

**DEVELOPMENT OF THE MALAYSIAN RIVER INTEGRITY INDEX
(MYRII) BASED ON BIOLOGICAL, CHEMICAL AND PHYSICAL
MULTI-METRICS**

By

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ABSTRACT

DEVELOPMENT OF THE MALAYSIAN RIVER INTEGRITY INDEX (MYRII) BASED ON BIOLOGICAL, CHEMICAL AND PHYSICAL MULTI-METRICS

Ng Keat Chuan

Malaysia is currently undergoing dramatic geohydrologic changes due to unsustainable land development activities and this threatens the integrity of freshwater resources. Considering the steady national population growth, Malaysia will need more freshwater into the future for household, recreation and industrial consumption. And yet, methodical river assessment and management is minimal as suggested by literature review.

Prompted by the predicament, this study's objective was to pioneer an assessment system that can be readily adopted to assess, monitor and drive river conservation in a wholesome manner. Literature review showed that the inclusion of biological, chemical and physical metrics is crucial for formulating a wholesome assessment system. Hence, three sets of *a priori* metrics were selected to form the Ichthyofaunal Quality Index (IQI; biological), Water Quality Index (WQI; chemical) and River Physical Quality Index (RPQI; physical). These indices were further normalized and integrated on equal weighting to construct a novel Malaysian River Integrity Index (MyRII). Additionally, the ecosystem service economic value of the study site was also calculated using the Market-Price-Method.

To test its robustness, the MyRII protocol was field tested in four eco-hydrological zones (i.e. Zone A, B, C and D) located along the Kampar River for 18 months to reveal its strengths and weaknesses. Statistical analysis functions of software IBM SPSS version 20 were applied to determine the variances, correlations and clustering patterns of metrics and indices. This was crucial as the metrics and indices were expected to detect any anomalies, non-compliances and distinguish the studied zones according to their biological, chemical and physical characteristics. Additionally, the 75%, 50% and 25% percentile thresholds were computed statistically from combined dataset of Zone A and B for establishing the “good”, “average” and “poor” rating, respectively.

The resultant MyRII showed a clear trend that corresponded with different levels of river impairment. Zone A which was a reference site with minimal disturbance achieved the highest MyRII (89.69 ± 4.42), followed by zone B (62.22 ± 6.02) and zone C (50.19 ± 4.28). However, the MyRII in zone D (63.37 ± 6.90), which was a heavily disturbed wetland, did not conform to such trend. Also unveiled and recognized, however, are some limitations in IQI assessment, namely the implications of species niches, species physiology, introduced species and the lack of taxonomy expertise in Malaysia. Sporadic non-compliances of water chemistry parameter namely bio-chemical oxygen demand, turbidity, ammoniacal nitrogen and dissolved oxygen were detected by the WQI assessment. The possible natural and anthropogenic causes and implications were critically discussed as precautions for interpreting and implementing the MyRII protocol.

Although this thesis deals mainly with an exemplar river in Malaysia, the core principles and approaches proposed have global relevance. The immediate issue at stake is, unless the ecological interactions between biology, chemistry and physical components are recognized and assessed in a multi-disciplinary manner, only partial or deficient data are available to drive restoration and management initiatives. This research adds to the mounting body of evidence that water resource stakeholders and policymakers must look at the big picture and adopt the “balanced ecosystem” mindset when assessing and managing Malaysia's freshwater resource.

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SUBMISSION OF THESIS

It is hereby certified that **Ng Keat Chuan** (Student ID No: **15ADD06629**) has completed this dissertation entitled “Development of the Malaysian River Integrity Index (MyRII) based on Biological, Chemical and Physical Multi-Metrics” under the supervision of Assoc. Prof. Dr. Gideon Khoo (Principle Supervisor), Adjunct Prof. Dr. Peter Ooi Aun Chuan (Co-Supervisor 1) and Asst. Prof. Dr. Wong Wey Lim (Co-Supervisor 2) from the Department of Biological Science, Faculty of Science.

