, the small fish that migrated to Nong Han at the end of flood season possibly be the offspring of the migratory adult fish migrated from Mekong River at TNNM fish pass at the onset of rainy season. This indicated biology of *Hemibagrus nemurus* that adult fish took the longitudinal migration from the Mekong mainstem to spawn in the tributary, after larvae hatched and developed in the floodplain along river, small fish migrated to Nong Han at the end of flood season.

Weak genetic structure and little genetic differentiation *Osteochilus hasselti* population indicating the occurrence of gene flow between populations, and it is supported by the result from Chapter 7; the small number of effective migrants per generation in the Nam Kam River system (8.38; Table 6.15). Mixed stock analysis also supported sub-adult fish that migrated through SRWD fish pass were young of the year fish that migrate from the Mekong River via TNNM fish pass and the other floodplains along the river system, especially from the downstream floodplain at SRWD (Table 6.15), which comprised several man made ponds that permanently store water in the dry season.

Pair-wise estimates of F_{ST} indicated *Hemibagrus nemurus* below TNNM and in the TNNM fish pass (A and T) were genetically different (Table 6.7), although fish that migrate upstream through the TNNM fish pass possibly migrated through or migrated from the area below TNNM watergate or both populations possibly originated from the same sourse: the Mekong River. This is because the timing of sampling were different; sample at T was fish that migrated upstream through the TNNM fish pass at the onset of flood season, while samples from A were collected downstream of TNNM at the end of flood season. Therefore, fish collected at the end of flood season could be the late migrating fish that migrated upstream from Mekong River. It also indicates a number of different populations in the Mekong River.

The subpopulation of *Osteochilus hasselti* at the most upstream sampling sites (G) was genetically different from the subpopulations downstream, possibly because the sample was collected before fish that had migrated from the downstream area arrive at this site and thus represent the resident population in Nam Kam River (Table 6.9). The other subpopulations were grouped indicating gene flow and migration between these sampling sites and this was supported by the low to moderate levels of genetic differentiation and genetic distance between subpopulations (Table 6.9).

Weak genetic structure and low genetic differentiation (F_{ST} and genetic distance) of the two target species also indicated that the subpopulations in the river system were not very different from each other (Table 6.7 and 6.9). Watergate operation, especially in the migration period, aids fish to migrate to habitats (spawning area and rearing grounds) in the upstream areas and permits gene flow into the upstream populations therefore the subpopulations in the river system were not very different from each other. Moreover, populations of adult fish migrated through the TNNM fish pass and sub-adults that migrated upstream through SRWD fish pass to Nong Han swamp exhibited big population size and high genetic diversity in the two target species and this supported the occurrence of gene flow in the river (Table 6.3 and 6.5). It suggests that watergate and fish pass operation is an important procedure that could mitigate impact on migration of fish in the river system. Many watergates are only passable during the flood period, when all of the sluice gates are fully opened and water velocity reduced, which increases the opportunity for upstream migration and also allows the passive drift of juveniles during this period.

6.5.3 Contribution of fish that migrate into the river system on fish population upstream

Results from the mixed stock analysis (Tables 6.13 and 6.15) also supported the assertion that target species that migrate upstream to Nong Han Lake are represented by a subpopulation that migrates from the Mekong River and subpopulation from the floodplains along the river, although they contribute in different proportions to the two species tested. However, two target species exhibited gene flow in the river system. *Hemibagrus nemurus* that migrated through TNNM fish pass at the beginning of the rainy season contributed most to the sub-adult population that migrated to Nong Han via SRWD fish pass a few months later. This also supports the conclusion that adult fish migrated to spawn in the Nam Kam River system at the onset of rainy season while young *Hemibagrus nemurus* migrate to upstream areas at the end of flood season for feeding opportunities. By contrast, *Osteochilus hasselti* recruited to Nong Han Lake was mostly contributed by resident populations along the Nam Kam River system. The different contribution of fish from Mekong River to Nong Han Lake was depended on biology of fish, timing and duration that fish migrate, coupled with watergate operation at that particular time.

This output is underpinned by observations on the location of spawning and rearing grounds of fish in the river system, which are in the floodplain areas upstream (Chapter 5). The contribution of recruitment to the populations of the two target species in the Nam Kam River is different due to differences in the reproductive biology and migration patterns: migration of *Hemibagrus nemurus* in the flood period was quite successful indicated it is longitudinal migrating species, but migration was quite limited for *Osteochilus hasselti*. These two target species represent fish from different groups -catfishes and carps- which are the dominant migratory species groups observed on the fish pass. It is known that barriers have a major impact on population isolation or habitat fragmentation, therefore practical management solutions to restore genetic integrity of the populations, as achieved in the Nam Kam, is needed and recommended for other fragmented systems where applicable.

6.6 Summary

Watergate operation in the Nam Kam River system has restricted the upstream migration of fish from the Mekong River and within the river system in the wet season and completely obstructed migration in the dry season. The impact on genetic diversity and population structure was examined in two species, *Hemibagrus nemurus* and *Osteochilus hasselti*, which represent longitudinal migratory and lateral migratory species.

Genetic diversity of *Hemibagrus nemurus* is relatively high, with moderate population size and weak structuring of population suggesting the cascade of watergates in the Nam Kam River system do not represent a closed system, but fish can migrate to their upstream spawning habitat and reproduce each year. Subpopulations along the river are not distorted from HWE and most juvenile *Hemibagrus nemurus* that recruited in the upstream lake have a major contribution from fish that migrate from Mekong River year by year (Chapter 5). Thus the Nam Kam River system functions as the spawning and nursery ground for *Hemibagrus nemurus*, and the natural fish migratory pathway between Nong Han and the Mekong River, but not refuge habitat for *Hemibagrus nemurus*.

Osteochilus hasselti exhibited lower genetic diversity than *Hemibagrus nemurus*, population structuring is weak, and population size at each block of river is moderate except in some areas where watergates are passable in flood season. This species is able to adapt to the impoundment conditions and inhabit occupy many parts of the river when all watergates are completely closed in the dry season. This is supported by the populations showing departure from HWE, indicating that *Osteochilus hasselti* was mixed stock, fish can adapt to grow and breed in the impoundment habitat. Mixed stock analysis (Chapter 5) also supports the assertion, because sub-adult *Osteochilus hasselti* that migrate to Nong Han at the end of flood season were mostly contributed by subpopulations from along the river system.

The two target species responded differently to the watergate operation; genetic diversity of both target species was weakly reduced according to the number of barriers, however, diversity of *Hemibagrus nemurus* tend to decline more rapid than *Osteochilus hasselti* in the area obstructed by many watergates. It suggests that migration of *Hemibagrus nemurus,* which is a longitudinal migratory species, is more sensitive and likely to be limited by the effects of watergate operation than lateral migrating species like *Osteochilus hasselti*. However, rate of decline is less than found in similar studies. Weak genetic structure and low genetic differentiation of the two target species indicates that subpopulations were not different from each other. Watergate operation in the wet period appears to facilitate migration and permit gene flow in this river system. It is supported by high genetic diversity and big population size of two target species. Genetic diversity is maintained by gene flow from the downstream populations and nearby populations when the watergates are opened, especially in flood season which is the spawning season for most species in this river system. Information about gene flow and migration rate is presented in Chapter 7.

The conclusion that a series of watergates has limited genetic impact on the two species investigated does not mean that there is no impact on other species in the Nam Kam River system. The results indicate that watergate operation is an important factor to maintain genetic diversity and population structure, especially in systems fragmented by a cascade of barriers.

Mixed stock analysis of two target species was used to determine the role of migration to the contribution of different stocks in this river system. Variation in recruitment of the two target species (*Hemibagrus nemurus* and *Osteochilus hasselti*) is according to differences in their reproductive biology; they represent different migratory guilds and spawning habitats. Larvae and juveniles of these guilds are normally found in the floodplain areas in flood season and thus account for the lack of difference between sampling sites. Thus, it appears that migratory species can reach the upstream areas in the Nam Kam, but recruitment might not be adequate to maintain diversity of fish in this river system. Recruitment appears to be limited by watergate operation since diversity and abundance of larval and juvenile fishes in the upstream floodplain was lower than the downstream floodplain and lower than the free-flowing river. There is a need to examine the quality of young of the year populations in the Nam Kam River and genetic diversity and effective population size of fish in this river (see Chapter 6).

Chapter 7: Patterns of fish migration in the Nam Kam River system

7.1 Introduction

The impact of dams and watergate structures on river systems and their associated biota can be considerable. They cause fragmentation at the location of the structure and river systems have been replaced by lacustrine environments. Barriers on rivers can cause fish population decline and limit the potential for numerous fish species to access different habitats needed to complete their life cycles, by isolating migratory fishes from their spawning and nursery grounds (Barthem *et al.,* 1991; Wei *et al.,* 1997; Ruban, 1997; Agostinho *et al.,* 2005). In addition, it is possible the loss of habitats and restrictions to the free movement, and thus distribution, of fish, could induce significant genetic differentiation between populations in river systems (Laroche & Durand, 2004), limit gene flow between populations (Neraas & Spruell, 2001), genetically degrade upstream populations and reduce genetic polymorphism within populations (Knaepkens *et al.,* 2004).

Currently, the Nam Kam River and its tributaries are impounded by a number of large watergates and sluices and most are fitted with fish passage facilities to aid fish migration. Srisatit *et al.* (1981) and Pongsri *et al.* (2008) reported on the ability of fish to migrate through three fish passes in the upstream reach of the Nam Kam River to Nong Han swamp. Ngoichansri *et al.* (2013) found 95 species of fish from the Mekong River passed through the series of Nam Kam fish passes in the early rainy season of 2012, most of which were mature and ready for spawning. Juveniles and sub-adult of several species also migrated upstream through the fish pass at the last watergate into Nong Han Lake at late rainy season (a few months after the upstream migration of mature adults). However, evidence that those juveniles are offspring of migratory fish from the floodplains in the lower reaches of the Nam Kam is not available. Similarly, several species of fish passing through the farthest downstream pass are different from those that pass through the upstream passages (Pongsri *et al*., 2008; Ngoichansri *et al*., 2013), but the whereabouts and source of fish passing through the fish passes has not been studied and little is known about the impact of watergate management on fish migration and the effect on genetic diversity, population size and structure, and recruitment of fishes in the area.

In this study physical tagging and genetic tagging were used to evaluate whether five watergates on the mainstem Nam Kam and two watergates on Nam Bang were barriers to migration of two economically important fish species (*Hemibagrus nemurus* and *Osteochilus hasselti*) that utilize the Nam Kam River system. Modified t-bar anchor fish tags were used to identify preferential migration routes of target fish such as direction, distance and duration of migration and ability to pass the watergate, while microsatellite DNA was used as a biological marker to assess population structure and migration patterns in the study area, as well as to determine effective number of migrants, migration rates, level of gene flow and genetic differentiation between subpopulations. Tagging was also used to evaluate the likely impact of water resources management and hydrological changes on migration patterns of target species along the Nam Kam River and its tributary. The information from this proposed study can be used to assist management of water resource scheme for the Nam Kam irrigation system to sustain fish production. It will also be transferrable to other water regulation schemes throughout the Mekong.

7.2 Objectives

1. To determine migration patterns of two economically important fish species migrating through fish passes and further into the Nam Kam River using physical tagging and genetic tagging.
2. To evaluate migration triggers of target species in the river system.
3. To evaluate likely impact of watergate operation and eco-hydrological change on migration patterns of the target species in the Nam Kam and its tributary by testing the hypothesis if the hydrological regime initiates isolation of populations in the river system.
4. investigate efficiency of the watergate operation and fish passage facilities to support the fish migration in the regulated Nam Kam River system.

7.3 Methodology

7.3.1 Sampling

Migration fish that migrated through the TNNM fish pass in the flood season were considered from number, length and weight of fish collected by seine netting in the pool upstream of TNNM fish pass both day and night time (every 6 hr.) during the upstream migration period (between May–August 2013). Mosquito nets were used to cover the exit orifice of the most upstream pool for one hour to restrict the upstream migration of fish and to prevent the downstream drift from the fish pass exit, so migrating fish were trapped at the most upstream pool. Then entry orifice of the most upstream pool was then blocked before doing the seine net sampling.

Physical tagging and genetic tagging were used to determine migration patterns of two economically important fish species (*Hemibagrus nemurus* and *Osteochilus hasselti*) after migrate through all fish passage facilities on the Nam Kam River.

7.3.2 Physical tagging

Samples of the two target species were collected by seine netting at the most upstream pool of the TNNM fish pass (Figure 7.1). The number of fish was recorded and target fishes tagged with modified plastic tag for clothes to use as t-bar anchor fish tags (Figure 7.2) and fin samples were taken for DNA analysis. Fish were then treat with antiseptic solution, and held in an aerated tank to recover before being released above TNNM (i.e. in the reservoir; Figure 7.1). The target number of tagged fish was set as at more than 4,000 (as much as possible). The procedure from capture to release of tagged fish was kept as short as possible to minimize handling stress of fish (Thorsteinsson, 2002).

7.3.3 Recapture process

Information about the project was provided to fishers upstream by meeting with fishing community organizations and river basin organizations. Information about location, capture date, length (weight and picture if possible) and tags were collected by fishers who recovered tags in upstream areas within 5 months after tagging.

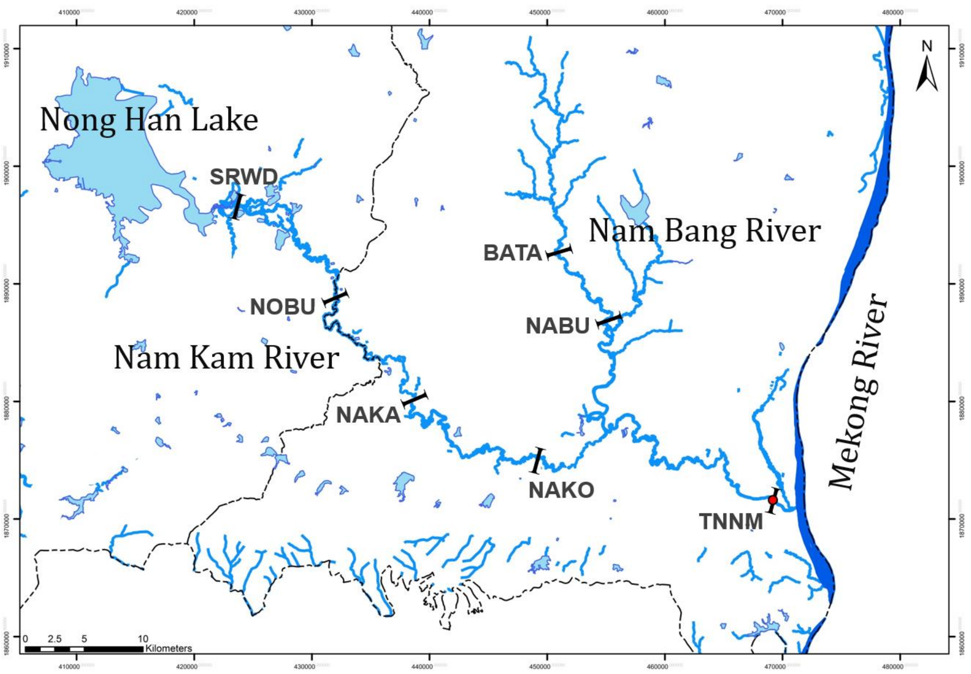


Figure 7.1 Location of tagging and releasing point: Thoranit Naruemit Watergate (TNNM).

Figure 7.2 Process of fish tagging. A: Tagging gun B: modified T-bar anchor tag (colours on tag represent the code of tagging date) C: Fish tagging D: Tagged fish; D1: *Osteochilus hasselti* and D2: *Hemibagrus nemurus.*

7.3.4 Genetic tagging

Microsatellite DNA markers were used to assess the migration patterns of *Hemibagrus nemurus* and *Osteochilus hasselti* as uses simple sequence repeats that are widely found in the genomes of most organisms. Genotyping data of fish that migrated upstream through TNNM fish pass, were used to matching with the genotyping data from fish that migrated through SRWD fish pass and fish from the other floodplains above each upstream watergates (from 6.3.2) to assess migration patterns in the Nam Kam River system and evaluate impact of watergate operation.

7.3.5 Data analysis

Upstream migration

Migration patterns of target species from Mekong River through TNNM fish pass

The number of fish, length, and weight of fish sampled from the TNNM fish pass in the migration period (from 7.3.1) represents fish that have migrated at the particular time (individual / 1hr) and was used to calculated the number of fish that migrated through the fish pass in one day (individual /day). The secondary data of fish migration in flood season 2012 provided by Ngoichansri *et al.* (2013), were used to investigate migration patterns of fish through the TNNM fish pass.

The influence factors and the restriction to fish migration were identified from abundance of fish that migrate into the river system in relationship with hydrological data from Chapter 3 (discharge, rainfall, lunar phase, flow in the fish pass and turbidity).

Moreover, amount of fish migration through the fish pass indicated the effectiveness of the fish passage facility in the Nam Kam River system.

Migration pattern of target species after migrated through TNNM fish pass

Information from the physical tags recovered was used to estimate the migration pattern of fish including migration period, distance travelled, time taken from the released point to the recapture area, and recaptured area, direction of migration and the purpose of migration. Reproductive biology of tagged fishes (secondary data provided by Ngoichansri *et al.* (unpublished) and Ngoichansri *et al.,* 2013) were also used to describe the migration patterns of fish.

Changing of catch data from gill net sampling (Chapter 4) and seine net surveys (Chapter 5) carried out between June 2014 and February 2015 were also used to determine upstream and downstream migration patterns in the regulated Nam Kam and unregulated Songkhram river systems.

The SHAdow Zone Analysis software (SHAZA) program was used to estimate % recapture corrected calculated by matching genotype of tagged adult fish that migrated through Thoranit Naruemit fish pass and adult fish sampled from each sampling site in the Nam Kam River system. This program is open source and can be downloaded from http://www.molecularfisherieslaboratory.com.au/shadow-zone-analysis-software-shaza/.

Downstream migration

Downstream migration of adult fish and drifting downstream of larval and juvenile were considered from changes of diversity and abundance of fish (from Chapter 4), larval and juvenile (from Chapter 5) at the end of flood season.

Distribution and migration patterns were determined through population structure and genetic differentiation of fish populations in each area (from Chapter 6) as well as, genetic distance between population (from Chapter 6), and correlation between geographic distance and genetic differentiation (Chapter 6) and migration rate and number of migrants per generation that indicated gene flow among population.

Effective number of migrants per generation (*Nm*)

Migration is the movement of organisms from one location to another. When used in a population genetics context, it usually means the movement of individuals into or out of a specified population. If the migrant stays and mates with the destination individuals, they can deliver a sudden influx of alleles. After mating with destination individuals, the migrants will add gametes carrying alleles that can modify the existing proportion of alleles in the destination population. Gene flow includeds all mechanism resulting in the movement of genes from one population to another, and it sometime called migration when migration between established population is the mechanism of gene flow (Slatkin, 1983) Gene flow explains the movement of alleles between previously separate populations initiated by migration and consequent mating (Miko & Le Jeune, 2009). Effective number of migrants (*Nm*) is a relative gene flow parameter, it represents amount of gene flow among populations and explains the number of reproductively successful individuals that can transfer their genetic inheritance among populations. It is well known that *Nem* or *Nm* can estimated from Fst. The expectation of F_{ST} is given by $F_{ST}=1/(1+4\,Nm)$ in the island model with equal effective sizes of subpopulations (*N*e) and uniform migration rates among them (*m*) (Wright, 1951; Slatkin, 1978). When *Nm* is large, F_{ST} is small because there is little difference in heterozygosity between subpopulations, while F_{ST} is large when *Nm* is small. In this study *Nm* were obtained from molecular data (Chapter 6) using the private allele method performed in GENEPOP, version 3.4 (Raymond & Rousset, 1995). Actual gene flow or *m* could be very high or very low depending on the value of *Ne* (Wright, 1951).

Effect of watergate operation on the relative gene flow parameter (*Nm*)

The barrier effect distance was quantified to determine if the watergate operation had affected gene flow (in this study focus on gene flow caused by fish migration). The reduction in the relative gene flow parameter (*Nm*) caused by barriers among populations were estimated. Multiple regression on all pairwise population comparisons was used to estimate the degree of correlation between the metrix of geographic distances between population and effective number of migrant (Nm), was tested using the Mantel test in the TFPGA program (Miller, 1997) with 10,000 permutations with the Spearman Rank correlation coefficient as statistical test (Mantel, 1967). Geographic distance can be expressed in distance between populations (in km) and also number of barriers between populations (Dehais *et al.,* 2010).