I understand that the University will upload softcopy of my dissertation in PDF format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

(Ng Keat Chuan)

APPROVAL SHEET

This dissertation/thesis entitled “**DEVELOPMENT OF THE MALAYSIAN RIVER INTEGRITY INDEX (MYRII) BASED ON BIOLOGICAL, CHEMICAL AND PHYSICAL MULTI-METRICS**” was prepared by NG KEAT CHUAN and submitted as partial fulfillment of the requirements for the degree of Doctor of Philosophy in Science at Universiti Tunku Abdul Rahman.

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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

(Ng Keat Chuan)

Date _____

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ACKNOWLEDGEMENT	v
SUBMISSION SHEET	vii
APPROVAL SHEET	viii
DECLARATION	ix
LIST OF TABLES	xiii
LIST OF FIGURES	xvi
LIST OF ABBREVIATIONS	xxiv
CHAPTER	
1.0 INTRODUCTION	1
1.1 Problem statement	3
1.2 Hypothesis and research questions	4
1.3 Main objective and breakdowns	4
2.0 LITERATURE REVIEW	7
2.1 Water resource status and trend in Malaysia	9
2.1.1 Economical value of water safety and security	16
2.2 Characteristics of the river ecosystem and integrity	20
2.3 Biological, chemical and physical (BCP) concept of multi-metrics assessment	26
2.4 Water physico-chemistry assessment	30
2.5 Physical assessment	40
2.5.1 Hydro-morphological variances	46
2.5.2 Meteorological disturbances	47
2.6 Biological assessment	50
2.6.1 Freshwater fish biogeography	58
2.6.2 Taxonomic of freshwater fishes in Malaysia	60
2.6.3 Ichthyofaunal biogeography pattern in Malaysia	64
2.6.4 Conservation and management status	68
2.6.5 Definition of fish and species concept	72
2.6.6 Overview of trends in the taxonomy discipline	74
2.6.7 Why are there so many species?	76
2.6.8 Taxonomy and systematics	79
2.6.9 How species are named and why	82
2.6.10 Species identification at the morphological level	87
2.6.11 Species identification at the molecular level	105
2.6.12 Reference type and traceability	109
2.6.13 Specimen collection and preservation	112
2.6.14 Taxonomic key	117
2.6.15 Integrative taxonomy	121
3.0 MATERIALS AND METHODS	124
3.1 Core principle	128

3.2	Biological metrics	129
3.3	Chemical metrics	133
3.4	Physical metrics	137
	3.4.1 Geomorphometric equations	151
	3.4.2 Geoinformatics data processing	154
3.5	Meteorological forecast	155
3.6	Surface water discharge	156
3.7	Economic valuation	157
3.8	Study site	158
3.9	Field sampling plan	160
3.10	Statistical analysis	163
	3.10.1. Variance	163
	3.10.2. Correlation	163
	3.10.3. Cluster analysis	164
3.11	Reference site and rating normalization	165
3.12	IQI, WQI and RPQI weighting	168
4.0	RESULTS	170
4.1	Fish-based biological data	170
	4.1.1 Fish taxonomic account	181
	4.1.2 Species occurrence in zones	231
4.2	Water chemistry data	234
4.3	River physical data	241
4.4	IQI, WQI and RPQI data	246
4.5	MyRII ratings	247
	4.5.1 Reference site and final MyRII results	258
4.6	Watershed geomorphology data	261
4.7	Ecosystem service economic value	268
5.0	DISCUSSION	270
5.1	Biological metrics	271
	5.1.1 Species niches	271
	5.1.2 Introduced species	273
	5.1.3 Species physiology and niche behaviours	274
5.2	Chemical metrics	276
	5.2.1 Non-compliances of BOD ₅ values	276
	5.2.2 Non-compliances of Turbidity values	277
	5.2.3 Non-compliances of NO ₃ -N and AN values	278
	5.2.4 Non-compliances of DO values	279
	5.2.5 Water chemistry and hydrology implications	283
5.3	Physical metrics	286
	5.3.1 Implication on IQI and WQI	286
5.4	Water provision ecosystem service value	288
	5.4.1 Economic comparisons	288
	5.4.2 Watershed integrity	292
	5.4.3 Community-based conservation	295
5.5	MyRII implementation challenges	297
	5.5.1 Stakeholder feedbacks	299
5.6	Limitations and future researches	302
	5.6.1 Fish taxonomy and IQI interpretation	303