The impact of watergate operation and flow modification on the migration patterns of the two economically important fish species were evaluated by testing four hypotheses to determine, if the series of watergates is an obstacle to fish migration in the river: (1) genetic diversity (see Chapter 6), in the isolated upstream population should be less than those of downstream populations (2) significant genetic differentiation should be observed between subpopulations determined from the F_{ST} statistic and genetic distance (see Chapter 6), (3) 'Isolation by distance+barriers' should be observed in the floodplains above the watergates if the watergates act as barriers (See Chapter 5), and (4) the relative gene flow parameter or effective number of migrants (Nm) between samples should be low if gene flow is interrupted by watergate operation.

7.4 Results

7.4.1 Migration of fish via the Thoranit Naruemit fish pass

Migration of fish from the Mekong River into the Nam Kam River system started at the onset of the rainy season from the end of May to the end of July 2013 and included a few days in October 2013 (Figure 7.3). As soon as the most downstream watergate, Thoranit Naruemit (TNNM), started to release water following release from the other upstream watergates, many migratory species were observed in the fish pass. This suggests upstream migration into the fish passage facility was triggered by the hydrological change created by watergate operation (Figure 7.3). A total of 440,015 fishes from 83 species of 21 families were recorded migrating from the Mekong River through the fish pass at TNNM. The total weight of fish migrating was 10,946.20 kg over a period of 60 days. The majority of fish migrated in the first week of operation (85.3 % of the total fishes observed) with an average migration rate of 46,831 individuals/day or 607 kg/day. The most abundant species in the first period or the early migrating species, were *Sikukia gudgeri, Dangila lineatus, Hypsibarbus malcomi, Laides longibarbis, Hypsibarbus wetmorei, Osteochilus hasselti, Poropuntius bantamensis* and *Barbonymus altus*. Cyprinids were the dominant group migrating in the daytime while bagrids and silurids were dominant during the night.

There was no difference between numbers of fish species that migrate at day and night time while abundance of fish that migrated in day time was more than night time (93.03-95.80% and 4.18-6.97%). The most abundant species observed in the fish pass were cyprinids (45 species) which contributed 54.9% of fishes recorded. The top ten species migrating were *Sikukia gudgeri, Labiobarbus lineatus, Hypsibarbus malcomi, Barbonymus altus, Osteochilus hasselti, Hypsibarbus wetmorei,* *Hemibagrus nemurus, Puntioplites proctozystron, Laides longibarbis* and *Poropuntius bantamensis.* After the main sluice gates were opened to maximum capacity in August, no fish were seen using the fish pass as it was easier to migrate through the main sluice (Figure 7.3).

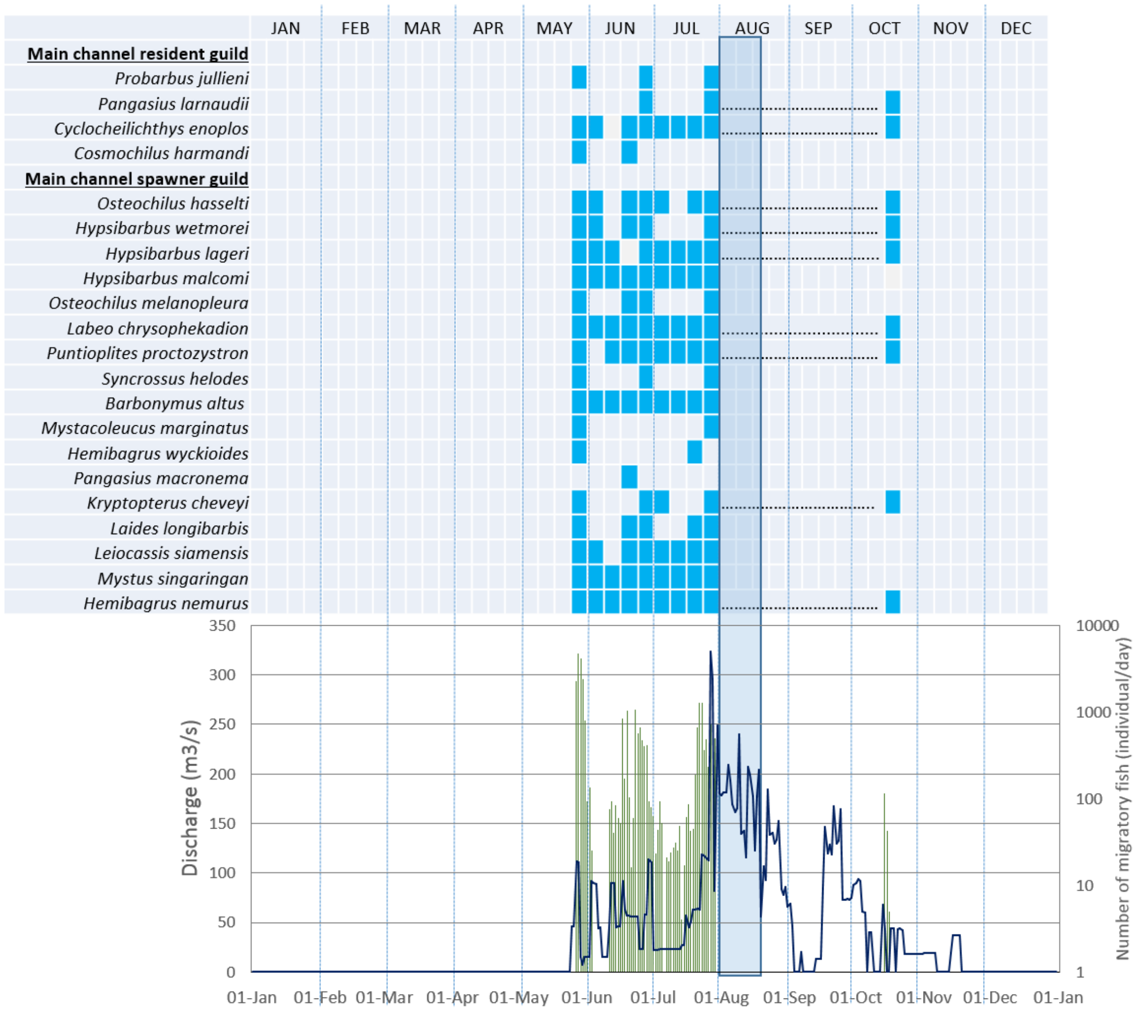


Figure 7.3 Upstream migration patterns of migratory species (very high impact species) at Thoranit Naruemit fish pass during 2013. Blue squares represent the period that fish migrate through the fish pass. Dotted line represents the time fish can migrate directly through the main sluice gates when the watergates were opened. The lower graph represents the number of individual fish that migrated through the TNNM fish pass against hydrological discharge at TNNM watergate. Blue rectangular represents the period that TNNM watergate was opened to maximum capacity. Blue line represents the discharge from TNNM watergate while the green bars represent the number of fish that migrated through TNNM fish pass.

Upstream migration through the fish pass was also recorded for three days at the end of the flood season (late October), and involved 20 of the same species as at the start of the flood season, but at a lower rate of passage (average 184 individuals passing per day). Fish migrated through the pass at a range of discharges through the main sluice gate (between 8-323 m^3/s; Figure 7.3). Athough the operational period for the fish passes was quite limited and restricted to the period of watergate operation, they supported the upstream migration of many species that would likely be impacted by watergate operation or the construction of dam in the mainstem river, including main channel resident and main channel spawning species (Figure 7.3).

The range of flow velocities at the TNNM fish pass during the migration period was 0.12-3.68 m/s, but upstream migration through the fish pass was only observed at velocities between 0.95-3.08 m/s.

Size distribution of migrating fish

The size of fishes that migrated through the TNNM fish pass in 2013 range between 45-700 mm (Figure 7.4); most were mature and ready for spawning. This observation suggests upstream migration of fish in the Nam Kam River system during this time is for reproduction.

Further evidence to support spawning migration of fish from Mekong River into the Nam Kam River system can be found from size frequencies of the two target species at the most downstream fish pass at the onset of rainy season and the upstream fish pass in a few months later (Figures 7.4-7.5) and development of juvenile fish along the river (Table 5.8). Size frequency of *Hemibagrus nemurus* migrated at TNNM fish pass at the onset of rainy season indicated they were mature fish (125-520 mm; Figure 7.5a). Juvenile fish observed in the floodplains along the Nam Kam River (DK and KA) in August sized between 44 and 96 mm long, and increased to between 95 and 354 mm by the time they pass through SRWD fish pass in October (Figure 7.5a). Similar result were found in *Osteochilus hasselti;* fish from TNNM were mature fish (83-274 mm) while the size distribution of juvenile fish observed in floodplains along the river (NK and KA) in August was between 18-43 mm, and increasing to 27-60 mm between September and October. Additionally, sub adult observed at the SRWD fish pass at the end of flood season were ranged between 42- 248 mm (Figure 7.5b).

Size frequency of fish from the fish passes and changes in size distribution of juvenile fish from floodplain along the river system indicated the spawning migration and the development of fish in the Nam Kam River system. Small size of fish that migrated through SRWD fish pass on October 2013 were possibly young of the year offspring of mature adults that migrated from Mekong earlier in the year.

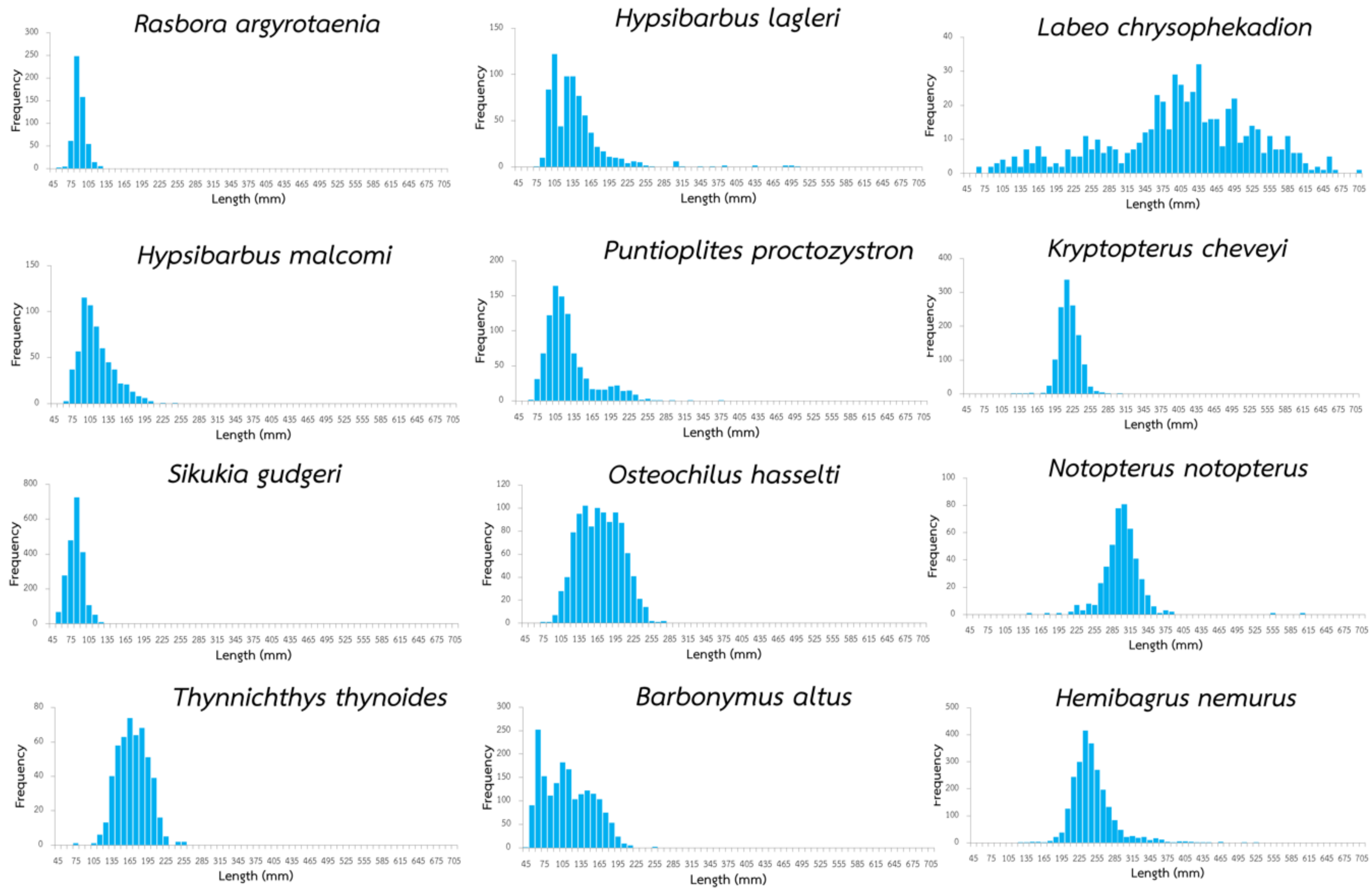
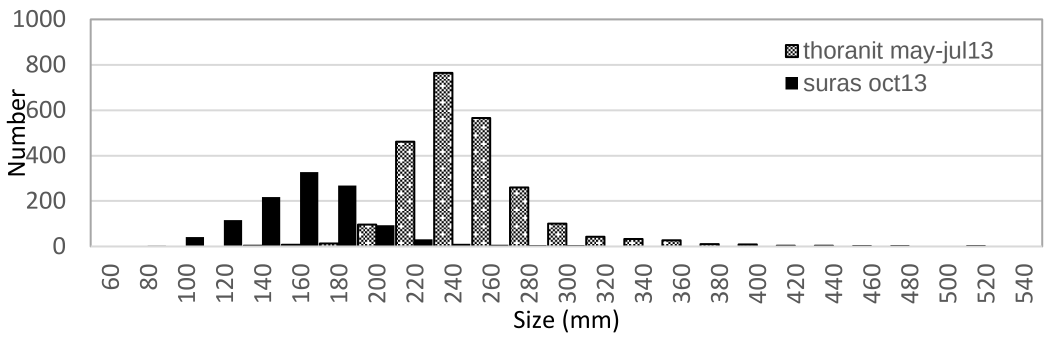
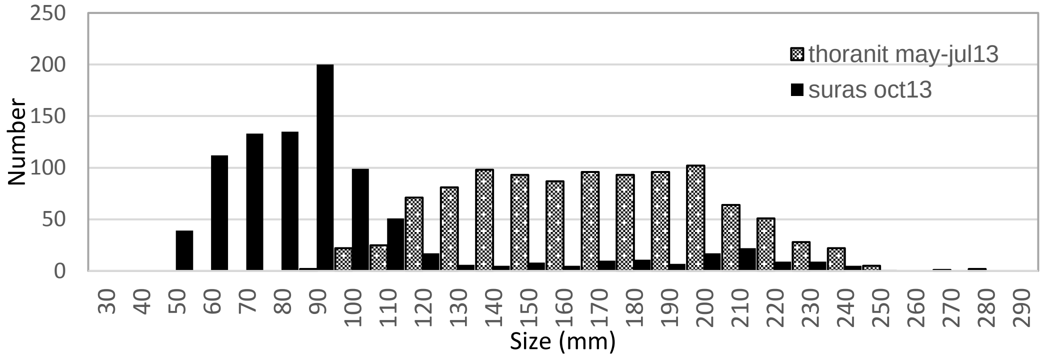


Figure 7.4 Size distributions of fish migrating through the Thoranit Naruemit fish pass during 2013. (Source: Ngoichansri *et al.*, unpublished)



a.



b.

Figure 7.5 Size frequency of *Hemibagrus nemurus* (a) and *Osteochilus hasselti* (b) that collected from Thoranit Naruemit fish pass at the migratory season and sub-adult fish from Suraswadi fish pass at the end of rainy season. (Sources: Ngoichansri *et al.,* unpublished and this study).

7.4.2 Migration triggers of target species in the river system.

Migration of *Hemibagrus nemurus* and *Osteochilus hasselti* through the TNNM fish pass was observed in 2013 after the water level in the Mekong River started to rise at the onset of the rainy season (Figure 7.6). Upstream migration through the fish pass was present as soon as the sluice gates at the top of the pass-were opened to release water, indicated that the upstream migration of two target species was triggered by flow and water level change. When all of the sluice gates were opened to full capacity, no fish were observed in the fish pass because they can migrate through the watergates and dispersed to the floodplains to spawn (Figure 7.3). This is also supported by the increased number of large fish (Chapter 4) and young of the year of the two species in the area above the most downstream watergate during the flood season (Chapter 5). The two target species used the fish pass across a broad range of discharge through the sluice gates (between 8 to 323 m^3/s) but the discharge when the peak movement was observed was different for each species. The greatest number of *Hemibagrus nemurus* was observed in the fish pass when the discharge at the main sluice gate was 100-214 m^3/s while *Osteochilus hasselti* was most abundant in the 120-130 m^3/s range.

In addition to hydrological cues, fish migration through the fish pass was influenced by the lunar cycle, and was greatest during the full moon phase, especially for *Osteochilus hasselti* that mainly moved 3-4 days before or after the full moon day (Figure 7.6). *Hemibagrus nemurus* migrated over a wide range of lunar phases, but avoided the new moon phase. *Osteochilus hasselti* usually migrated in shoals, taking 3-5 days to move upstream; the number of individual fish that migrated per day increased according to lunar phase (Figure 7.6).

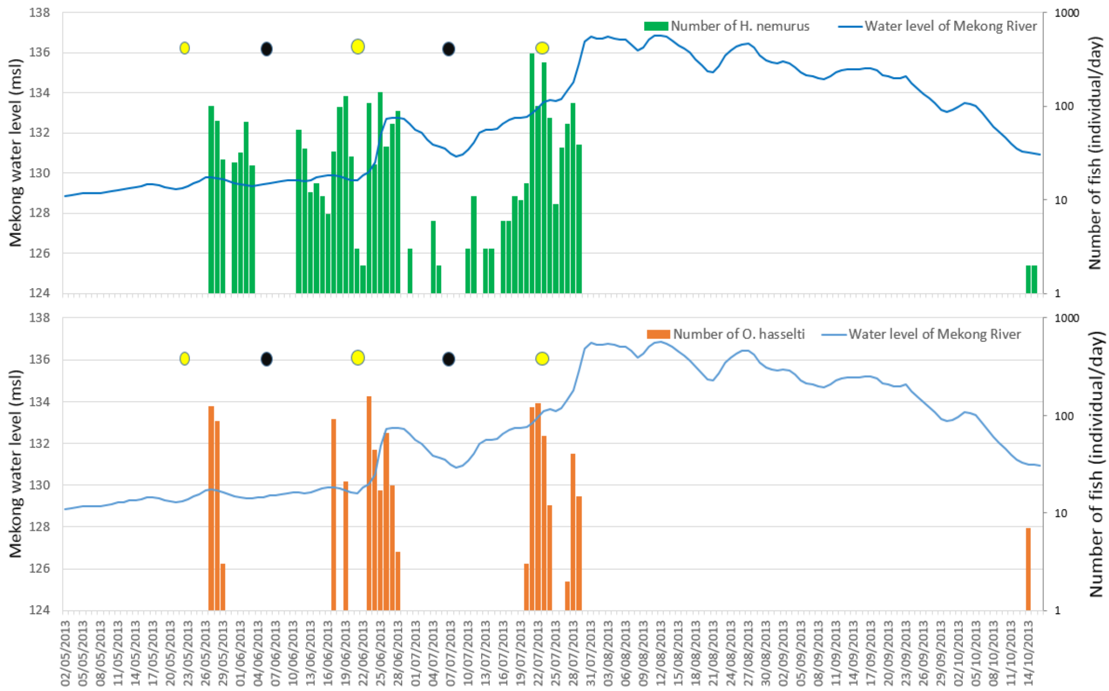


Figure 7.6 Migration periods of *Hemibagrus nemurus* and *Osteochilus hasselti* at Thoranit Naruemit fish pass in relationship with water level of Mekong River and lunar cycle during 2013. Yellow circles represent full moon period and black circles represent new moon period.

7.4.3 Migration pattern of target species after migrate through the TNNM fish pass using physical tagging

A total of 2,429 *Hemibagrus nemurus* and 1,040 *Osteochilus hasselti* were caught in the TNNM fish pass accounting for 8.6 and 3.7%, respectively, of all fish caught (Table 7.1). About 64% (1,552 fish) of *Hemibagrus nemurus* and 50% (515 fish) of *Osteochilus hasselti* were tagged with modified anchor T-bar tags and released upstream of TNNM during migration period through the TNNM fish pass (30 May to 29 July 2013).

Survival after tagging was very high (99.7%). Tagged fish were recovered from the mainstem river (Nam Kam and Nam Bang River) as well as in seasonal floodplain areas, for example Nong Kam Had, Nong Pa Cha and Nong Tao, which are connected to the main river in the rainy season. Within two months after tagging, 18 of 2,067 tagged fish were recovered; 15 *Hemibagrus nemurus*, and three *Osteochilus hasselti.* Thirteen tags were recovered from the Nam Kam River, and three tags from the Nam Bang River (Table 7.1 and Figures 7.7-7.8). Most of the returned tagged fish were caught within 43 km upstream of the tagging site (Table 7.2). Tagged fish were recaptured from main river channel and seasonal floodplains (9 from each). Recovering rate was low (0.97 for *Hemibagrus nemurus* and 0.58 for *Osteochilus hasselti*; Table 7.1). No tagged fish were caught by fisherman downstream of TNNM (Fisherman, personal communication) suggesting they only move upstream during the study period.

Table 7.1 Number of *Hemibagrus nemurus* and *Osteochilus hasselti* recorded migrating through Thoranit Naruemit fish pass, and number of tagged and recaptured fish.

	Hemibagrus nemurus	*Osteochilus hasselti*
No. of migratory fish sample from Mekong River that migrated through Thoranit Naruemit fish pass	2,429 individuals	1,040 individuals
% from all migratory fish	8.6%	3.8%
No. of tagged fish released	1,552 individuals	515 individuals
% tagged fish	63.9%	49.5%
No. of recaptured fish	15 samples	3 samples
Recapture rate from physical tag	0.97	0.58

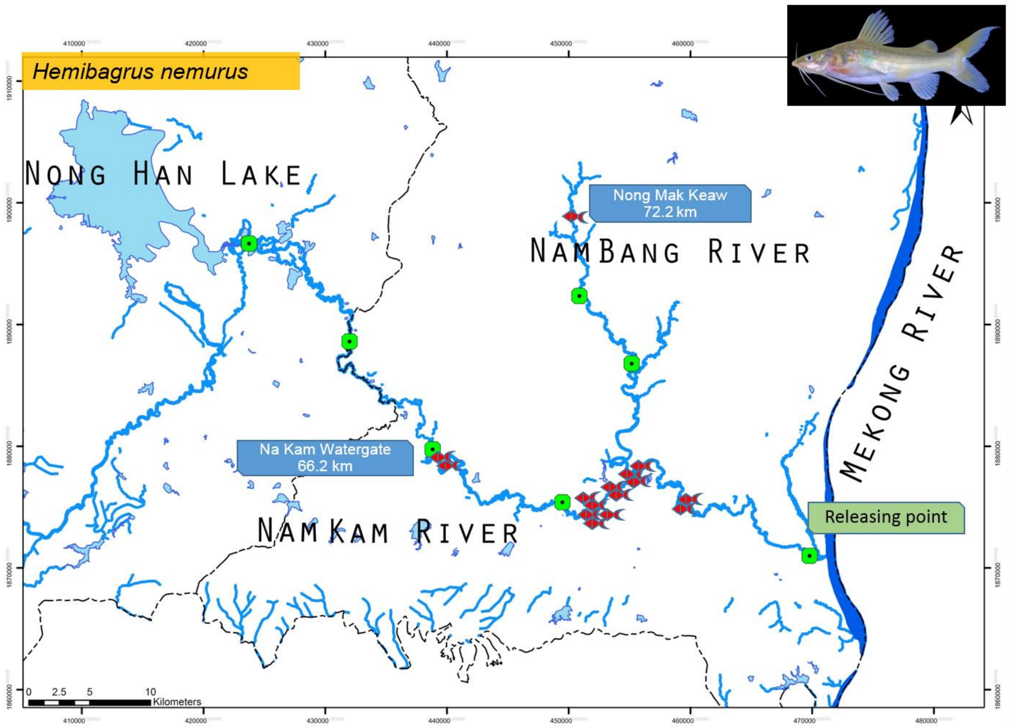


Figure 7.7 Tag and recapture distribution of *Hemibagrus nemurus* in the Nam Kam River system. represent recapture fish location.

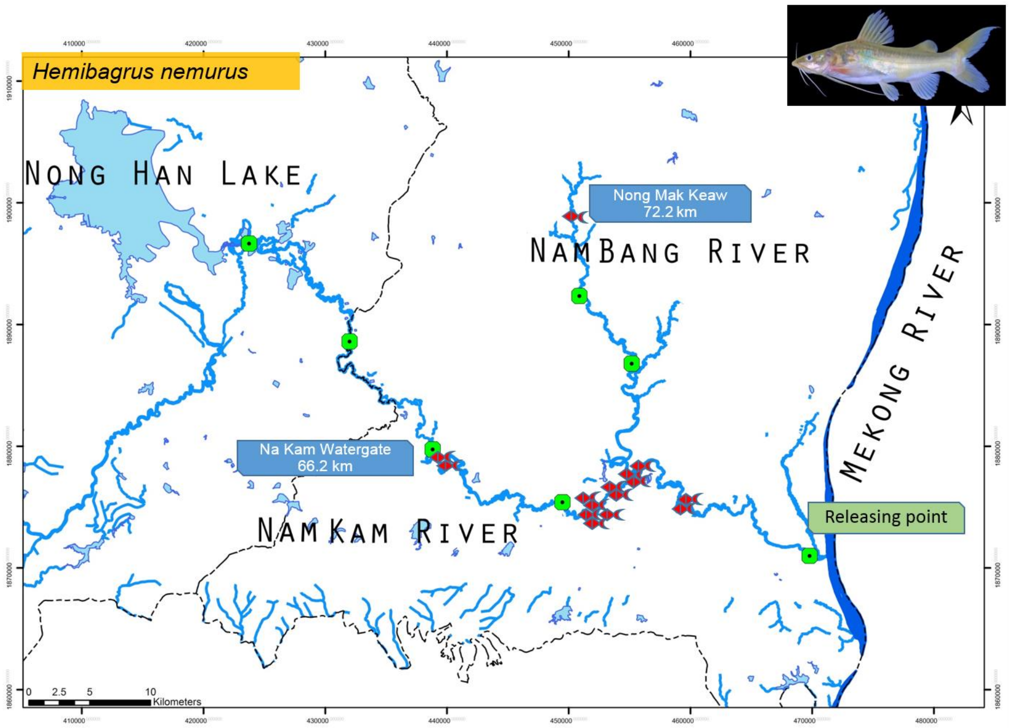


Figure 7.8 Tag and recapture distribution of *Osteochilus hasselti* in the Nam Kam River system. Represent each recaptured fish location.

Table 7.2 Details of recaptured fish from physical tagging (species, number, released date, recaptured date, distance travelled, time taken, and recaptured area/zone according to zone of genetic sampling sites in Figure 6.1)

Species	No.	Recaptured area	Zone	Distance travelled (km)	Time taken (d)
Hemibagrus nemurus	1	Pimantha	B	37.4	18
	1	Below Nakham watergate	E	66.2	17
	1	Below Nakham watergate	E	66.2	46
	1	Nong Pa Cha, Pimantha	B	37.4	41
	1	Nong Tao, Pak Bang	B	32.3	30
	1	Below Na Koo watergate	B	42.8	10
	1	Below Na Koo watergate	B	42.8	18
	3	Below Na Koo watergate	B	42.8	23
	1	Nong Mak Keaw	D	72.2	48
	1	Nang Lert	B	20.9	15
	1	Nang Lert	B	20.9	21
	1	Nam Bor	B	35.3	38
	1	Nam Bor	B	35.3	44
Osteochilus hasselti	1	Dong E num	C	52.6	42
	1	Dong E num	C	52.6	53
	1	Nong Pa Cha, Pimantha	B	37.4	41

Migration pattern of *Hemibagrus nemurus*

Based on physical tagging, *Hemibagrus nemurus* was found to be able to migrate upstream and bypass the second watergate, i.e. NAKO in the Nam Kam River, but were only caught in the area below the third watergate, i.e. NAKA, not above it. The longest distance *Hemibagrus nemurus* migrated was 66.2 km up the Nam Kam from TNNM. The species were found to bypass two watergates in the Nam Bang River, i.e. NABU and BATA. Tagged fish were recaptured at Nong Mak Keaw village 72.2 km from TNNM (Table 7.2 and Figure 7.7); eight recaptured fish were found in the main river channel and the rest (7 fishes) from seasonal floodplains.

The fastest recapture of tagged fish was within 10 days after being released; a fish caught at NAKO in the Nam Kam River (42.8 km distance from TNNM; Table 7.2). In all, 12 tagged fishes were recovered from the confluence area of the Nam Kam and Nam Bang rivers (Table 7.2 and Figure 7.7), probably because a lot of fishermen operated in this area when the water level started to increase in the rainy season (June to July 2014). Most tagged *Hemibagrus nemurus* were caught by hooks follow by fish traps and gill nets during both the day and night. *Hemibagrus nemurus* migrate more during night time than during day time through TNNM fish pass.

Two fish tagged during the first period of migration were recaptured below NAKA, the second watergate upstream of the release point; duration of migration from release to the recapture area was 10-48 days and five tagged *Hemibagrus nemurus* were recaptured in the upstream area of Nam Kam River within two months (Table 7.2). After all watergates were fully opened in the last week of July 2013, five fish were recaptured upstream in the Nam Kam while another one tagged fish was recaptured in the most upstream area of the Nam Bang although they were tagged in the same period. Two tagged fish were recaptured again in seasonal floodplain above TNNM at the end of the flood season (September) when water receded and all watergates were closed to store water for the next dry season (Figure 7.7).

Migration pattern of *Osteochilus hasselti*

Only three tagged *Osteochilus hasselti* were recaptured; two fish from the Nam Bang and one from the Nam Kam River. The species could migrate through the first watergate in the Nam Bang River (NABU) and one fish was recaptured 61 days after release at Dong E-Num village, 52.6 km upstream from TNNM, after all the watergates were fully opened at the end of July. The other two tagged fish were caught 41 days after release at Pimantha village located below the second watergate in the Nam Kam River (NAKO), 37.4 km from TNNM (Figure 7.8). Given the recapture rate of tagged fish was very low (< 1%; Table 7.1) it is not possible determine much about the migration rate of *Osteochilus hasselti*.

7.4.4 Migration pattern of target species after migrate through the TNNM fish pass using genetic tagging

Fins of the two target species were collected for microsatellite DNA analysis from the flooded area above TNNM. Up to 70 existing primers from 15 related species were tested for possible PCR cross-specific amplification. The amplification was successful for 6 primers for *Osteochilus hasselti* (BgOn75, Ns16, Hmo34, Ost03, Ost05 and Ost07) and 6 primers for *Hemibagrus nemurus* (Hw04, Hw08, Hw25, Hw26, Hw32 and Hw35). These primers were used for genetic analysis of the target species. All 12 loci were tested for null alleles with Microchecker (Van Oosterhout *et al*., 2004) and no null alleles or stuttering was detected.

Migration pattern of *Hemibagrus nemurus*

All pair-wise estimates of F_{ST} and genetic distance suggested a low to moderate level of genetic differentiation but significant and weak structuring across the sample in the

Nam Kam River system (Table 6.3). It suggested limited dispersion throughout the river system and therefore the rates of migration may be relatively small.

Although there was no tagged *Hemibagrus nemurus* recaptured from the upstream areas of the Nam Kam River (Zone F and G; Figure 7.7), genetic tagging estimated recapture rates of 1.27% and 1.37% whereas it was 1.15% in the Nam Bang River. Numbers of recaptured fish showed that *Hemibagrus nemurus* reached the upstream area of two rivers and migration rate in the Nam Kam River was slightly higher than the Nam Bang River (1.37 and 1.1%; Table 7.3).

Migration pattern of *Osteochilus hasselti*

There were indications of genetic structuring of *Osteochilus hasselti* populations in the Nam Kam River system. Genetic differentiation between samples was significant but relatively low (Table 6.9) suggesting a limited number of migrants in the spawning period. The same conclusion could be interpreted from the lack of physical tag recaptures from the upper Nam Kam River (E, F and G) and Nam Bang River (D), and few fish migrate upstream in either the Nam Kam or Nam Bang River (1.32% and 1.08%; Table 7.3).

Table 7.3 Number of recaptures corrected for *Hemibagrus nemurus* and *Osteochilus hasselti* in Nam Kam and Nam Bang River

	Number of recapture corrected	
	Hemibagrus nemurus	*Osteochilus hasselti*
Between Thoranit Naruemit fish pass (T) and Kudla-A floodplain (B)	1.1	1.21
Between Thoranit Naruemit fish pass (T) and area upstream of Nam Bang River (D)	1.15	1.08
Between Thoranit Naruemit fish pass (T) and area between Nong Bueng watergate and Na Kham watergate (E)		1.23
Between Thoranit Naruemit fish pass (T) and area between Nong Bueng watergate and Na Kham watergate (F)	1.27	1.13
Between Thoranit Naruemit fish pass (T) and upstream area of Nam Kam River (G)	1.37	1.32

7.4.5 Effective number of migrant (*Nm*)

Effective number of migrants (*Nm*) of *Hemibagrus nemurus* or number of reproductively successful individual that can transfer their genetic among population along the Nam Kam River (between TNNM fish pass and Zone G) was estimated at

4.20 (about 100 km distance) while *Nm* in the Nam Bang River (between area TNNM fish pass and Zone D), which is about 60 km distance, was 3.71 (Table 7.4). Although the number of migrants between TNNM fish pass and the upstream sampling site was low, ranging between 2.63 and 4.20, overall *Nm* in the Nam Kam River system was 29.83 which is about 30 individuals per generation (Table 7.4). Gene flow level in the study area indicated that subpopulations in the Nam Kam River system were not closed populations; there were gene flow among these populations. *Hemibagrus nemurus* could migrate from downstream (throught TNNM fish pass), although in limited numbers, for almost 100 km to the upstream area, especially after all watergates were fully opened.

Table 7.4 Number of migrants per generation (*Nm*) for *Hemibagrus nemurus* and *Osteochilus hasselti* in Nam Kam and Nam Bang River

	Number of migrant per generation (*Nm*)	
Area	*Hemibagrus nemurus*	*Osteochilus hasselti*
Overall	***29.83***	***8.38***
Between Thoranit Naruemit fish pass (T) and Kudla-A floodplain (B)	2.63	2.55
Between Thoranit Naruemit fish pass (T) and area upstream of Nam Bang River (D)	3.71	3.62
Between Thoranit Naruemit fish pass (T) and area between Nong Bueng watergate and Na Kham watergate (E)	*ns*	3.43
Between Thoranit Naruemit fish pass (T) and area between Nong Bueng watergate and Na Kham watergate (F)	3.00	3.39
Between Thoranit Naruemit fish pass (T) and upstream area of Nam Kam River (G)	4.20	2.07

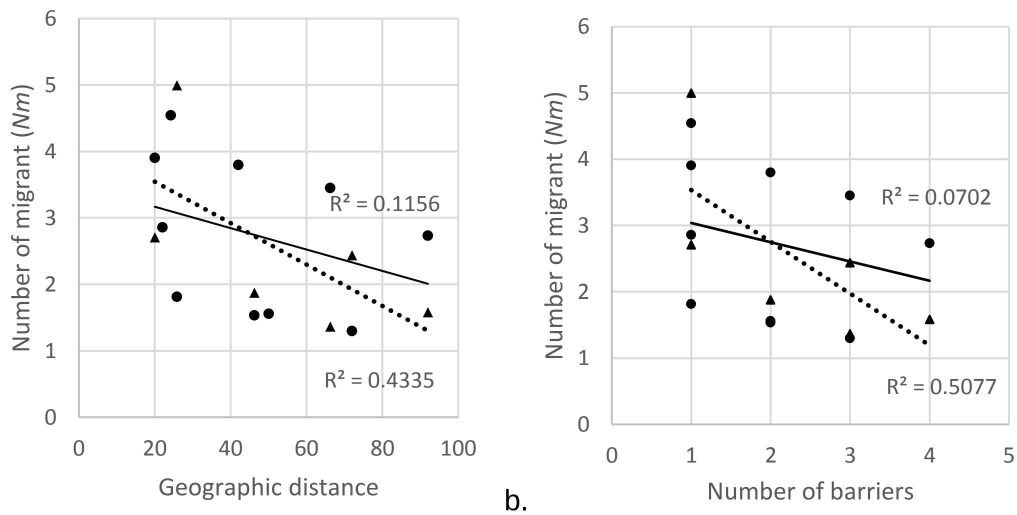
The number of migrants per generation of *Osteochilus hasselti* in the Nam Kam River system ranged between 2.07 to 3.43 with overall 8.38 which is about 9 individuals per generation (Table 7.4). The number of migrants moving between Thoranit Naruemit fish pass to the upstream area of Nam Kam River (over 100 km. distance) was estimated from downstream to upstream as 2.25, 3.43, 3.39 and 2.07, respectively. *Nm* in the Nam Bang River, which is about 60 km from the confluence of Mekong River, was greater (3.62).

Nm presents amount of gene flow among populations, results from Table 7.4 showed that there were gene flow occurred between each pair of subpopulations, adult fish from TNNM can contribute genetic inheritance to populations at the upstream area where physical tagged were not recaptured (F and G for *Hemibagrus nemurus* and D, E, F and G for *Osteochilus hasselti*).

7.4.6 Isolation by distance and barriers

If the gene flow was affected by watergate operation, it would have essentially eliminated dispersal of fish, although the two target species have different migration patterns and reproductive biology. Negative relationships were found between relative gene flow parameter of target species (*Nm*) and geographic distance (distance in km and number of barriers between population; Figure 7.9). Subpopulation at the upstream area which obstructed by many watergates exhibited the low migration rate. It also indicated the distance from between two population also be a factor on the migration of fish.

Two target species reacted to the watergate operation and the distance from the confluence of the Mekong River in different way, *Hemibagrus nemurus* tended to decline rapidly than *Osteochilus hasselti* in the area that located far from the confluence of Mekong River and obstructed with many barriers (Figure 7.9).



a. b.

Figure 7.9 Scatter plots illustrating the pairwise relationship between effective number of migrants (*Nm*) as a function of geographic distance (km). a.shows *Nm* variation in distance between population for *Hemibagrus nemurus* (triangle; r=-0.6584, $P \leq 0.05$) and *Osteochilus hasselti* (dot; r=-0.3400, $P \leq 0.05$). b. shows *Nm* variation in number of barriers between population for *Hemibagrus nemurus* (triangle; r=-0.7125, $P \leq 0.05$) and for *Osteochilus hasselti* (dots; r=-0.2650, $P \leq 0.05$).

7.4.7 Downstream migration of fish

Downstream movement of fish in the Songkhram River, both adult fish and juvenile fish, coincided with the decline in water level as the flood receded at the end of the rainy season in September 2014. Abundance and CPUE by weight of fish in October was significantly greater than previous sampling periods indicating the movement of fish from the floodplain to the main river associated with downstream migration when the water level receded (Table 4.5-4.6). Downstream migration of adult fish and drifting of larval and juvenile fish were observed in the Nam Kam River when the water started to recede in September, but differed from the Songkhram because migration was obstructed by watergate operation, especially when all sluice gates were closed. As a consequence, the fish assemblage in the downstream floodplain (NK4) was enhanced while the upstream floodplain assemblage (NK1-3) declined at the end of the flood season (October) (Table 4.5), and the drifting of eggs and larvae showed a different pattern than found in the free flow river. This was affected by the closing of the watergate, such that diversity and abundance of larvae and juvenile fish in each section of the river was retained at the end of flood season while larval and juvenile fish in the free flow river drifted downstream with the recession of the water level started in September (Tables 5.3-5.4), i.e. fish were stranded in each section of the regulated river after the watergates were closed. Many white and grey fish species were stranded in the most downstream floodplain above TNNM and needed to adapt to feed and grow in the impounded area during the dry season. However, there remain concerns about the quality of individuals and population size of fish stranded in these river sections. Genetic analysis revealed that the diversity of *Hemibagrus nemurus,* which is a representative longitudinal migrating species, was relatively high, but only a moderated population size and weak population structure (Chapter 6). This suggests the Nam Kam River system is not a closed system, and fish can migrate to upstream spawning habitats and reproduce although recruitment is more limited than the open access system. *Osteochilus hasselti*, which represent lateral migrating species, exhibited relative high genetic variation and greater effective population size, except subpopulations from some small floodplains that exhibited low genetic diversity and small population size (Chapter 6).