5.6.2	Water chemistry variations	305
5.6.3	Other form of ecohydrological systems	306
5.6.4	Geomorphology	307
5.6.5	Water provision ecosystem service value	308
6.0	CONCLUSION	310
	REFERENCES	313
	APPENDICES	368

LIST OF TABLES

Table		Page
2.1	Responsibility differs and overlaps among federal and state agencies in terms of water resource management (Chan, 2004; Rahman and Khalid, 2009; Saimy and Yusof, 2013; Academy of Sciences Malaysia, 2016; Khalid, 2018).	12
2.2	Examples of formidable assessment systems that adopted the BCP approach	28
2.3	Water parameter thresholds, Water Quality Index (WQI) and class designation specified in National Water Quality Standards (NWQS) of Malaysia	34
2.4	Results of water quality parameter from Sg. Buloh, Selangor, watershed	39
2.5	Width designation of riparian reserve	42
2.6	IBI scoring criteria	52
2.7	Fish voucher specimen depositories in Malaysia	70
3.1	Summary of all materials and methods deployed in this study	125
3.2	The metrics of Ichthyofaunal Quality Index (IQI). The peak number of species/families and percentage of native species is the highest number obtained during the study duration in the four zones	132
3.3	The metrics of Water Quality Index (WQI) established by the Ministry of Natural Resources and Environment, Malaysia (MNRE, 2009). The metrics are the standard parameters tested to determine river integrity in Malaysia	134
3.4	Sub-index (SI) of each metric established by the Ministry of Natural Resources and Environment, Malaysia, for calculating the WQI	135
3.5	Standardized water quality classes in accordance to the Ministry of Natural Resources and Environment, Malaysia	136

3.6	The metrics of River Physical Quality Index (RPQI). The rating criteria and score follow Stream Visual Assessment Protocol Version 2 (SVAP2) that originated from the Natural Resources Conservation Service, US	139
3.7	Criteria for Channel Stability	140
3.8	Criteria for Bank Stability	142
3.9	Criteria for Hydrologic Continuity. Development in the flood plain refers to transportation infrastructure (roads, railways), commercial or residential development, land conversion for agriculture or other uses, and similar activities that alter the timing, concentration, and delivery of precipitation as surface runoff or subsurface drainage. As used here, “natural flow regime” refers to stream flow patterns unaffected by water withdrawals, flood plain development, agricultural or wastewater effluents, and practices that change surface runoff (dikes and levees) or subsurface drainage (tile drainage systems)	144
3.10	Criteria for Riparian Quantity	145
3.11	Criteria for Riparian Quality	146
3.12	Criteria for Canopy Cover	147
3.13	Criteria for Pool Availability	148
3.14	Criteria for Riffle Embeddedness	150
3.15	Geomorphometric equations applied for this study and the respective originators	152
3.16	Standard tariff of water in Perak state	158
3.17	Zone description and GPS coordinates of sampling points	162
4.1	List of fish species encountered in each zone	172
4.2	Summary of fish-based metrics averages (n=18, mean \pm SD)	178
4.3	Summary of water chemistry values (n = 36, mean \pm SD) in compliance to class IIA-IIB Standard	235

4.4	Pearson correlation (r) between WQI and IQI metrics. Only the relationship between dissolved oxygen (DO) and percentage of native species (NS) shows a strong correlation	250
4.5	Pearson correlation (r) between WQI and RPQI metrics	251
4.6	Pearson correlation (r) between IQI and RPQI metrics	252
4.7	Geomorphological data for the tributary watersheds	262

LIST OF FIGURES

Figure		Page
2.1	Ranking of biodiesel consumers by 2030 based on IEA APS projected scenario	10
2.2	Annual trend of Water Quality Index (WQI) classification of rivers showing the percentage of “slightly polluted” and “polluted” rivers (Department of Environment, 2018)	14
2.3	Typical spatial fluvial patterns that form riverine systems	24
2.4	Strahler's concept of stream orders. Not all precipitation will eventually reach the watershed outflow because there is an amount that is transferred back to the atmosphere by evaporation.	25
2.5	Fluvial ecosystem integrity is an overlap of biological, chemical and physical component	27
2.6	Biochemical Oxygen Demand (BOD) loading in Klang river basin	31
2.7	Ammoniacal Nitrogen loading in Klang river	31
2.8	Temporal trend of papers that cited "Karr, 1981"	51
2.9	Characteristics of the world’s forests in 2010	56
2.10	Major freshwater fish ecoregions encompassing 1,054 rivers as classified by the Fish-SPRICH database. Malaysia is located in the Oriental ecoregion	60
2.11	Major freshwater ichthyofaunal families in Malaysia	61
2.12	Comparing the east-west faunal line postulated by Abell et al. (2008) with north-southern crescent faunal line suggested by Johnson (1967)	63
2.13	Major river networks in southeast Asia during the Pleistocene era, namely East Sunda River (A), West Sunda River (B) and North Sunda River (C)	65