7.5 Discussion

7.5.1 Migration pattern of two target species after migrating through TNNM fish pass

In this study, physical and genetic tagging provided key information about the migration of two important fish species into the Nam Kam River in 2013.

Hemibagrus nemurus (Asian red tail catfish) belongs to the Family Siluridae, common fish in the Mekong River and are found throughout the year. *Hemibagrus nemurus* was believed to be a black species (Shiraishi, 1970) but fish species of the family Siluridae were categorized as grey species by Halls and Kshatriya (2009). It occupies most habitat types but prefers large slow flowing rivers with soft substrate (Kottelat, 1998). This particular species undertakes short local migrations (Poulsen & Valbo-Jørgensen, 2000) between the main channel and nearby floodplains for their spawning and migrate only at night (Shiraishi, 1970; Welcomme, 1979). *Hemibagrus nemurus* spawns in floodplain areas or the trees and shrubs along the flooded fringe of streams or in flooded rice fields. Migration is triggered by water level increases, turbidity and the first rainfall. Moreover, fishermen from many sites in the Mekong mention that upstream migration is related to the lunar (full moon) cycle (Poulsen & Valbo-Jørgensen, 2000). Peak spawning is April to July when fish eggs, larvae and juvenile fish are observed along Mekong River (Poulsen & Valbo-Jørgensen, 2000; Cowx *et al.,* 2015). Young of the year return to the main river a few months later (Rainboth, 1996) when water levels start to recede at the end of the flood season (November-December). This species spends the dry season in tributaries and not on the floodplains, hence its classification as a grey species (Welcomme & Halls, 2004; Halls & Kshatriya, 2009). Halls *et al.* (1998) found that it is a genus of catfish that is heavily impacted by flood control drainage and irrigation schemes, with the number of fish much less inside the irrigation scheme area than outside and under unmodified conditions.

Findings from this study, however, suggested the original black fish categorization may be inaccurate. In this study, *Hemibagrus nemurus* performed relative long distance migration into the Nam Kam River system as far as 70 km upstream for spawning (Figure 7.10), and the migration takes place both during the day and night. Moreover, genetic analysis indicated that fish migrated even further upstream in the Nam Kam River system to around 123 km from the confluence of the Mekong River (Figure 7.10). Mature *Hemibagrus nemurus* migrated from Mekong River to spawn above KA and DK around the end of May to early June, and fish larvae drift on to the floodplains at KA and DK and use them as nursery grounds until they reach the sub-adult stage (size around 100-200 mm; Figure 7.5). Upstream migrations of small fish (50-240 mm) to Nong Han Lake via SRWD fish pass was then observed at the end of the flood season around September to October (Ngoichansri *et al*, unpublished). This was supported by data from a previous survey that found *Hemibagrus nemurus* was widely distributed in upper, middle and downstream areas of the Nam Kam River Basin (Ngoichansri *et al.,* 2013). This is also supported by mixed stock analysis that found more than 73% of sub-adult fish that migrated to Nong Han at the end of the rainy season were offspring of migratory fish from the Mekong River (Table 6.13). These indicated *Hemibagrus nemurus* can be self-sustaining populations of white fish in the tributary rivers as occurs in other river system. It would have tought, according to it behaviour that *Hemibagrus nemurus* should perhaps be more appropriately categorized as a grey fish to white fish than its original designation as a black fish, which are often referred to as sedentary species with little or no migration. Migration behavior of fish from this study supported the grey fish guild that Utsugi *et al*. (unpublished) reclassified the species and as a *main channel spawner* guild as categorized by Halls and Kshatriya (2009, drawing on Welcomme *et al*. (2006)). Furthermore, records from TNNM fish pass show that the species migrates more during the night than the day (71% and 29%). The migration pattern of *Hemibagrus nemurus* is summarized in Figure 7.10.

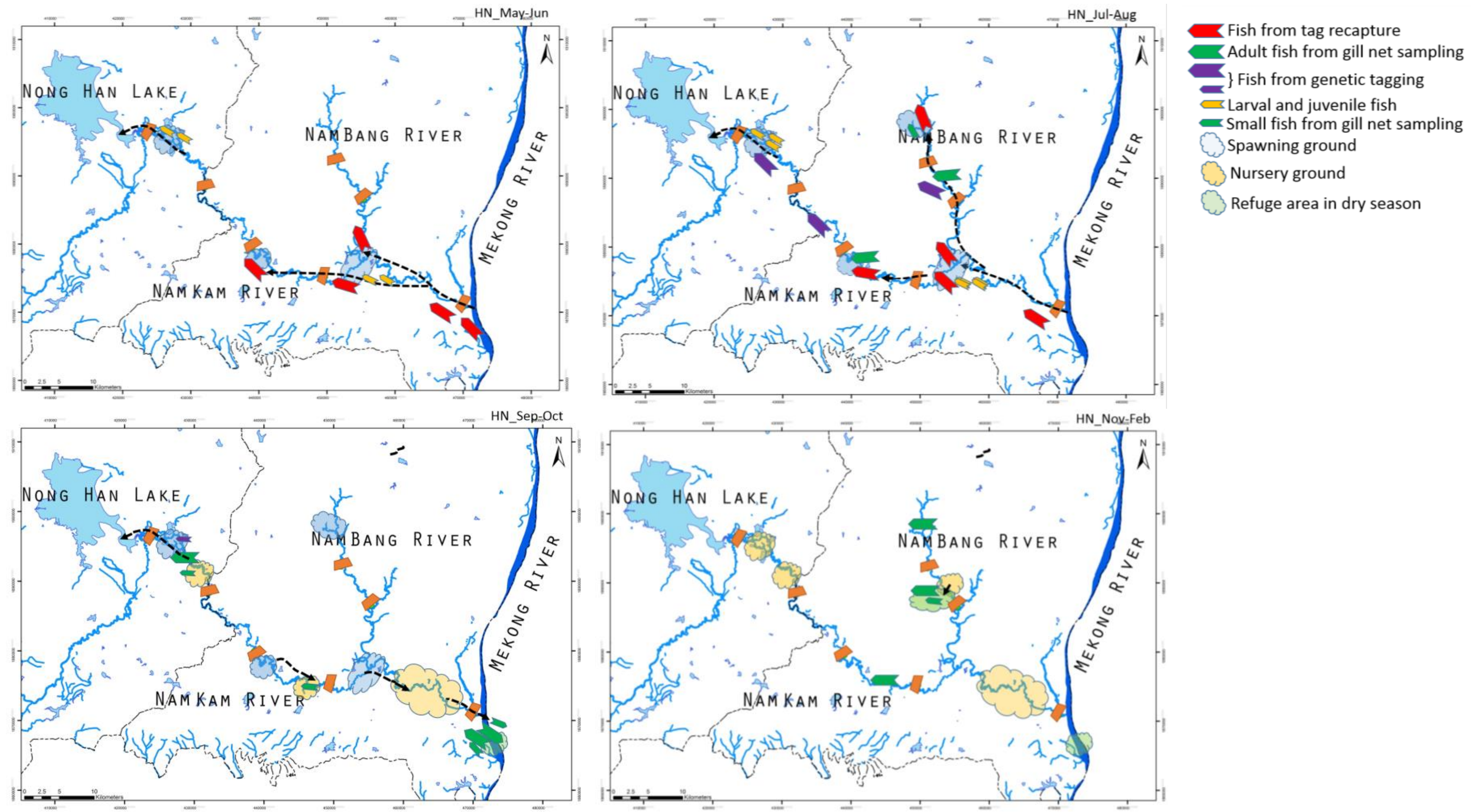


Figure 7.10 Life cycle of *Hemibagrus nemurus* described by the model and assumptions regarding to habitat distribution and migration of fish relative to the watergate locations. Red arrows represent tagged fish from recapture; orange arrows represent fish from seine netting; green arrows represent fish from gill netting and purple arrows represent recapture from genetic tagging. Big arrows represent adult and small arrows represent larval and juvenile fish. Blue clouds represent spawning ground; orange clouds represent nursery grounds and green clouds represent refuge area in dry season.

Osteochilus hasselti belongs to the family Cyprinidae*,* normally found in a wide range of habitats but usually connected with large rivers with slow current and muddy to sandy substrate (Kottelat, 1998). In the Mekong river basin, this species is mostly found living in small tributaries (Poulsen & Valbo-Jørgensen, 2000). This species is well adapted to the impoundedarea (Vidthayanon, 2012). The fish typically migrate from the river channel to the flooded area to spawn at the onset of flood season. Adult fish return to river habitats at the end of the flood period (Poulsen & Valbo-Jørgensen, 2000) while juveniles move to the main river and shelter in brush piles, tree roots and other solid objects on the river fringe when the water recedes (Rainboth, 1996). At the end of flood season, the species returns to its river habitat in tributaries and some return to the Mekong mainstem (Poulsen & Valbo-Jørgensen, 2000). Developed eggs have been observed from May to June and juvenile fish until August. This species was categorized as a grey fish species, which migrate between the river and floodplain (Dugan, 2008). However, according to Welcomme *et al*. (2006), *Osteochilus hasselti* could be categorized in the '*Generalist guild'* or fish that occupy a wide range of habitats in floodplain areas and slow-flowing downstream reaches of river. The species is abundant in most rivers because it is highly adaptable and tolerant of low oxygen concentrations (Vidthayanon, 2012). Mainstem dams probably have little or no impact on their migration if the flooding cycle is not compromised because they undertake lateral migrations to floodplain areas and longitudinal migrations in mainstem.

Results from this study reveal *Osteochilus hasselti* migrate during the same period as *Hemibagrus nemurus* and many other species. Spawning migrations started at the onset of the rainy season, when matured fish move from the Mekong River and from within in the Nam Kam River system to spawning areas. Fish migrate in shoals from May to July, each batch taking 3-5 days coinciding with the full moon period. Larval and juvenile fish were observed in flooded marginal areas above NAKA and in the KA and DK floodplains between June and October, indicating the potential breeding and nursery areas. Fish occupy these floodplains until they mature. Fish that migrated from the Mekong River contributed just 16% of fish population of the upstream Lake, Nong Han and the remaining 84% was contributed by resident sub-populations from floodplains along the river system (Table 6.15). Genetic tagging suggests few fish migrate upstream and dispersal is localized and fewer fish migrate into the Nam Bang. Fish were observed moving in both directions and this species migrates during both the day and night. The migration pattern of *Osteochilus hasselti* is summarized in Figure 7.11.

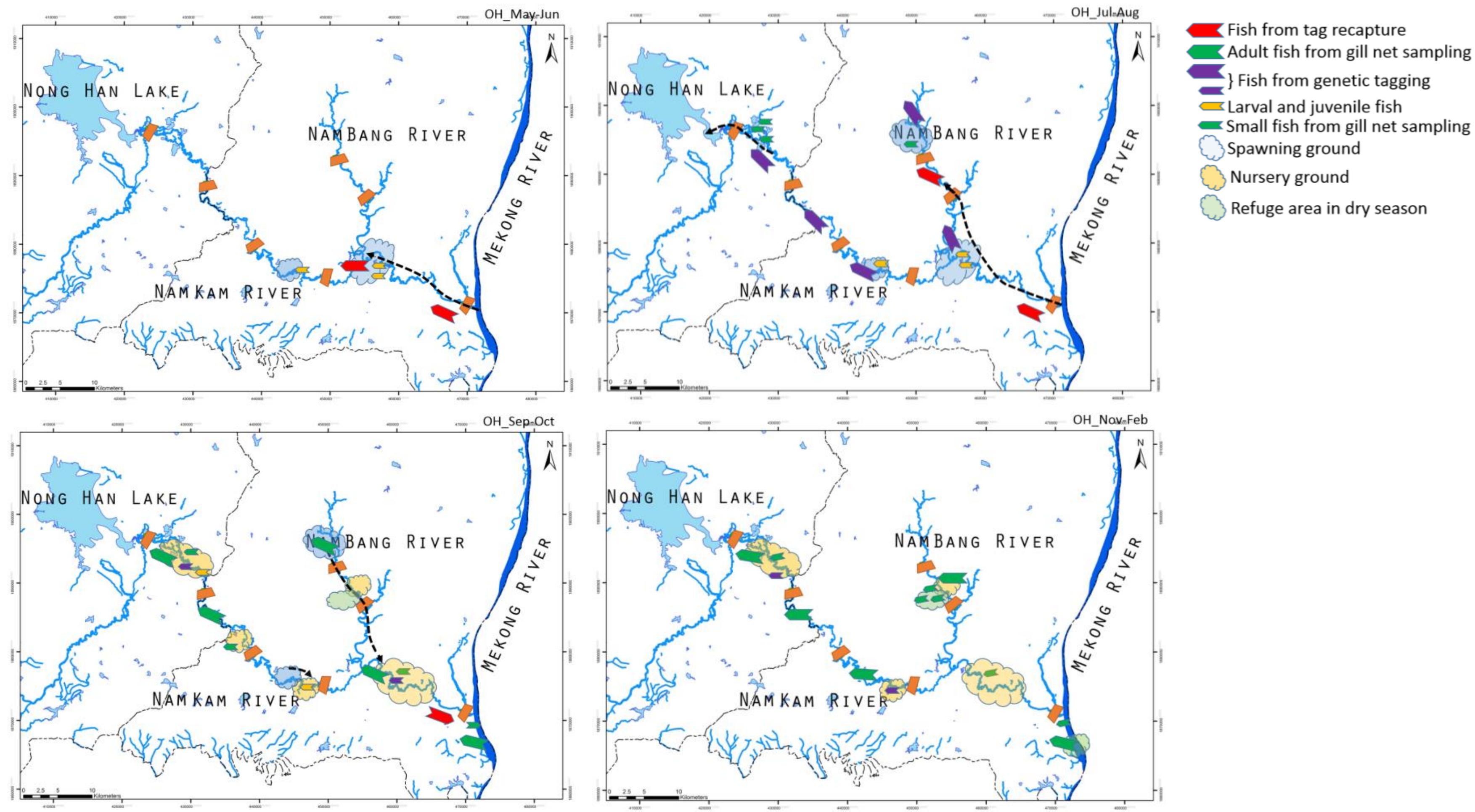


Figure 7.11 Life cycle of *Osteochilus hasselti* described by the model and assumptions regarding to habitat distribution and migration of fish relative to the watergate locations. Purple arrows represent tagged fish from recapture; orange arrows represent fish from seine netting; green arrows represent fish from gill netting. Big arrows represent adult and small arrows represent the larval and juvenile fish. Blue clouds represent spawning ground; orange clouds represent nursery grounds and green clouds represent refuge area in dry season.

In conclusion, results from this study highlight the different migration patterns of the two target species and the potentially differing threats to the species. Species like *Hemibagrus nemurus* that undertake long-distance migrations from refuge habitat in the Mekong River to upstream spawning habitat in the Nam Kam River system (KA and DK floodplain) are more likely to be impacted by watergate operations than species like *Osteochilus hasselti* because they mostly undertake localize lateral spawning migrations from the mainstem channels on to the floodplain and juveniles move to the main river and shelter amongst riparian vegetation; brush piles, tree roots and other solid objects in the margins when water recedes (Rainboth, 1996). *Osteochilus hasselti* is also well adapting to fluctuating flow regimes and can exploit the impoundment areas after the watergates are closed (Vidthayanon, 2012).

The physical and genetic tagging studies showed that the overall number of effective migrants (*Nm*) within the Nam Kam River system was greater for *Hemibagrus nemurus* than *Osteochilus hasselti* (Table 7.4). These differences reflect the migration patterns of the species, with *Hemibagrus nemurus* migrating longer distances than *Osteochilus hasselti*. Notwithstanding, short distance migrations can induce genetic differentiation among cyprinids populations (Dehais *et al*., 2010) due to weaker capacities to disperse (Bainbridge, 1958), even when larval and juvenile drift contributes to dispersal among populations. This is seen by the greater contribution of *Hemibagrus nemurus* from the Mekong River to the populations in the most upstream area of the Nam Kam than that of Mekong River *Osteochilus hasselti* to the upstream populations (Chapter 5). Observed *Nm* in the upstream reaches of both the Nam Kam and Nam Bang rivers indicated *Hemibagrus nemurus* and *Osteochilus hasselti* can migrate into and within the Nam Kam River system. Additionally, the *Nm* of both target species in the Nam Kam River was higher than the recommended level of gene flow for conservation and maintaining the populations by 'the-one-migrant-per-generation rule: OMPG' (*Nm* ≥1; Wright, 1931; Wang 2004). Franklin (1980), Frankel and Soule (1981), Mills and Allendrof (1996) and Wang (2004) stated that the appropriate level of gene flow to maintain genetic variation and avoid inbreeding depression in fragmented populations is one migrant individual per local population per generation, it means that only one migrant per year class is sufficient to obscure any disrupting effect of genetic drift. OMPG provide balance between genetic drift and gene flow. It prevents the loss of alleles and minimizes loss of heterozygosity within subpopulation but allows genetic divergence to exist amont subpopulations (Mills & Allendorf, 1996).

Fish in free flowing river have been found to have a greater number of migrants because they are able to move freely between different reaches, resulting in no statistically differences in genetic integrity between populations in upstream and downstream areas. Salmon in the free flowing river, Cape Race Newfoundland in Canada also showed high *Nm* around 28.9 although the recovery rate from physical tags was low at 0-4.1% (Wilson *et al*., 2004). This contrasts with the present study and movement of *Labeo chrysophekadion* in the Mun River, another Mekong tributary, where, despite Pak Mun Hydropower Dam being fully opened in the flood season the migration rate was still low (*Nm*=2.0) (Hanpongkittikul *et al.,* 2010) This is because there are several fast flowing rapids and reefs in the Mun River that act as natural obstacles and obstructed upstream migration of *Labeo chrysophekadion.* It highlights the need to establish effective watergate management rules at TNNM to allow Mekong fish to migrate to the upper part of the river in the spawning season. Notwithstanding, in some case low dispersal rather than lack of the suitable habitat limit in-stream distribution but this does not affect genetic integrity (e.g. Diana & Lane, 1978). The restricted movement paradigm might explain the contribution of localized stocks to maintenance of genetic structure on a micro-geographic scale, and even maintaining differentiation between populations in the same drainage (Gerking, 2008).

7.5.2 Efficiency of the fish passage facility in the Nam Kam River system

To date, more than 135 fish species from 22 families have been recorded migrating through the series of fish passes in the Nam Kam River system (Pongsri *et al.*, 2008; Ngoichansri *et al*., 2013, unpublished and this study) (Table 7.5). The highest number of fish species (103 species) and the highest number of fish (440,015 fish), converting to around 11 tonnes of fish, was recorded at the most downstream passage, TNNM fish pass in 2013 (Table 7.5). The large number of fish observed migrating through the fish passage facilities in the Nam Kam River system during 2012-2013 indicated the effectiveness of the fish passage facility and ability to maintain the diversity of fish in this river system. The size of fish that migrated through the series of fish passes in 2012 and 2013 ranged between 22-700 mm and 45-700 mm respectively. This suggests that these fish passage facilities support the upstream migration of huge numbers of various sizes and fish species with different swimming capacities.

Fish passage facilities are a key measure to improve ecological status in rivers worldwide (Bunt *et al*., 2012; FAO/DVWK, 2012). The fishways installed in the Nam Kam River are weir and pool type and one of most efficient designs. Noonan *et al.*

(2012) highlighted that fish passage efficiency was dependent on species, type of fish way and length of fish way.

Among the 10 fish passage facilities in Thailand that have been investigated for fish migration, it appears that the seven passes in the in the Nam Kam River system are the most effective passing a greater diversity of fish. Pak Mun fish pass, for example, supported 77 fish species and is inefficient due to the location of the fish pass not being appropriate, i.e. too steep and the fish pass is dry around six months a year (Roberts, 2001). Pak Mun fish pass was based on very little knowledge and experience, and the design was not well prepared (Amornsakchai *et al.,* 2000). Two fish passes at Pak Phanang and Uthogwipat Prasit Watergate on the Pak Phanang River do not work effectively because they are too short and flow velocity in the fish passes is too high (Rattanavinitkul *et al.,* 2011). They supported migration of only 23 fish species and 9 other aquatic fauna, although it should be noted they are located between estuaries and freshwater habitats. Katopodis and Williams (2012) stated that the installation of steep fish ways would pass large volumes of flow and might not work effectively.