2.14	Comparison between Neotropical and Australian fish genera and species richness	77
2.15	Modes of speciation	78
2.16	Species from each family have a similar morphological profile to provide identification clues	80
2.17	Taxonomic ranking and naming convention	81
2.18	The species name <i>Leptobarbus rubripinna</i> is derived from Greek word “leptós” which means thin or slender, and the Latin word “barbus” meaning barbel. <i>Rubripinna</i> originates from the Latin words “ruber” and “pinna” which mean red and fin, respectively	83
2.19	An example of key morphological features of a species from the Cyprinidae family	90
2.20	Common morphometric data collected for fish identification (Rainboth, 1996)	91
2.21	Common measurements between key points to construct patterns to quantify morphometric variance between species	92
2.22	A close-up view of fin rays which epitomises fish under the Actinopterygii class	93
2.23	An example of fin positions and ray structures of a fish with a contiguous dorsal fin	93
2.24	A specimen from the <i>Gastromyzon</i> genus with specialized suctional pectoral fins and fused pelvic fins for adhering to substratum rocks in riffles	94
2.25	Common caudal fin shapes	95
2.26	Common mouth types	96
2.27	Common meristic data collected by taxonomists	98
2.28	Common terms used to describe body markings and patterns on a representative teleost	100

2.29	An illustration of the fish cephalic-lateralis system consisting of neuromast sensors that run across canals on the head and body	103
2.30	Fresh specimen is photographed facing left together with a ruler to indicate scale	114
2.31	A live specimen is best photographed with high-resolution photography to record subtle details and colouration	114
2.32	Noticeable variations of the same species should be photographed for species-level studies. For example, in the case of <i>Tor tambra</i> (above), individuals in the same population may display differing forms of mental lobe and barbels	115
2.33	Fixed specimens are usually stored in glass jars with heads pointing downwards. Note that specimens become pale and lose their colouration quality, which is why photography of live specimens is crucial as part of the data collection process	116
2.34	The key characteristics of a genus are typically described at the start of the taxonomic key. For example, the <i>Glyptothorax</i> genus's key characteristic is the presence of a unique thoracic adhesive apparatus (arrow) that can only be observed in the ventral view	119
2.35	An example of a dichotomous key produced by Silfvergrip (2009, p.25) for the identification of freshwater eels from the Anguillidae family	120
2.36	The morphological phylogenetic tree of the genus <i>Anguilla</i> showing correlation species occurrence in various regions	122
3.1	The multi-disciplinary metrics framework and algorithm of the MyRII assessment system. The IQI was developed in this study while the RPQI was adapted from the SVAP2 protocol (NRCS, 2009). The WQI was developed by the Ministry of Natural Resources and Environment, Malaysia (2009). Collectively, the three indices were integrated to form the MyRII	129

3.2	QGIS® was utilized to process SRTM’s Digital Elevation Model (DEM). Contour, watershed and stream compositions were extracted with GRASS GIS®, GDAL/OGR® and SAGA® geo-algorithm functions. The processing revealed four tributary watersheds in upriver of Kampar River, namely 1) Geruntum River 2) Ulu Kampar River 3) Geroh River and 4) Dipang River	155
3.3	The study site consisted of tributaries namely Geruntum, Ulu Kampar, Geroh and Dipang that feed into Kampar River’s water treatment plant. The watersheds were mainly inhabited by the Semai and Temiar indigenous communities and the black dots denote their village settlements	159
3.4	The study zones and locations of sampling transect along the Kampar River. Zone A represents a natural forested area while zone B and C represent a semi-disturbed rural area and heavily disturbed human settlement area, respectively. Zone D is a heavily disturbed perennial wetland area that is disjoined from the Kampar River	161
3.5	MyRII data collected from the reference site is used to estimate the central tendency, or median. Once the median is known, or 50th percentile (interquartile range) is established, the MyRII can then be normalized and the thresholds can be classified. Any MyRII result that falls between the 50th to 75th percentile is classified as “good” and a result that is above 75th percentile is classified as “excellent”. A MyRII result that falls between 25th to 50th percentile is classified as “average” and any result below 25th percentile is classified as “poor”	167
4.1	Monthly bar chart profiles for comparing fish-based metrics between zones throughout the study period	179
4.2	Monthly bar chart profiles for comparing Shannon and Pielou indices between zones throughout the study period	180