Table 7.5 migration of fish through fish passage facilities in the Nam Kam River system during 2005-2013 (Sources; Pongsri *et al*., 2008; Ngoichansri *et al*., 2013, unpublished and this study)

Name of fish passes (year)	Period of migration (days)	No. of fish that migrated through fish passes	No. of species that migrated through fish passes
Suraswadi 1981 (experiment)	6	934,656	23
Suraswadi 2005-2006	39	227,146	54
Na Kham 2005-2006	6	6,614	42
Na Koo 2005-2006	13	31,361	55
Suraswadi 2012	22	234,540	43
Nong Bueng 2012	2	1,048	11
Na Kham 2012	4	4,772	16
Na Koo 2012	2	932	8
Thoranit Naruemit 2012	31	347,375	82
Suraswadi 2013	40	413,471	50
Thoranit Naruemit 2013	60	440,015	83

The fish passes on the Nam Kam can, however, support migration even when the water level above the main watergate is low, and technically not allow sufficient water to flow through the fish pass to support full functioning of the pass. If small volumes of water are directed through the fish pass, fish can use the fish pass and migrate upstream to reach the area above the watergate. This is supported by evidence from tagged fish that were recaptured further upstream area of the NAKO after tagging, although in less number (Figures 7.7-7.8), but it does indicate that any residual water should be passed through the fish pass.

7.5.3 Influences factors on fish migration in the Nam Kam River system.

Migration of fish will be successful when it is initiated at the right time, so tuning migration triggers to ambient environmental conditions plays an important role, to increase the chance of survival at the scale of population. The result from this study suggests several migration triggers in the Nam Kam River system.

Water level and flow changes

Spawning migration of fish from Mekong River into the Nam Kam River system was observed when water levels in the Mekong River rise at the onset of the rainy season (Figure 7.12), which was supported by Warren *et al*. (2005) and the MRC (2009). Water level and flow changes manipulated according to watergate operation are also important factors that trigger migration of fish from the Mekong River into the Nam Kam River system. Migration started as soon as the sluice gates at the most downstream watergate, TNNM, were opened (Figure 7.3); the number of fish migrating through the fish pass increased according to changes in flow and water level in the downstream area. After fish get in to the river system, discharge, flow changes and turbidity caused from watergate operation play important roles to stimulated further migration of fish in to the Nam Bang or Nam Kam.

Water level and flow in the Nam Kam River, especially downstream of watergates fluctuated according to watergate operation (Chapter 3) and variation rather than the threshold of water level is one of the main migration cues (Baird *et al*., 2004; Singhanouvong *et al*., 1996a, b). The MFD (2013) and MRC (2006) also record that several fish species are triggered by discharge and water level changes, including: *Barbonymus gonionotus, Cyclocheilichthys enoplos, Cyprinus carpio, Labeo chrysophekadion, Parachela oxygastroides, Parachela typus, Pangasius larnaudii, Pangasius macronema, Phalacronotus bleekeri, Hemibagrus filamentus, Tenualosa thibaudeaui, Botia modesta*, and *Pristolepis fasciata*. Result from this study adds more species. As soon as the discharge from the watergates changed, fish migration through the fish pass was observed. The dominant species in this period were *Sikukia gudgeri, Labiobarbus lineatus, Hypsibarbus malcomi, Laides longibarbis,* *Hypsibarbus wetmorei, Osteochilus hasselti, Poropuntius bantamensis* and *Barbonymus altus*.

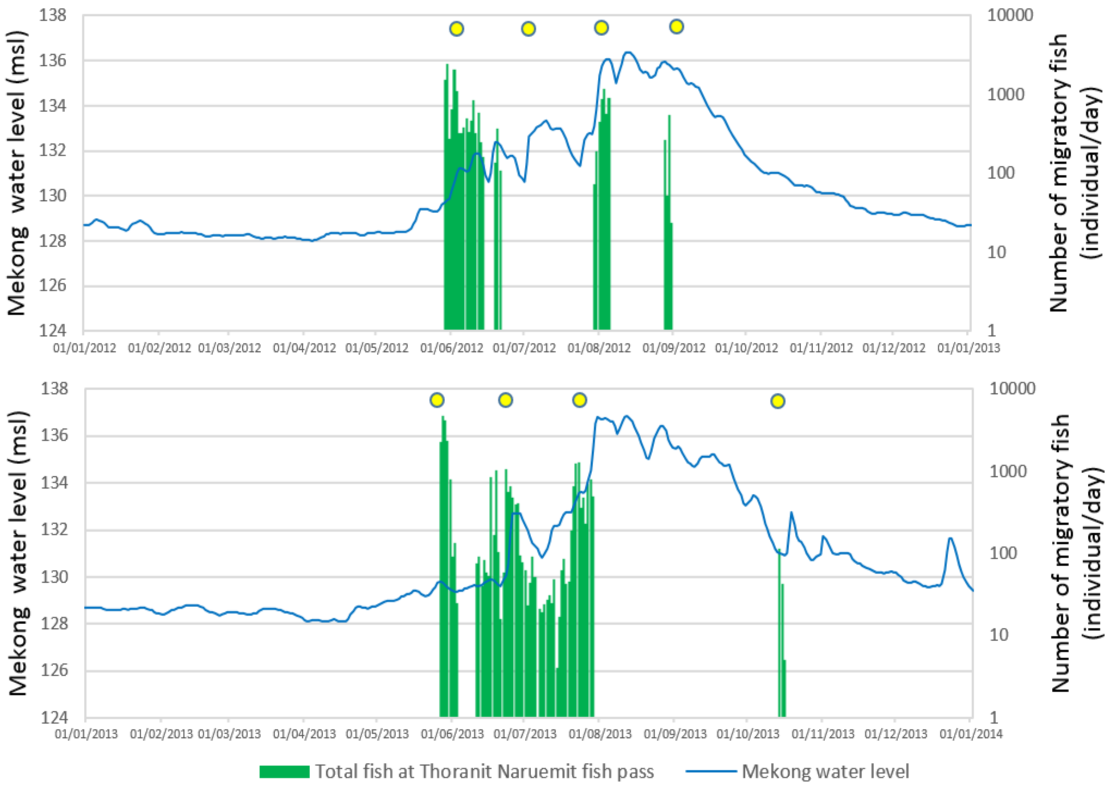


Figure 7.12 Mekong water level, lunar phase and number of migratory fish that migrated through the Thoranit Naruemit fish pass during 2012-2013. (Sources; Ngoichansri *et al.,* 2013 and this study)

Additionally, it is not just the release of water through the fish passes that triggered migration through the fish pass facilities. In the rainy season, changes of discharge from the watergate and water level whenever the TNNM sluice gate was opened also stimulated the migration of fish through the TNNM fish pass. Generally, flow from adjacent sluice gate operations can assist in attracting fish to migrate into fish passes (Katopodis & Williams, 2012). The relationships between discharge at the TNNM in flood season of 2012-2013 and migration of the 20 dominant migratory species, representing 90.5% of total migratory fish (Ngoichansri *et al*., 2013 and this study) suggests that fish migrate through the TNNM fish pass over a broad range of discharges from the sluice gates between 0 to 286 m^3/s in 2012 and 0 to 323 m^3/s in 2013, but peak migration for each species was different (Figure 7.13).

The peak in migration of the most abundant migratory species occurred at discharge levels around 50-215 m^3/s. These *Hemibagrus nemurus, Kryptopterus cheveyi, Kryptopterus cheveyi, Dangila lineatus, Osteochilus hasselti, Puntioplites* *proctozystron, Henichorhynchus siamensis, Thynnichthys thynnoides*, *Notopterus notopterus* and *Pseudomystus siamensis* contributed 46.6 % of fish that migrated through the fish pass were in 2012-2013. Some less important fish species migrated at higher discharge levels (200-215 m^3/s; Figure 7.13), for example *Hemibagrus nemurus, Rasbora argyrotaenia*, *Puntioplites proctozystron* and *Hypsibarbus malcomi,* and peak migration for two catfish species; *Mystus singaringan* and *Kryptopterus cheveyi,* was at discharge around 300-323 m^3/s (Figure 7.13).

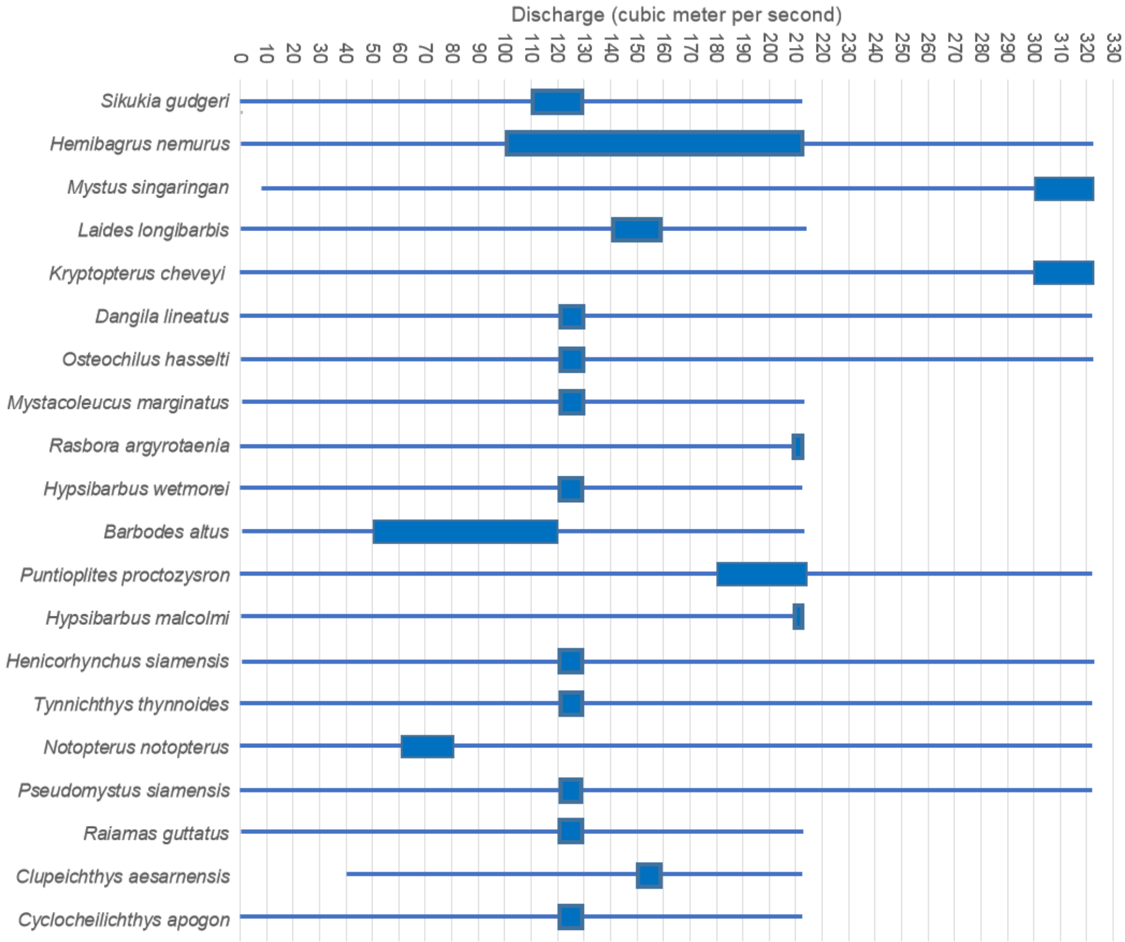


Figure 7.13 Discharge from Thoranit Naruemit watergate operation and top 20 species migration patterns through Thoranit Naruemit fish pass based on 2012-2013 data. Abundance express in term of number of migratory fish in daily catches and discharge was taken from records measured at the Thoranit Naruemit watergate. Blue line represents the distribution range of fish via fish pass in number and the blue bar represents peaks with in the distribution range as a function of discharge. (Sources; Ngoichansri *et al.,* 2013 and this study)

Watergate operation

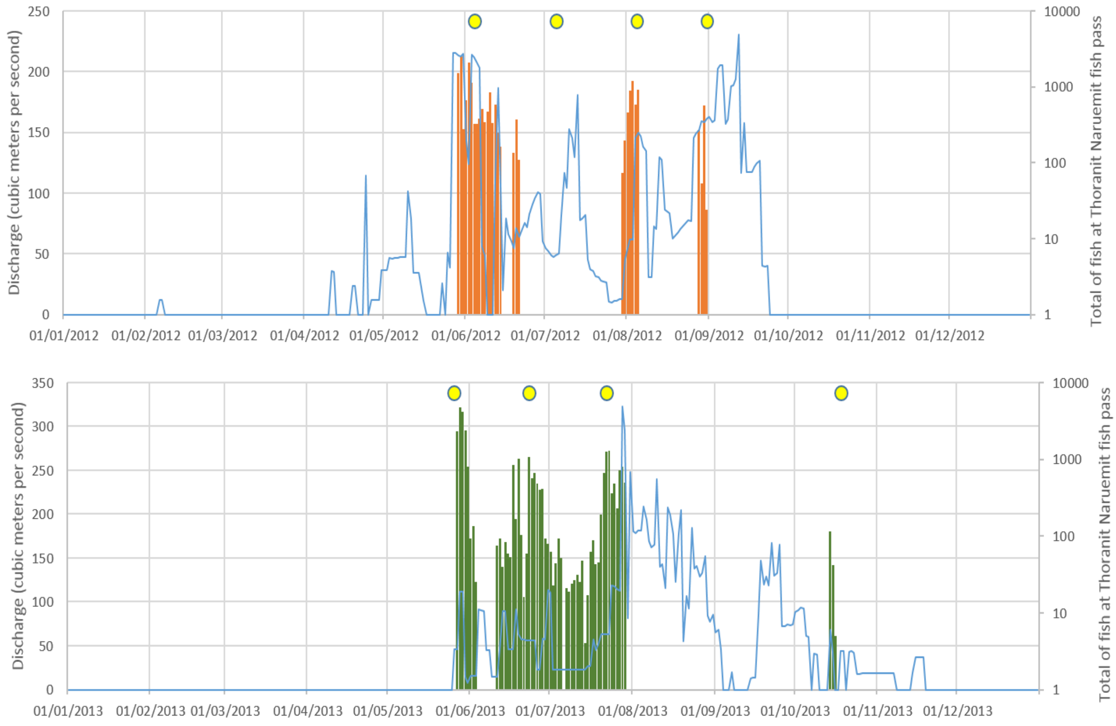
Watergate operation influences migration of fish in the river system through modification of the water level and flow regimes (Chapter 3). The flow regimes created are dependent on the operating rule curve for each watergate and the water runoff, rainfall above the watergate, water level above and below the watergate, and timing of operation which vary between years.

Watergates in the Nam Kam River system were operated by opening sequentially from the most upstream watergate to the downstream watergate, after the onset of the rainy season. Thus regulation in the Nam Kam River is controlled by the most upstream watergate, such that water is released until the water there build up in the downstream area in flood season. Thus fish passes become operational when water level above the watergate is over the retention level and can drain through the pass. The most downstream sluice gates, TNNM, are opened when water builds up downstream and water level above and below the watergate was similar (see 3.4.1-3.4.2).

The watergate and fish pass operation associated with rising water level in the Mekong River (Figure 7.12) and discharge at the most downstream watergate (Figures 7.14) stimulated upstream migration of Mekong fish through the fish passes and the main sluice gates and in part was synchronized with the spawning season of most Mekong fish species (Poulsen & Valbo-Jørgensen, 2000).

Timing of watergate operation influences on migration of fish and composition of fish in the river system. Differences were found between the two years of observations at the TNNM fish pass. In 2012 most fish migrating during the rainy season were large and adult fish, while upstream migration of sub-adult fish was observed a few months later at the most upstream fish pass (SRWD) (Ngoichansri *et al.*, 2013). By contrast, in 2013, all the watergates were opened later because of delays in the onset of the rainy season therefore size frequency of fish that migrated into the river changed. Both large and small fish were observed at the TNNM fish passes because some species had already spawned downstream of the fish pass and movement was triggered by the first rainfall and water level rise in the Mekong. Consequently, small fish also migrated into the river system when triggered by discharge from the watergate operation.

Thoranit Naruemit



Suraswadi

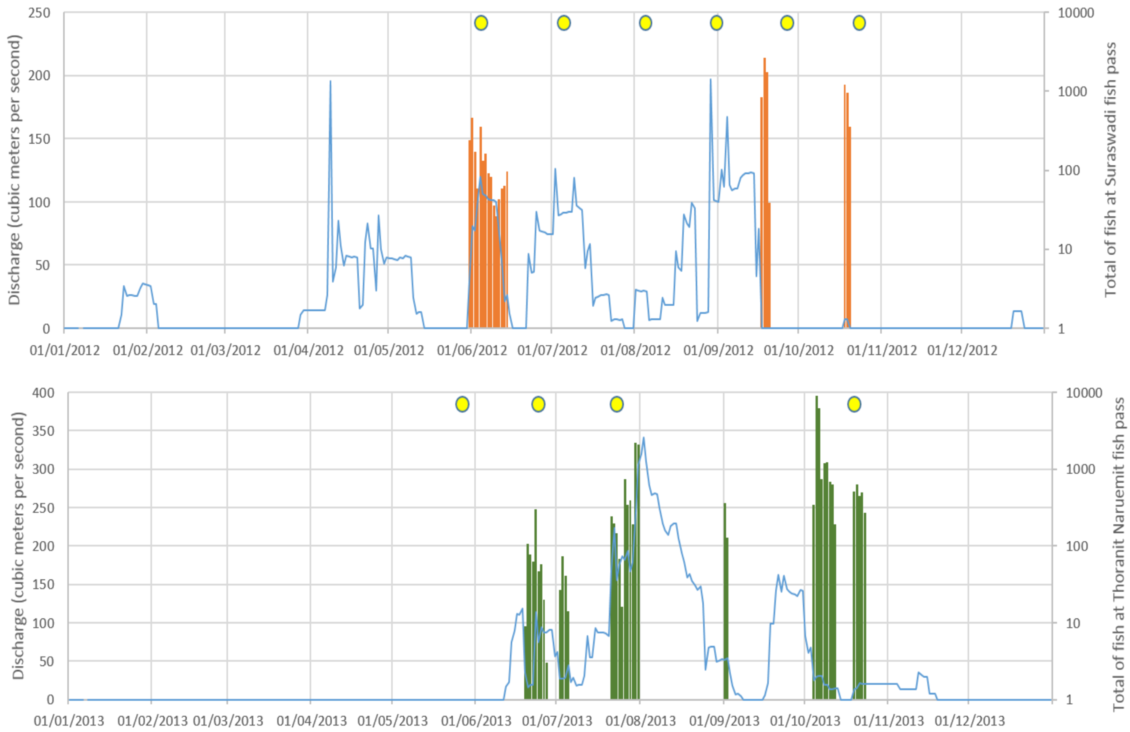


Figure 7.14 Migration periods of fish at Thoranit Naruemit and Suraswadi fish pass in 2012 and 2013 in relationship to discharge and lunar cycle (bars; number of fish, lines; discharge) (Sources; Ngoichansri *et al.,* 2013 and this study)

Nevertheless, knowing the main migration period of high risk species (Figure 7.3) can help inform when the sluice gates should be opened to maintain diversity of fish in the river system, and to mitigate the impact of the watergate on the migration of high risk species, including main channel resident and main channel spawning species, that would likely be impacted by watergate operation or the construction of dam in the mainstem river.

Further upstream movement was also stimulated by discharge and flow changes in particular reaches and periods. The regulation of water from the watergates in the river system also influence direction of movement of fish in the river. At the onset of the rainy season 2013, when little water being released from SRWD, delayed the migration to the Nam Kam River. The increasing flow and high discharge driven by maximum capacity of gate opening in the Nam Bang direction stimulated the migration of fish to the Nam Bang direction rather than Nam Kam direction. This was supported by the increased prevalence of white fish in gill net catches above Na Bua floodplain in the Nam Bang River in June 2014, which was higher than from above the Na Koo floodplain in the Nam Kam River (Table 4.9).

Moreover, the operation of the fish pass associated with the main sluice gate opening could support the upstream migration of fish from Mekong River. Sometimes the sluice gate was not raised high enough for fish to migrate through, moreover, velocity was also too high for fish to swim against or higher than maximum sustainable swimming capacity of migratory fish, but the discharge range was high enough to make a flow changes and attracted the migration of fish through the lower flow from fish pass instead. For example at the onset of rainy season of 2013, migratory fish were observed in TNNM fish pass when TNNM watergate opened with the distance just 0.1-0.2 m and created discharge around 41.39-78.39 m^3/s.

Although there was not a significant relationship between the flow and discharge from the watergate operation and migration of fish in the Nam Kam River system (Ngoichansri *et al*., unpublished), this relationship in this case is suppressed because a very high flow may deter and limit migration of fish that would migrate through the fish pass. The capacity of fish pass may also be limited and unable to handle very high volume of migrants at high flow. The observation from this study spotted that as soon as the water discharge and water level changed by the watergate operation, more migratory fish were observed in the fish pass. However, not just the discharge that needs to be controlled, it needs to be concerned about the timing as the migration of fish was significantly influenced by the lunar cycle and water level changes.

Lunar cycle

The lunar cycle has been known to trigger the migration of fish in the Mekong since 1945 (Blache & Goosens 1945) and Poulsen (2000) stated that lunar phase influences the migration of many Mekong fish species. Numerous other studies have reported large-scale movement of fish during various phases of the lunar cycle, such as at Khone falls (Warren *et al.*, 1998; Baird & Flaherty, 2001; Baird *et al.*, 2003) and in Tonle Sap (Lieng *et al.*, 1995; Deap, 1999; Phallavan & Ngor, 2000; Heng *et al.*, 2001; Poulsen *et al.,* 2004). However, Baran (2006) has argued that it is unclear which phase of the moon triggers migration and it varies depending upon species and location.

The number of fish that migrated through the upstream and downstream fish passes on the Nam Kam River at the onset of the 2012 and 2013 rainy seasons were also associated with the lunar cycle (Figures 7.14), and tended to increase during the full moon phase. We observed that when of main sluice gate was opening spectacular migration occurred around the full moon phase; the number of fish increased around 3-4 days before to after the full moon day, but this was also associated with water level fluctuations and flow changes. A total of 89 species were observed to migrate upstream in flood season (Table 7.6)

Table 7.6 List of 89 Mekong fish species that migrated through Thoranit Naruemit fish pass on the full moon period during flood season of 2012 and 2013.

Acanthopsis choirorhynchos (GF)	*Mystacoleucus marginatus* (WF)
Amblyrhynchichthys truncatus (WF)	*Mystus atrifasciatus* (BF)
Bagrichthys obscurus (GF)	*M. mysticetus* (BF)
Barbichthys nitidus (GF)	*M. singaringan* (BF)
Barbonymus altus (GF)	*Notopterus notopterus* (WF)
B. gonionotus (WF)	*Opsarias koratensis* (GF)
Channa striata (BF)	*Oreochromis niloticus* (GF)
Chitala ornata (WF)	*Osteochilus hasselti* (GF)
Cirrhinus macrosemion (WF)	*O. lini* (GF)
Clarias batrachus (BF)	*O. melanopleura* (GF)
C. macrocephalus X C. gareipinnus (GF)	*O. microcephalus* (GF)
Clupeichthys aesarnensis (GF)	*O. wandersii* (GF)
Cosmochilus harmandi (WF)	*Pangasianodon hypophthalmus* (WF)
Crossocheilus reticulatus (GF)	*Pangasius larnaudii* (WF)
C. siamensis (WF)	*P. macronema* (WF)
Cyclocheilichthys apogon (GF)	*P. pleurotaenia* (WF)
C. armatus (GF)	*Parachela siamensis* (GF)
C. enoplos (WF)	*Paralaubuca riveroi* (GF)
Cyprinus carpio (WF)	*P. typus* (GF)
Epalzeorhynchos frenatum (WF)	*Parambassis notatus* (GF)
Esomus metalicus (WF)	*P. siamensis* (GF)
Euryglossa siamensis (WF)	*Phalacronotus bleekeri* (WF)
Glyptothorax lampris (WF)	*Poropuntius bantamensis* (WF)
Gyrinocheilus aymonieri (WF)	*Pristolepis fasciata* (BF)
Hampala dispar (GF)	*Probabus jullieni* (WF)
H. macrolepidota (GF)	*Pseudolais pleurotaenia* (WF)
Hemibagrus filamentus (GF)	*Pseudomystus siamensis* (GF)
H. nemurus (GF)	*Puntioplites falcifer* (WF)
Hemimyzon nanenis (WF)	*Puntioplites proctozystron* (WF)
Henichorhynchus lobatus (WF)	*Puntius brevis* (GF)
H. siamensis (WF)	*Raiamas guttatus* (WF)
Heterobagrus bocourti (GF)	*Rasbora argyrotaenia* (GF)
Hypophthalmichthys molitrix (WF)	*R. trilineata* (GF)
Hypsibarbus lageri (WF)	*Scaphognathops bandanensis* (WF)
H. malcomi (WF)	*Sikukia gudgeri* (WF)
H. wetmorei (WF)	*S. stejnegeri* (WF)
Kryptopterus cheveyi (WF)	*Syncrossus helodes* (GF)
K. geminus (WF)	*Systomus orphoides* (GF)
K. palembangensis (WF)	*Tenualosa thibaudeaui* (WF)
Labiobarbus lineatus (WF)	*Thynnichthys thynnoides* (WF)
Labeo chrysophekadion (WF)	*Xenentodon cancila* (GF)
Laides longibarbis (WF)	*Yasuhikotakia lecontei* (GF)
Leiocassis siamensis (WF)	*Y. modesta* (WF)
Lobocheilos melanotaenia (WF)	*Y. morleti* (GF)
Mastacembelus armatus (BF)	

Note; Based on species of fish that migrated on the full moon periods of 2012 and 2013. (Ngoichansri *et al.,* 2013 and this study)

Rainfall/Precipitation

The first rainfall associates with the Mekong water level rising triggers breeding and reproductive migration of fish of most fish species in Mekong River Basin (Lowe-McConnell, 1987; Poulsen, 2000; MRC, 2006). Heavy monsoon rains start in the Mekong River Basin in May-June and continue until October while the rainy season during the study period in the Nam Kam River started around the end of May to June and continued until September (Figures 7.13 and 7.15).

However, this divergence in rainfall period is masked by the watergate operation, which affects migration of fish by blocking movements and changing water level and flow. Nonetheless the presence of larvae and juvenile grey and black fishes in the floodplains along the Nam Kam indicated that fish had spawned in the floodplain (see Chapter 5), presumably triggered by rainfall at the onset of rainy season thus the impact of the obstruction was in part ameliorated by the newly created environment. Although the upstream watergates in the Nam Kam River system were operated to drain the water from upstream before the rainy season (since mid-April), migration of fish through the fish pass was not observed until the end of May when Thoranit Naruemit Watergate was opened when water level in the Mekong River increased. Thus discharge and flow changes at the downstream of watergate associated with timing and rainfall are important elements to trigger migration of fish in to the Nam Kam River system. According to MRC (2006), species that are triggered by the first rainfall are *Barbonymus gonionotus, Cyclocheilichthys enoplos, Paralaubuca typus, Phalacronotus bleekeri,* and *Tenualosa thibaudeaui*. These MRC species were also found to be the first to migrate in the Nam Kam River system in 2012 and 2013 (Ngoichansri *et al.,* 2013 and this study).

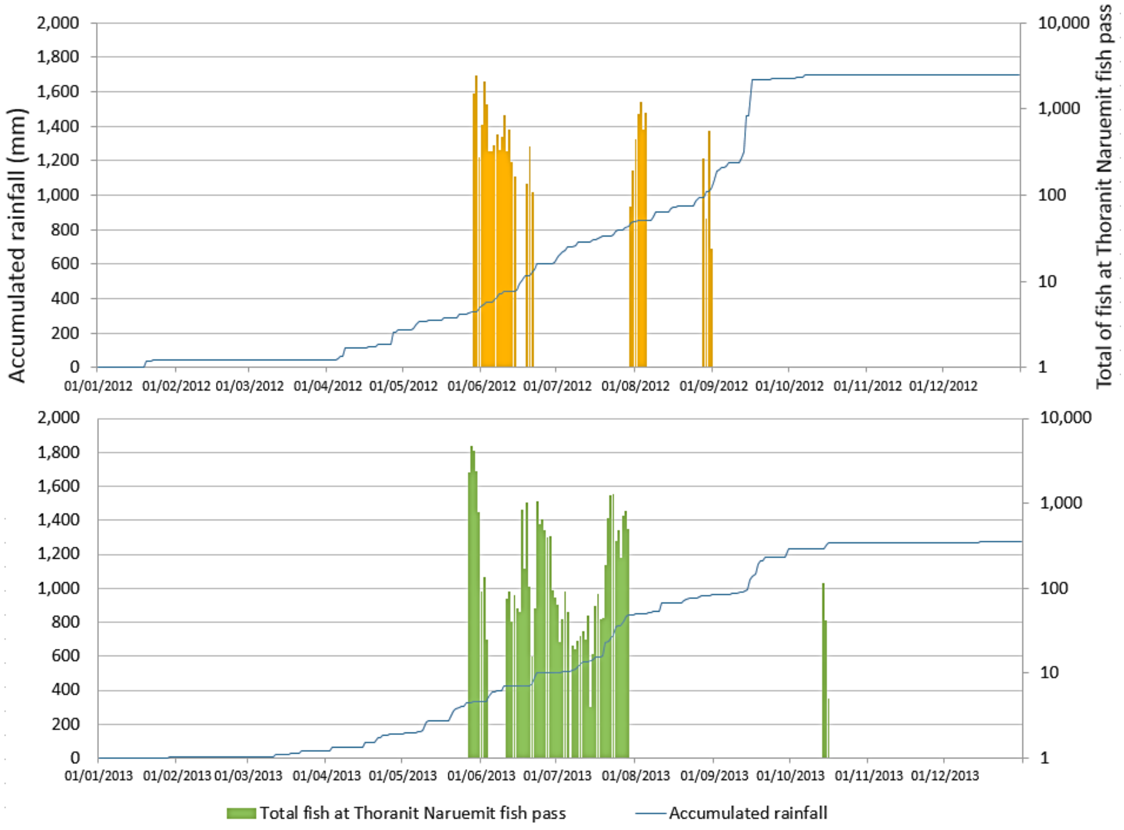


Figure 7.15 Accumulated rainfall at Thoranit Naruemit watergate and number of fish that migrated through the fish pass during 2012-2013. (Sources; Ngoichansri *et al.,* 2013 and this study)

Flow in the fish pass

The flow in the fish pass is the important factor that allows fish to migrate through the fish pass. Fish that migrated upstream usually swim against the current, but do not migrate within the maximum flow; it may swim along rivers edge. If the migration was blocked by the obstacle, fish can seek on passage by trying to escape laterally at one of the dam's sites and the attracting current from the fish pass guided fish into the fish pass (FAO/DVWK, 2002). Therefore, the flow velocity in the fish passes should be as low as possible to allow fish to migrate through independently. FAO/DVWK, (2002) suggests that the flow in the fish pass should not exceed 2 m/s at any point and it should be limited significantly lower than this current velocity. The upstream migration through the fish pass was only observed at velocities between 0.95-3.08 m/s.

Compared with the other fish way, Srisatit *et al.* (1981) reported that fish can swim effectively in the Suraswadi fish pass at flow between 0.46-0.67 m/s with the number of fish migrated 250,000 fish/day. Attracting fish is the most important consideration in locating and operating an effective fish passage facility. Ngoichansri *et al.* (2013) determined effect of the water current on the migration pattern of fish at the Thoranit

Naruemit fish pass and found that migration of fish was not significantly differences among three different velocities from varies level of fish pass opening (15, 20 and 25 cm) which created flow velocities between 0.95-3.08 m/s. However, the highest number of fish migrated when the fish pass opening was 20 cm. Although there was not directly correlated between migratory pattern of fish and the discharge from the main sluice gate, water level and rainfall in the study area, it was noted that as soon as the discharge from sluice gate was changed, numerous fish were observed migrating in the fish pass.

Turbidity

Changes in turbidity after rainfall are considered one of the migration triggers for many species of fish in the Mekong River system (MRC, 2006). Poulsen and Valbo-Jørgensen (2000) reported that higher turbidity associated with rising water level and the first rainfall triggered upstream migration at the onset of rainy season.

However, turbidity changes in the Nam Kam River system does not seem to influence fish migration. There was no relationship between turbidity and relative abundance of fish in the river. This is probably because turbidity is directly linked to rainfall events and the increased discharge and rise in water override other triggers of migration. Moreover, the maintenance of the channel in Nam Ban River in dry season created high sediment loading in the rainy season. High turbidity that observed in Nam Bang direction when the watergates were operated with the maximum capacity at the onset of rainy season, caused from the siltation from the rehabilitation above Ban Tabtao watergate since the dry season 2014, these disrupt the living of fish, it was supported by the abundance of fish were less than the others sampling sites.

7.5.4 Barrier effect

Rate of gene flow in fragmented landscape was lower than the continuous landscape due to gene flow was apparently eliminated by barrier (Epps *et al*., 2005; Blanchet *et al*., 2010). In this study, negative relationships were found between relative gene flow parameter of target species (Nm) and geographic distance (distance in km and number of barriers between population; Figure 7.9). It indicated that gene flow of target species was restricted by watergate operation. Gene flow in this study is also geographically restricted. However, the effective number of migrant from this study was still higher than those which has been faced with the fragmentation in isolated rivers for a long time (Yamamoto *et al*., 2016; Epps *et al*., 2005; Dehais *et al*., 2010) and also higher than recommendation level for maintaining population ($Nm \geq 1$; Wright 1931; Wang 2004).

Moreover, low and significant F_{ST}, and low genetic distance indicated that the structure of each subpopulation in the river were not genetically very different (Chapter 6). The decline in gene flow and genetic diversity at the sampling sites obstructed by many watergates (Chapter 6) indicated minor effects of the watergate operation in the Nam Kam River system. Therefore, the watergate operation by release water through the fish pass instead of the main sluice gate at the onset of rainy season could improve the genetic diversity in the river. The spawning migration of fish in the right time will prevent the declining of genetic diversity and increase rate of gene flow in this river system.

7.5.5 Efficiency of tagging study

The results indicated that physical tagging was not effective for determining the migration patterns of *Hemibagrus nemurus* and *Osteochilus hasselti* because of low recaptured rates, but genetic tagging can increase the efficiency of monitoring migration patterns in fishes and, in addition, indicated gene flow between subpopulations in the river system. Furthermore, recapture rates from genetic tagging were higher than physical tagging in both two species (1.1-1.37% and 0.96% in *Hemibagrus nemurus*; 1.08-1.32% and 0.58% in *Osteochilus hasselti*). Willson *et al.* (2004) also reported that higher recovery rates from indirect methods (microsatellite tagging) than mark-recapture surveys in salmonids in Canada.

Recovery rates of physical tags in this study was relative low (0.58-0.96%) but compared favorably with a study in a free flowing river; the proportion of recaptured salmonids that migrated from one population area to another in the Cape Race River in Newfoundland Canada was also low (0-4.1%) and indicated the pattern of limited movement (Wilson *et al.,* 2004). Recapture rate also depends on fishing pressure in the river system. In a tagging study on the Tonle Sap and Mekong rivers in 2003-2005 tagged fish were recaptured within 5 km of the tagging point and the tag-returned rate was very high (16%) because of high fishing pressure. Tagged fish in the Tonle Sap were recaptured by commercial fishing gears, stationary trawls known as dai nets (Hogan *et al.,* 2006). Recovery rate is also dependent on factors such as fishing effort, and relationship and effective communication between scientists and fishermen in the study area.

Based on this study, physical tagging is a viable and useful means to assess movement and upstream migration of fish. It was easily and readily applied, caused minimal mortality after tagging and was easily observed by fisherman. It provides information about direction, area that fish migrated to, as well as estimates of the distance and duration that fish migrate. However, there are disadvantages, for example, the number of tagged fish recovered was relatively low and the time taken for fishermen to find tags is quite long, especially in *Osteochilus hasselti,* so may not represent the true time fish take to migrate.

However, a combination of physical tagging and genetic tagging will provide more information about the distribution and migration patterns of fish, than either approach alone. The use of genetic tagging also provides more information besides migration pattern of the fishes, including structure of the populations in the river, estimated number of recaptured fish, and effective number of migrants. This provides scientists the information to formulate effective fisheries management plans.

7.6 Summary

Spawning migration of fishes from the Mekong River into the Nam Kam River system was initiated by a rise in the water level of the Mekong at the onset of the rainy season and another peak was observed at the end of the flood season. The majority of fish observed using the fish pass at the most downstream watergate was as soon as the pass was opened. About 11 tonnes of fish comprising 83 fish species migrated into the river system via the most downstream fish pass in 2013. Upstream migration of fish was triggered by hydrological changes driven by watergate operation, although the number of fish migrating was higher in the full moon period, and during increased rainfall and high turbidity periods. Migration of fish through the fish pass responded to a broad range of discharge (0-323 m^3/s) once the sluice gates were opened, and it was different between species; the majority of fish migrated upstream when the discharge ranged between 50-215 m^3/s. Fish were observed migrating through the fish pass when the water velocity was 0.95-3.08 m/s. Results from mark and recapture physical tagging suggested the target species could migrate bypass a few of the watergates but genetic tagging indicated that fish can migrate to the most upstream area. Although the actually migration rate was low, it was still higher than the recommended level for genetic conservation ($Nm \geq 1$; Wright 1931; Wang 2004).

There was negative relationship between relative gene flow and geographic distance in the river system, thus gene flow of target species were restricted by watergate operation and also distance between population. The low migration rate observed suggests that distribution of the two target species was likely impacted by watergate operation. However, relative gene flow in the Nam Kam River system is higher than the other river that are affected by barrier for a long period and also higher than the recommended level for maintaining natural population. Watergate operation and fish passage facilities enabled the upstream spawning migration of 135 fish species into the river system. Consequently, genetic diversity in the Nam Kam River was maintained by gene flow between populations. Watergate management in the system will therefore be important to help mitigate any impact on fish migration and to maintain the fisheries resources in the Nam Kam River system. Therefore, watergate management schedule is need to be adjust to increase gene flow in this river.

Chapter 8: Conclusions and recommendations

8.1 Introduction

The series of watergates on the Nam Kam River system is operated for two purposes: to release water for flood control in the wet season, and to store water for agricultural supply in the dry season. Watergate operation has had both negative and positive impacts in the river system. The change in hydrological regime has resulted in habitat changes (Chapter 3), watergate structures obstructing the flow of water and the operation of watergates impacting on migration of fish both from the Mekong River and within the river system (Chapter 7). These are key issues that affect fish diversity (species diversity in Chapter 4 and genetic diversity in Chapter 6), population structure (Chapters 4 and 6) and recruitment processes (Chapter 5) in the river system. The overall aims of this study were to examine the impact of the watergate operation on the river system and identify the factors that influence the migration of fish in the river system and investigate the efficiency of fish passage facilities installed at watergates.

To the end, this chapter integrates the knowledge presented in Chapters 3 to 7, summarizes the key conclusions and provides recommendations about how to operate watergates and fish passes to benefit both fisheries resources and irrigation in the cascade system.

8.2 Conclusions

8.2.1 Impact of watergate operation on hydrology

Watergate operation in the Nam Kam River system created hydrological changes. Discharge, flow and water level, timing of floods, and frequency and duration of floods in the river system were altered according to the functioning and purpose of the watergate operation (Chapter 3).

Operation for flood control: watergates were open to pass water downstream resulting in high flow pulses in the flood season (June-September), flow modifications and fluctuation of flows and water levels at all watergates. Operation of the most upstream watergate to control flooding in the wet season has modified the timing of flooding in the river system by delaying the onset of the annual flood in the downstream area. Watergate closure at the onset of the rainy season also prevented inflow of water from the Mekong River. After the river was regulated by the watergates, the highest flows were in the most upstream floodplain and then flow and size of flood were reduced when released subsequently at each watergate from upstream to downstream.

Operation for irrigation in the dry season: watergates are closed from the end of the flood season to the onset of the rainy season to store water and remove low flows and create long periods of no flow in the dry season (December-April or May). The river becomes stagnant and water levels in the upstream floodplains were higher than before the watergate operation. The size of the flooded area expanded after the watergates were closed and persisted for longer than the pre-operation period. The downstream floodplain, Kud La-A, experienced a longer flood period after the most downstream watergate was completely closed to store water.

8.2.2 Impact of watergate operation on floodplain environment

Flow and water level in each floodplain, which are nursery, rearing and refuge areas, were modified according to the upstream and downstream watergate operation. Many new nursery and feeding habitats were created above the watergates after construction, particularly above Na Karm, Na Koo and Na Bua watergates. When water level rises over bank in the flood season, the seasonal floodplains in low lying areas, and paddy fields and vegetable fields are flooded with static water that remains through the dry season. These are feeding and rearing grounds of black fish, generalists or maybe grey fish, and support recruitment to the fisheries in this river. On the other hand, water retention and abstraction by watergate operation has caused habitat disconnection between the mainstem river and the floodplains below the watergates, even in the flood season, for example at Na Koo watergate. This has resulted in loss of a variety of habitat (Chapter 3), leading to loss of productivity in the river system especially black and grey fish, which have potentially lost breeding opportunities when the floodplains dried out.

The longer duration of flooding is beneficial for fish larval development and feeding opportunities, and thus provides greater potential for survival and improved recruitment success in the river (Welcomme, 1985). However, the longer duration of the flood in the dry season can also result in the blooming of filamentous green algae in the impoundments after all watergates are completely closed (Figure 3.16). The longer flood period also possibly creates de-oxygenated conditions that might impact on white and grey fish larvae and juveniles. Although, it was not detected in this study, it is recommended that water quality monitoring is carried out in this river system to determine the severity of this issue.

The flooding cycle was also changed in the post construction period (Chapter 3): the timing of the flood, and frequency and duration of floods in each habitat were altered by watergate operation. The increase in water level downstream of the water gates took place later because watergates delayed the onset of the flood season to control flooding downstream and the recession occurred earlier than natural conditions before the river was regulated by the series of watergates.

8.2.3 Impact of watergate operation on fish migration

The watergate structures obstruct fish migration between the Mekong River and Nong Han Lake. The main spawning migration of Mekong fish into the Nam Kam River system was at the onset of the rainy season, with another peak at the end of the flood season (Chapter 7). Despite the Nam Kam River being open in the migration period, species are clearly unable to migrate throughout the system to the same extent as prior to watergate construction. This may result from fish only being able to use the fish passage facilities when the sluice gates were closed or partially opened during high discharge in the onset of the wet season. Upstream migration of fish was only completely unobstructed when the watergates were fully open in the peak of the wet season. The migration period at the end of the flood season has shorter duration and is less important than migration at the onset of rainy season in terms of species richness and abundance (Chapter 4). Moreover, the species observed at this time were mostly the same as those migrating at the onset of the flood season. For comparison, upstream migration of fish into the free-flowing Songkhram River occurred as soon as the migration cues - rainfall and water level changes - started. However, flow modification driven by watergate operation in the Nam Kam delays the onset of flooding in the downstream area and likely delays the cues to upstream migration of fish into the Nam Kam River system.

Fish species that migrate early at the onset of the rainy season and the late migratory species are the most likely to be impacted and this will also likely impact on the population structure. Four species, *Labeo chrysophekadion*, *Phalacronotus bleekeri, Pangasius larnaudii* and *Cyprinus carpio*, were rarely observed while nine species, *Probarbus jullieni, Cyclocheilichthys enoplos, Hemibagrus wyckioides, Pangasius macronema, Pseudolais pleurotaenia, Tenualosa thibaudeaui, Osteochilus melanopleura, Mystus bocourti*, and *Raiamas guttatus,* were absent at the floodplains above the Thoranit Naruemit watergate after the watergate begun operation in 2012 (Ngoichansri *et al., 2013,* unpublished; Phomikong *et al.,* 2014 and this study), although they were able to migrate through the Thoranit Naruemit fish pass. Main channel resident, *Probabus jullieni,* and two pangasids (*Pangasius larnaudii* and *Pangasius macronema*) was observed upstream of the most downstream watergate, Thoranit Naruemit, when it was under construction (Pongsri *et al.,* 2008), but has not been observed since the watergate has become operational (Ngoichansri *et al., 2013,* unpublished; Phomikong *et al.,* 2014 and this study). Jutagate *et al*. (2002) similarly found the loss of these species above Pak Mun hydropower dam on the Mun River, whilst these species were observed in the free flow Songkhram River (Phomikong *et al.* 2014) and mainstem of Mekong (Poulsen *et al.,* 2004). Watergate operation also obstructed some late migratory species at the end of the flood season (October), including *Pangasius larnaudii, Pangasius macronema, Mystus bocourti,* and *Phalacronotus bleekeri* (Chapter 4). Thus several migratory white fish species are affected by the hydrological alteration driven by watergate operation in the Nam Kam, despite the construction of fish passage facilities. Thus, to maintain the fisheries resources, this river system requires decision rules on watergate and fish passage operations to facilitate upstream migration of the majority of species.

Downstream migration of fish, eggs and larvae drift is also limited by the fish passage and watergate operational procedures due to the watergates being closed at the end of the flood season. Downstream migration of adult fish and juvenile fish in the free-flowing river is triggered by water levels receding at the end of rainy season (September), but in the Nam Kam is obstructed by watergate operation after all sluice gates are closed in October. Many white and grey fish species were stranded in the section above the watergate and need to adapt to feed and grow in the modified habitat during the dry season (Chapter 4). Larvae have the opportunity to develop in the closed system in the dry season (Chapter 5) but the quality of fish population and population size needs to be monitoring to assess long term changes.

Populations of the target species in the river system exhibited high genetic diversity, relatively large population size (Chapter 6) and the effective number of migrant was still greater than the recommended level for genetic conservation (Chapter 7). These indicated genetic diversity in this river was maintained by gene flow between other populations that migrated through the sluice gate and the fish passage facilities. The number of barriers in the river system had minor effect on the increasing of genetic differentiation (Chapter 6) and reducing relative gene flow (Chapter 7) of the two target species. Although the Nam Kam River is a relatively short river, gene flow in the river system was geographically restricted (Chapter 7). It means that the distance between population may also be a factor that effects migration in the river. However, the significantly lower genetic differentiation observed between sub-populations (Chapter 6) associated with the low migration rate (Chapter 7) also indicated that distribution of target species was likely to be impacted by watergate operation. It indicated migration of fish may also affect by the distance from between two populations.

8.2.4 Impact of watergate operation on diversity, population structure and recruitment of fish

Watergate operation for flood control and irrigation limits upstream migration of fish at the onset and the end of flood season and completely obstructs migration of fish in the dry season (Chapter 7). These affect diversity, abundance and population structure of fish in the river system. Sluice gate operation also removes low flows (Chapter 3), which are important for fish larvae development at the onset and the end of wet season. The life cycle and recruitment of fish is impacted by alteration of the timing, frequency and duration of flooding. Migration of some adult fish and recruitment of fish in the river was delayed according to the delayed timing of flooding caused from watergate opening.

The loss in fish diversity increased with increasing number of barriers and the upstream sections exhibited a lower species diversity than the area downstream of Thoranit Naruemit watergate (Chapter 4). Furthermore, diversity and abundance of white fish was significantly different between above and below the Thoranit Naruemit watergate at the onset of flood season (Chapter 4). Thus watergate management that limits fish migration appears to be the main factor determining species composition.

Watergate operation in the Nam Kam River also affects recruitment of fish as the duration of the flood season is reduced. This potentially reduces the time for fish larvae to feed and grow, and this may lead to lower survival and reduced recruitment in the river system. However, the appearance of early life stage in the floodplains along the Nam Kam River system highlight the species are using the floodplains as nursery grounds and feeding habitat (Chapter 5). Common larval and juvenile fish species observed in this river system were floodplain spawning (grey) and generalist (black) fish species that migrate laterally between the main river channel and floodplain. These species are well adapted to the impoundment habitat conditions. The number of species and abundance of larval and juvenile fish observed in Nam Kam River decreased from downstream to upstream and was negatively correlated with the number of barriers. Additionally, late opening of the Thoranit Naruemit sluice gates restricts the upstream migration of some white fish from the Mekong River and consequently these might spawn in the floodplain downstream below the watergate or move to another suitable area. Nevertheless larvae and juvenile fish were observed in the Nam Kam River system during the flood season and suggest most fish spawned between May and November, in both upstream and downstream areas (Chapter 5). The recruitment of some white fish species was restricted by watergate operation as it obstructed the migration of adult fish during the spawning season, especially early and late migratory species, pangasids and some cyprinids species. Fish passage facility supported the spawning migration and partly mitigates the impact of delayed watergate opening on the recruitment of fish in this river system. However, watergate operation obstructed the downstream drift of larvae, and larvae and juvenile fish are stranded in the floodplains above the watergates after they were completely closed (Chapter 5). The appearance of young of the year upstream of the watergate in 2014 suggests fish can adapt to the impoundment habitat during the dry season.

Habitat modification and habitat fragmentation in the Nam Kam River system also occurs every year, especially in the dry season, when all watergates are completely closed to store water for agricultural use (Chapter 3). This possibly leads to genetic diversity loss and increase genetic differentiation within populations of fish (Chapter 6). The change of genetic diversity (Chapter 6) and gene flow (Chapter 7) in the area that obstructed by many watergate suggested on minor effect of the watergate operation on geographic distance. Although weakly reduced genetic diversity in both target species was observed in areas upstream of this study, the rate of decline was significantly lower than previous investigations that are based on rivers with longer histories of isolation by barriers (e.g. Yamamoto *et al.,* 2004; Wofford *et al.,* 2005; and Blanchet *et al.,* 2010). Weak but significantly different genetic structure of populations in the river indicated that fish in this fragmented river system comprised of many sub-populations which do not differ much from each other (Chapter 6). This is probably because fish can still migrate to the upstream areas when the sluice gates are opened and gene flow still occurs in this river system, although it was partially limited by the many barriers. This was supported by the rate of migration (Chapter 6) and results from the mixed stock analysis (Chapter 5) that showed the populations of the two target species in the most upstream lake, Nong Han, were contributed by migratory fish from the Mekong River and resident populations within the Nam Kam river system. By chance, population sizes of two migratory species that migrated through the Thoranit Naruemit fish pass and Suraswadi fish pass were relatively large (Chapter 6). Moreover, gene flow in the river system was supported by the operational schedule of the watergates, which fully open in the flood season and the fish pass operation at the onset and the end of the flood season (Chapter 6).

8.2.5 Migration and recruitment of two economically important fish species in the Nam Kam River system

This study added more information about the migration patterns of two target species. The mature adults of *Hemibagrus nemurus* undertake longitudinal migrations from dry season refuges in the Mekong River to upstream spawning habitat in the Nam Kam River at the onset of rainy season. Mature *Osteochilus hasselti* migrated at the same time but the migration pattern was different, *Hemibagrus nemurus* continually migrated throughout the rainy season while *Osteochilus hasselti* migrated in many short batches associated with the lunar cycle (Chapter 7). According to the physical tagging study, the two target species were able migrate through a few watergates but the genetic analysis indicated *Hemibagrus nemurus* migrated further and into both the Nam Kam and Nam Bang (Chapter 7). Both *Hemibagrus nemurus* and *Osteochilus hasselti* used the Nam Kam River system as spawning and nursery grounds in flood season. *Hemibagrus nemurus* spawns in the main river then larvae drift to nearby floodplains including Dan Muang Kham, Kudla-A and other small floodplains above Na Koo, Na Bua and Ban Tabtao watergates (Chapter 5). *Osteochilus hasselti* undertook lateral migrations to spawn in the flooded areas along the river system, including Dan Muang Kham, Kud La-A and other small floodplains above Na Kham, Na Bua and Ban Tabtao watergates (Chapter 5). Offspring of both species develop in downstream feeding habitats over about 3 months in the wet season before returning to the main channel. Feeding migrations of sub-adult fish were observed at the most upstream, Suraswadi fish pass, a few months after the migration of adult at the most downstream fish pass, Thoranit Naruemit (Ngoichansri *et al.*, unpublished). These migrating sub-adults comprised fish migrating fish from Mekong River at the onset of rainy season and subpopulations from along the river. However, the percentage contribution from these sources were different according to their reproductive biology; juvenile *Hemibagrus nemurus* that recruited to the upstream area of the Nam Kam River system at the end of the flood season were mostly fish from the Mekong River plus some resident fish. By contrast, the *Osteochilus hasselti* that migrated to Nong Han Lake at the end of flood season were mainly from resident populations from floodplains along the Nam Kam River system rather than migratory fish from the Mekong River (Chapter 5).

The two target species responded differently to the watergate operation: migration of the longitudinal migrating species, such as *Hemibagrus nemurus*, are more sensitive and tend to be more limited by the watergate operation than the lateral migrating species or short distance migrating species, such as *Osteochilus hasselti*. Although rate of gene flow of the two target species was restricted, the number of migrants was still higher than recommended level for genetic conservation by FAO (1981), Franklin (1980), and Nelson and Soulé (1987).

8.2.6 Factors that stimulated the migration of fish into Nam Kam River system

Migration of fish in the Nam Kam River system is triggered by lunar cycle, water level and flow changes, the latter two of which are modified by the watergate operation, rainfall or precipitation and flow in the fish pass.

The migration of fish increased around 3-4 days period before or after the full moon. Sluice gate opening at Thoranit Naruemit watergate in the full moon period (three days before and after the full moon date) supports the upstream migration of more than 89 fish species from Mekong River in the flood season (Chapter 7). The spawning migration is also stimulated by rainfall at the onset of the rainy season when water level of Mekong River rises.

The discharge and water level changes from the watergate operation play an important role to trigger upstream migration of fish. It was noted that migration of fish via the fish passes were observed as soon as the main sluice gates were operated and resulted in hydrological changes especially in the downstream area. Fish responded to discharge from the opened sluice gates but the peak of migration was different for each species. Most of the top 20 dominant migratory species from the Mekong River or 46.6 % of fish observed at Thoranit Naruemit fish pass moved when the main sluice gates discharged between 50-215 m^3/s (Chapter 7). Further upstream movement was also stimulated by discharge and flow changes in particular reaches and periods. Flood control by opening watergates sequentially from the upstream to the downstream gates can benefit migration to upstream areas by releasing water to encourage opening to full capacity and opening access throughout the river system. Discharge and flow changes downstream of the watergate associated with timing and rainfall are important elements to trigger migration of fish in to the Nam Kam River system. Fishes also undertake lateral migrations from the main channel to spawn on the floodplains, presumably triggered by rainfall at the onset of rainy season. The influence of the rainfall period on longitudinal migration of Mekong fish into the Nam Kam River system was modified by the watergate operation due to barriers effects and modified water levels and flows downstream.

Fish passes in the Nam Kam River system usually operate during the same period as the watergates are functional operation and support migration of fish when they cannot swim against the high current through the main sluice gate. The flow through the fish pass is one important factor that enables fish to migrate upstream through the fish passage facilities and occurs when flows through the fish pass are mostly optimal velocities, e.g. 0.95-3.08 m/s in the Thoranit Naruemit fish pass.

8.2.7 Efficiency of fish passage facilities on the Nam Kam River System

The pool type fish passage facilities in the Nam Kam River system, comprise seven fish passes in the main river and its tributary. These are operated at the same time and closed a bit later than the sluice gate operation. Opening started at the onset of the rainy season (around the end of May) and closed in early October. The fish passage facilities in Nam Kam River can cope with massive migration of fish and high species diversity in the river basin. To date, it supported the migration of more than 135 fish species from 22 families both from Mekong River and within the river system (see Chapter 7). In 2013 large number of Mekong fish, more than 440,015 fish converting to around 11 tonnes of fish per year, migrated into the river system via the Thoranit Naruemit fish pass. Fish passage facilities supported the upstream migration of a broad size of fish between 22 and 700 mm.

To sum up, large numbers and biomass of fish species migrate through the fish passes (see Chapter 7) confirming they provide effective passage for migrating fish and thus help maintain the diversity of fish in the Nam Kam River.

8.3 Recommendations

The watergate structures and watergate management have many negative impacts on hydrology and habitat, diversity, population structure, fish migration and fisheries recruitment in the river system. To mitigate these impacts on the hydrological changes and habitat changes, to ensure free movement of fish through river system and to enhance the fisheries in the Nam Kam River system, management of the watergate operations is essential.

8.3.1 Watergate management to mitigate impact on hydrologic alteration

The Range of Variability Approach (RVA) pinpoints river sections that are impacted by flow alteration as a result of the installation of the series of watergates in the Nam Kam River 4-6 years ago (see Chapter 3). Many of the annual values of the IHA parameters in the post-alteration or after watergates were operational (Table 3.6) fluctuate outside the RVA targeted range (Tables 8.1). The recommended RVA target ranges (Table 8.1 and Figure 3.6) will be used to guide efforts to restore or maintain the natural hydrologic regime using the range of natural variability of different ecologically relevant flow parameters as the basis for setting management target.Therefore, to mitigate the impact on hydrologic alteration based on the impact and present RVA targets of each watergate (Table 8.1), it is recommended that the operation rules for each watergate should be designed separately to restore or maintain the natural hydrologic regime (Table 8.2).

Table 8.1 Selection of RVA targets for 32 IHA parameters at five watergates in the Nam Kam River system.

	Nong Bueng		Na Koo		Ban Tabtao		Na Bua		Thoranit Naruemit	
	Low	High	Low	High	Low	High	Low	High	Low	High
Parameter Group #1										
April	0.23	1.70	0.61	2.08	0.00	0.35	0.00	0.35	0.12	1.73
May	2.47	21.94	1.36	26.74	0.07	4.02	0.07	4.02	2.40	24.17
June	23.69	40.50	23.02	26.45	3.78	22.80	3.78	22.80	26.30	55.22
July	42.68	104.90	46.38	132.90	16.45	47.46	16.45	47.46	44.27	92.82
August	69.16	134.20	38.01	146.40	25.16	73.59	25.16	73.59	76.01	142.10
September	48.47	133.50	55.30	141.80	30.06	94.16	30.06	94.16	110.10	149.20
October	8.46	40.04	8.33	28.73	2.12	3.32	2.12	3.32	22.56	40.77
November	5.35	36.84	2.94	35.39	0.07	1.76	0.07	1.76	2.64	35.23
December	0.15	1.96	0.39	3.02	0.00	0.53	0.00	0.53	0.05	15.46
January	0.04	1.35	0.21	2.14	0.00	0.20	0.00	0.20	0.00	1.40
February	0.00	0.95	0.09	1.59	0.00	0.15	0.00	0.15	0.00	0.99
March	0.00	0.66	0.06	1.08	0.00	0.07	0.00	0.07	0.00	0.68
Parameter Group #2										
1-day minimum	0.00	0.26	0.03	0.43	0.00	0.01	0.00	0.01	0.00	0.00
3-day minimum	0.00	0.28	0.03	0.44	0.00	0.01	0.00	0.01	0.00	0.04
7-day minimum	0.00	0.29	0.04	0.45	0.00	0.01	0.00	0.01	0.00	0.04
30-day minimum	0.00	0.64	0.09	0.98	0.00	0.02	0.00	0.02	0.00	0.66
90-day minimum	0.02	1.23	0.17	1.93	0.00	0.19	0.00	0.19	0.00	1.27
1-day maximum	184.30	272.20	144.10	307.40	230.30	277.30	230.30	277.30	232.70	271.30
3-day maximum	179.80	266.30	140.80	297.60	196.90	259.10	196.90	259.10	229.70	264.70
7-day maximum	170.80	249.70	132.10	274.70	147.80	213.90	147.80	213.90	220.10	259.90
30-day maximum	108.10	195.60	102.90	202.70	77.22	109.10	77.22	109.10	139.00	210.40
90-day maximum	73.32	134.30	61.45	143.20	58.42	68.98	58.42	68.98	94.64	146.90
Number of zero days	0.00	81.05	0.00	44.88	0.00	151.80	0.00	151.80	4.78	107.10
Base flow index	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Parameter Group #3										
Date of minimum	90.60	94.40	89.28	92.68	92.00	113.20	92.00	113.20	92.00	94.48
Date of maximum	227.90	267.70	211.70	260.00	224.00	258.20	224.00	258.20	252.60	263.20
Parameter Group #4										
Low pulse count	2.60	7.35	1.60	7.04	0.00	2.03	0.00	2.03	1.00	3.37
Low pulse duration	3.66	6.72	5.00	36.00	30.65	117.60	30.65	117.60	3.46	93.12
High pulse count	2.95	6.40	3.64	5.68	1.97	4.06	1.97	4.06	3.26	6.37
High pulse duration	5.98	35.35	3.98	10.44	18.60	60.29	18.60	60.29	10.88	19.30
The low pulse threshold is										
The high pulse threshold is										
Parameter Group #5										
Rise rate	1.31	3.96	1.07	2.67	0.89	1.95	0.89	1.95	1.99	4.80
Fall rate	-2.38	-0.54	-1.15	-0.47	-1.93	-0.52	-1.93	-0.52	-5.14	-2.28
Number of reversals	76.45	99.55	85.48	103.80	43.61	58.21	43.61	58.21	64.04	86.18

Table 8.2 Recommendations for the watergate operations to mitigate impacts on the hydrological regime according to RVA target range.

RVA recommendation	NOBU	NAKO	BATA	NABU	TNNM
Expand the duration of flow by allow low flow at the onset of rainy season (May) by drain water through the fish pass rather than open the sluice gate	✓	✓	✓	✓	✓
Control discharge through the watergate opening in rainy season (June-September) according to RVA target range	✓		✓	✓	✓
Moderate lower flows in the high flood period (August) according to the RVA target range	✓				✓
Expand the duration of flow by allow low flow at the end of flood season (October-November) by drain water through the fish pass rather than open the sluice gate			✓	✓	✓
Moderate lower flows during dry season (December-April) by drain water through the fish pass rather than open the sluice gate	✓	✓	✓	✓	✓
Reduce the number of zero flow days by allowing annual low flows rather than closing the watergates in the dry seasons (December-April).	✓	✓	✓	✓	✓
Capacity to reduce the frequency of low pulses according to the RVA target range	✓		✓	✓	✓
Capacity to increase the duration of low pulses according to the RVA target range		✓	✓	✓	
Capacity to reduce the frequency of high pulses according to the RVA target range	✓	✓	✓	✓	✓
Capacity to increase the duration of high pulses according to the RVA target range		✓	✓	✓	✓
Control rate of change in RVT target range	✓	✓	✓	✓	✓

Monhtly mean flow at each watergate needs to be adjust by redesigning the watergate operation schedule to create discharge to achieve the RVA targets (Table 8.1-8.2 and Figure 3.6).

NOBU needs to be managed by control discharge at the onset of the rainy season (June-August) with an RVA target around 23.69-134.20 m^3/s. Fortunately, the operation at the end of flood season meets the discharge in the RVA boundary (5.35-40.04 m^3/s). Discharge in the dry season (December-April) needs to be adjusted to the RVA boundary between 0.04-1.96 m^3/s.

Watergate operation at NAKO needs to be adjust at the onset of the rainy season (May) by increasing the discharge to meet the RVA target range of 1.36-26.74 m^3/s

Operation during the dry season requires a target range of 0.61-3.02 m^3/s. Fortunately, watergate management in the flood season (June-September) provides discharge in the RVA target range (Table 8.1)

BATA and NABU have the capacity to release higher flows in the flood period (June-September) by controlling discharge within the RVA boundary between 3.78-94.16 m^3/s and still release water during around 1.76-3.32 m^3/s at the onset and the end of flood season (May and October-November). Low flows of 0.07-4.02 m^3/s need to be allowed during dry season (December-April).

Watergate operation at TNNM needs to expand the duration of opening to be all year round but moderate the high flow in the flood season (July-September) while allowing the annual low flow at the onset and the end of flood season and during the dry season according to the RVA target range (Table 8.1).

All required low flows could be created bypassing water through the fish pass rather than releasing it through the main sluice gates. Similary, the number of zero flow days at each watergate needs to be reduced by allowing annual low flows through the fish passes rather than closing the watergates completely during the dry season. Timing of the extreme flows need to be delay at BATA, NABU and TNNM. All watergates need to reduce the frequency and increase the duration of low and high pulses to prevent continuous fluctuations in flow in the river. NOBU and TNNM have the capacity to increase the rate of change, while BATA and NABU have to reduce rate of change (both positive and negative change of flow) (Table 8.1).

All required low flows could be created bypassing water through the fish pass rather than releasing it through the main sluice gates. Similary, the number of zero flow days at each watergate needs to be reduced by allowing annual low flows through the fish passes rather than closing the watergates completely during the dry season. Timing of the extreme flows need to be delay at BATA, NABU and TNNM. All watergates need to reduce the frequency and increase the duration of low and high pulses to prevent continuous fluctuations in flow in the river (Table 8.1).

This will involve redesigning watergate operation rules based on water level above the watergate (rule curves) that specify desired flow releases on a monthly basis, although the requirement to decrease annual high flow in wet season and increase annual low flow in both wet and dry season are quite difficult to manage due to it conflicts with the purpose of the watergates to store water for agricultural supply. The operating criteria for each year need to account for water required for irrigation supply, variability in water runoff and rainfall above the area, water level above and below the watergate, the retention area of the downstream area, impact from turbulence on fish migration and rate of erosion in the downstream area. It should also be noted that the timing of operation is different between years depending on prevalent climatic conditions, i.e. timing and intensity of the seasonal rains (Royal irrigation Department, personal communication). Moreover, any impact on habitat changes, migration of fish, and diversity and fisheries resources in the river system needs to be considered.

8.3.2 Solutions to improve the habitats in the Nam Kam River system

Watergate operation and the hydrologic alteration impact on habitat changes, frequency and duration of flood and disconnect the important floodplains from the mainstem river, which can negatively affect aquatic life in the river system. ***Reconnecting the essential habitats and conserving spawning and nursery habitat*** are required to maintain habitat and fisheries resources.

Reconnect the habitat

The continuance of longitudinal connectivity is needed to ensure migration of fish and maintain genetic diversity and gene flow into this tributary of the Mekong, especially for longitudinal migratory species. Operating the watergates to simulate the natural hydrograph is firstly suggested to maintain habitat in the river. Opening all watergates and fish passage facilities in the spawning season (end of May to July) are recommended to reconnect the river system, although the downstream floodplains will be partially dry and isolated from the Mekong in the dry season because the primary function of the watergates. Watergate management or water abstraction for irrigation needs to be balanced against the potential damage to upstream fish sub-populations caused by limiting inbound migrant. Therefore, to maintain the function of the disconnected downstream floodplains, for example the floodplain below Na Koo Watergate (Figure 3.14), ***releasing water through the various watergates to the downstream area in the flood season*** could help maintain connectivity between the floodplain and the main river. ***Rehabilitation that creates functional habitat and connectivity between floodplains and the main river is also another measure to recover the disconnected habitat***. For example reconnecting floodplain wetland that have been isolated by sediment build up due to the change in flow (see disconnected floodplain in Figure 3.14).

Conserve spawning and nursery habitat

Floodplain habitat along the river system, such as Dan Muang Kham, Kudla-A and other small floodplains above Na Kham, Na Koo, Na Bua and Ban Tabtao watergates, are the nursery and rearing grounds for fish larvae and juveniles in the flood season, and are flooded continuously, even in dry season. As a result, all of the above mentioned floodplains should be preserved in the good condition although this may not necessarily be the case. The long periods of stagnant water when watergates are closed during the dry season might alter water chemistry, create die-back of vegetation and decomposition of aquatic plant, which may de-oxygenate the water resulting in severe impact in some group of fish (for example, white and probably grey fish). ***It is recommended a water quality monitoring programme is established, especially the impoundment areas in the dry season, to identify any deterioration and establish a suitable protocol to protect the fish populations in the river system and Nong Han swamp should a problem arise.*** Such a response might include emergency flushing of the floodplain to refresh the static water, this would benefit recruitment and development of larval and juvenile fishes stranded in the impoundment above the watergates. It would also improve to fish access to upstream and downstream areas in the dry season. Although in previous study and this study resulted that water quality met the level of water quality standard of Thailand (WQD, 1991) and meets the standard water quality for fisheries purpose (Duangsawasdi & Somsiri, 1985). The variation in natural water quality characteristics that effect on the distribution and productivity of the system like Conductivity, Total dissolved solid and Dissolved oxygen (Duangsawasdi & Somsiri, 1985; WHO, 1989; Svobodova *et al*., 1993; Sharma, 2015) are needed to continually monitor.

8.3.3 Solutions to enhance fisheries resource

Increase opportunity of fish migration through fish passage facility and free flowing the migration of fish

Flow regulation in the Nam Kam River is heavily influenced by operation at the most upstream watergate (Suraswadi Watergate), which is controlled by DoF. They are able to control releases of water that influences subsequent opening of watergates from upstream to downstream. If this operation is deigned and carried out correctly at the onset of the rainy season this regulation of discharge can be used to stimulate migration of fish into the river system, especially when the downstream watergate (Thoranit Naruemit Watergate) and its fish pass are opened (see 3.4.1-3.4.2). The operation may vary each year, depending on the onset and the recession of the flood season.

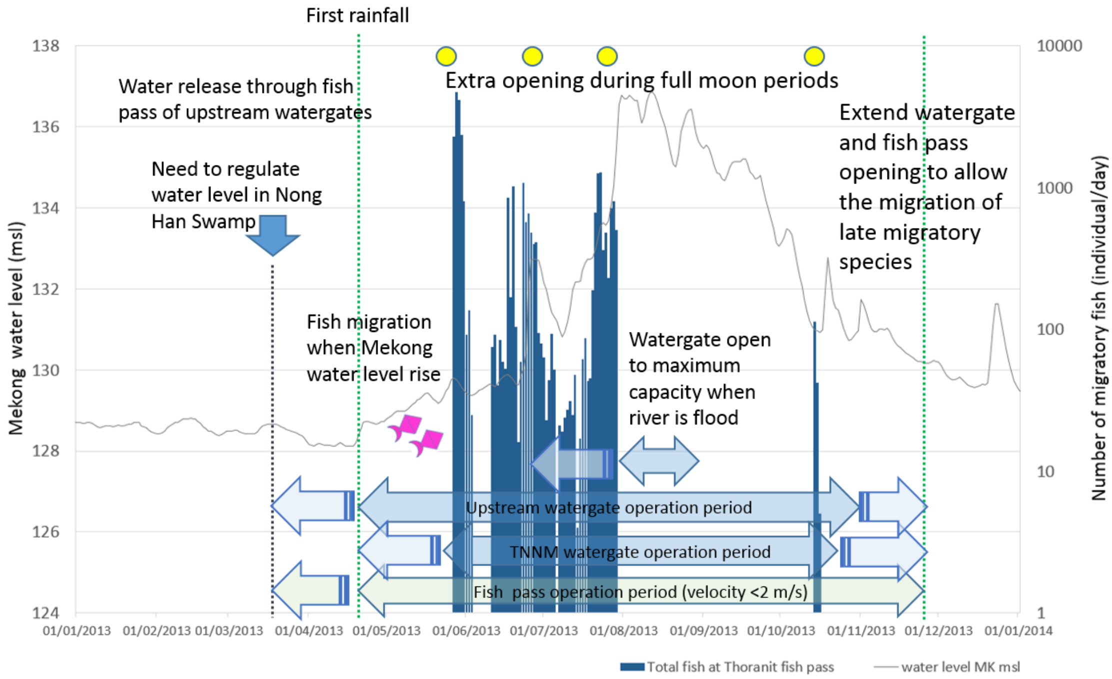


Figure 8.1 Flood cycle of Mekong River, migration period of fish and recommendations for watergate and fish pass operation in the Nam Kam River system.

To improve fish migration in the Nam Kam River and through the fish passes, it is suggested ***the most upstream watergate, Suraswadi, is opened earlier to release water at the end of dry season (April-May)*** to prepare the downstream impoundment areas for the coming flood season (Figure 8.1). ***Consequently, other downstream watergates (Nong Bueng, Na Karm and Na Koo) should store water where possible for release into the fish passage facilities and thus make the pass operational earlier to reconnect the habitats before the start of the migratory season or at least at the onset of the migratory period. Water should be directed through the fish pass instead of the main sluice gate in this early period***. The key criteria here is to ensure ***water released from Suraswadi watergate builds up in the most downstream floodplain above Thoranit Naruemit watergate so there is sufficient water that the sluice gate can be opened to synchronize with the migratory and spawning periods of most migratory fish (end of May to July) and linked to the start of the level rise in the Mekong River. If any of all watergates are not ready to open at the onset of the rainy season, it is suggested any water is released through the fish pass instead of the main sluice gates*** in the first weeks that water level in the Mekong River is rising to coincide with the peak in migration of fish (more than 85% of total migratory fish). These will support spawning migrations of fish from the Mekong River in to Nam Kam River at the onset of rainy season (end of May to July) and increase the opportunity for fish to migrate further upstream when the watergates are not ready to open. It is also suggested that all ***watergates are operated by matching the pattern of fish migration with opening the sluice gates to their maximum capacity when the river is in flood (July-August).*** These would allow fish to migrate directly through the sluice gate to further upstream. It should be able to increase the rate of migration with little or no impact on watergate operation. ***Because it is necessary to lower the main sluice gates at the end of the rainy season (around middle of October to November) to impound water, it is recommended that the fish pass facilities are opened during the late migratory period (until November) to facilitate late migrating fish*** (Figure 8.1). During this time it is necessary to ***ensure that flow velocity in the fish pass does not exceed the maximum sustainable swimming capacities for fish using the pass. It is suggested to maintain water velocity in the fish pass around 0.95-3.03 m/s to support the migration of fish through the fish pass.***

Fish migration in the Nam Kam was also influenced by the lunar cycle (see 7.5.3) therefore it is recommended to increase the ***frequency of gate opening and link it to the lunar cycle***; i.e. ***open the sluice gates and fish passes for short periods during the full moon period***; this could support upstream migration of more than 20 late migratory fish species and increase fisheries resources in the river system (Figure 8.1).

Migration of fish was observed to occur at a broad range of discharges through the sluice gates, ranging between 8 to 323 m^3/s. However, the peaks of each species were different. ***In 2012-2013, the majority (88.9-90.5%) of migratory fish was observed in the fish pass when discharge from the sluice gates ranged between 50-215 m^3/s. This indicates that it is important to have a range of flows and also include lower discharges below 50 m^3/s to facilitate migration of fish with lesser swimming capacity.***

It is also essential to open a few watergates to their maximum capacity rather than open all sluice gates partially with a narrow gap at the onset of rainy season as these partially opened gates are very turbulent and restrict migration. Similarly, these gates should be opened to support the downstream migration of fish and larvae drifting through the main watergate at the end of rainy season.

All watergates created turbulence of water in front of the sluice gate and it appears to create sedimentation and erosion below the watergate. Turbulence also is an obstacle to the stimulation and smooth passage of fish through the gates (Marsden et al., 2014). Consequently, mechanisms to ***minimize the turbulence of water should be sought*** through consultation with hydrologists or engineers.

Malfunction of sluice gate and fish pass, although rare were observed in some watergates in 2015. To reduce this problem it is recommended ***watergate maintenance is carry out after the flood period to prepare for use in the next flood season.***

Stop illegal fishing

Illegal fishing has been observed in the fish pass during the study although there were security guards working in the area. ***It is recommended to restrict access to the fish passes to only watergate managers, maintenance workers and scientists to reduce this illegal fishing practice.*** Similarly, illegal fishing was observed in the spawning season and it is suggested that ***fisheries inspections, as well as awareness building and education of fisherman about fisheries conservation, are required and should be implemented to regulate this activity***.

8.4 Recommendations for watergate management in Thailand

This case study on the Nam Kam River system has proved that the watergate management and an effective fish passage facility are important elements to mitigate the impact of instream structures on fish migration and maintain the fisheries resources in the river system. The recommendations from this study (8.3.1-8.3.3) will be passed through to the watergate managers on the Nam Kam and upscale to Thailand. In particular, the operational regimes at each watergates will be redesigned to enhance the environmental conditions by coordinating between the watergate managers of RID and DoF; suitable operational schemes will be discussed for that benefit fishery resources as well as protect supply water for irrigation and flood control in the Nam Kam River system.

Recently fish passes have become key elements for ecological improvement in rivers to recover ecological connectivity and restore free passage for fish and other aquatic species (Bunt *et al*., 2012; FAO/DVWK, 2012). The impact of artificial structures on migration of fish has been a key concern of decision maker and the stakeholders (e.g. engineers, biologist and administrators) in Thailand. However, many of the existing fish passes do not function correctly and effectively, and there is little knowledge about the migration and efficiency of fish passage facilities. ***Therefore the lessons***

learnt and solutions to mitigate the impact of the watergates on the fisheries resources in the Nam Kam River System (see 8.3.3) could be adapted for other Mekong tributaries and the other tropical river system which face with the same situation.

There are more than 16 fish passage facilities in Thailand, 6 of which operate like the 7 on the Nam Kam system, one each at Chonnabot and Roi-et watergates in the Chi Basin, two fish passes at Uthokwipat Prasit Watergate in Pak Phanang Basin, Ban Had Sanam Jan Watergate in Yom Basin and Pak Mun Dam in Mekong Basin. Although these fish passes operate in the flood season, some of them do not work effectively. For example, Pak Mun fish pass is not located in the optimal position and the fish pass is too steep (Amornsakchai *et al.,* 2000; Roberts, 2001), and the fish pass structure at Uthokwipat Prasit Watergate are too short and creates high velocity in the fish pass (Rattanavinitkul *et al.,* 2011). The other operations are also based on very little knowledge and experience for watergate management.

The installation of fish passes to support the migration of fish and enhance fish populations, as well as establishing good practice for watergate management, are recommended, especially for the many watergates and dams constructed more than 20 years ago that have not provided the fish passage facilities to mitigate the impact on fish migration. For example, 21 weirs/dams in Chi, Mun and the Mekong Basin in the northeast of Thailand that have not been provided with fish passage facilities (see Thalerngkietleela *et al*., 2013).

In addition, three fish passes have not been operated or maintained for a long time, because they are in the wrong location (Kwan Phayao and Bueng Borapet) or the slope of the fish pass is too steep (Huay Luang) (Department of Fisheries, personal communication; Thalerngkietleela *et al.,* 2013). ***Re-designing and installing appropriate fish passage facilities at these sites is recommended***.

For another three fish passage facilities, Chonnabot, Roi-et, and Ban Had Sanam Jan, are functioning but have not been investigated for their effectiveness for migration of fish (Department of Fisheries, personal communication; Thalerngkietleela *et al.,* 2013). Solutions to operate each watergate might vary according to the hydrology and regulation of the river, position and type of the fish pass, and composition of fish in the river. ***Thus, it is recommended that migration of fish through these fish passes and their efficiency are investigated and appropriate watergate management options are developed.***

It is recommended that where any new dams or watergate structures are constructed ***well designed and appropriate fish passage facilities and watergate management protocols are included in the construction and maintenance costs to ensure free passage of fish.*** The general requirements for any fish pass design and construction, including the optimal position, design of the fish pass (entrance, exit, length, slope, and resting pools), attraction flow and discharge current condition in the fish pass, should be thoroughly investigated and appropriate consultation is made with fish passage experts to avoid the problems of the past (see FAO/DVWK, 2002). ***Moreover, long term monitoring programmes are recommended to monitor any changes in hydrology, habitats, fish populations and recruitment of fish in the river systems.*** These investigations are required for the watergate management protocols to mitigate the impact of these obstacle on fish migration.

8.5 Recommendations for future research

Throughout this study there has been limited access to hydrology data because recording of hydrological data at the gauging station has stopped since the construction of the gates and pre-construction records some watergates (Suraswadi and Na Kham) are missing. This has limited investigation into hydrological changes in this river system. ***It is recommended that the gauging station network is rehabilitated and improved to collect adequate hydrological data for future management of watergate and other water resource operations in the region.*** The will help managers establish environmental flow criteria based on real empirical data and enable greater protection of fisheries in these river systems***.*** Additionally, information on water quality and sediment dynamics is required to guide decisions to minimize the impact of flow alterations on ecosystem functioning and fisheries dynamics***.***

Unfortunately, no eggs or early life stage larvae, especially white fish, were collected in the conical net sampling therefore the exactly spawning areas for these species could not be identified and the spawning period was based on estimated age of larval and juvenile samples collected by conical net and seine net sampling in the 2014 flood season. It is recommended larval and juvenile drift sampling is carried out ***at least once per week or even more frequent at the onset of flood period in the peak spawning season to better understand the recruitment dynamics of migratory fish species in the Nam Kam and other impacted rivers in Mekong region.*** Where possible, studies should include unregulated rivers or pre-construction phases in rivers that are to be modified to help understand recruitment dynamics and impacts thereon of dams and watergate construction and operation.

Due to limited budgets, only two species could be investigated. These were selected because they represent the economically dominant species in the river system. However, ***further studies on migration patterns and impact of watergate operation on other fish species are suggested to complete the whole picture of impact and to create optimal mitigation solutions for the diversity of fish species in the river system.***

All of suggestions and recommendations in this study are based on the possible impact on fishery resources in just one year, which was actually a drought year. Considering the level of impact appears to depend on rainfall and watergate operation in that particular year, ***further studies about impact of watergate operation on fish migration in the river system are required for a series of year*** to determine if there are differences between drought and wet years to guide the watergate operation***. Long term studies and monitoring programmes are required to*** investigate further the population dynamics and the adaptation strategies of white fish to the hydrological and habitat changes and ***develop recommendations for operation in wet and dry years.***

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