4.3	Visual data for species 1) <i>Notopterus notopterus</i> ; 2) <i>Barbodes cf. rhombeus</i> ; 3) <i>Barbonymus gonionotus</i> ; 4) <i>Barbonymus schwanefeldii</i> ; 5) <i>Crossocheilus obscurus</i> ; 6) <i>Cyclocheilichthys apogon</i> ; 7) <i>Cyprinus carpio</i> ; 8) <i>Danio albolineata</i>	195
4.4	Visual data for species 9) <i>Esomus metallicus</i> ; 10) <i>Hampala macrolepidota</i> ; 11) <i>Toxabramis cf. houdemeri</i> ; 12) <i>Hypophthalmichthys nobilis</i> ; 13) <i>Labeo rohita</i> ; 14) <i>Labiobarbus leptocheilus</i> ; 15) <i>Leptobarbus hoevenii</i> ; 16) <i>Leptobarbus rubripinna</i>	196
4.5	Visual data for species, 17) <i>Mystacoleucus obtusirostris</i> ; 18) <i>Neolissochilus soroides</i> ; 19) <i>Osteochilus vittatus</i> ; 20) <i>Poropuntius smedleyi</i> ; 21) <i>Puntigrus partipentazona</i> ; 22) <i>Rasbora vulgaris</i> ; 23) <i>Homalopteroides smithi</i> ; 24) <i>Balitoropsis zollingeri</i>	197
4.6	Visual data for species 25) <i>Piaractus brachypomus</i> ; 26) <i>Pterygoplichthys disjunctivus</i> ; 27) <i>Glyptothorax schmidti</i> ; 28) <i>Silurichthys schneideri</i> ; 29) <i>Clarias aff. batrachus</i> ; 30) <i>Clarias gariepinus</i> ; 31) <i>Clarias leiacanthus</i> ; 32) <i>Clarias nieuhofii</i>	209
4.7	Visual data for species 33) <i>Pangasianodon hypophthalmus</i> ; 34) <i>Hemibagrus capitulum</i> ; 35) <i>Mystus singaringan</i> ; 36) <i>Aplocheilus armatus</i> ; 37) <i>Poecilia reticulata</i> (male); 38) <i>Poecilia reticulata</i> (female); 39) <i>Monopterus javanensis</i> ; 40) <i>Mastacembelus favus</i>	216
4.8	Visual data for species 41) <i>Parambassis siamensis</i> ; 42) <i>Pristolepis fasciata</i> ; 43) <i>Cichla monoculus</i> ; 44) <i>Mayaheros urophthalmus</i> ; 45) <i>Oreochromis aureus</i> ; 46) <i>Oreochromis niloticus</i> ; 47) <i>Oxyeleotris marmorata</i> ; 48) <i>Anabas testudineus</i>	223
4.9	Visual data for species 49) <i>Helostoma temminckii</i> ; 50) <i>Betta pugnax</i> ; 51) <i>Trichopodus pectoralis</i> ; 52) <i>Trichopodus trichopterus</i> ; 53) <i>Trichopsis vittata</i> ; 54) <i>Channa gachua</i> ; 55) <i>Channa lucius</i> ; 56) <i>Channa micropeltes</i>	229
4.10	Visual data for species, <i>Channa striata</i>	231
4.11	Rank abundance, diversity and sympatric occurrences in native species population among studied zones	232

4.12	Rank abundance, diversity and sympatric occurrences in introduced species population among studied zones	233
4.13	Regional precipitation pattern in peninsular Malaysia during the study duration. March 2016 was notably the driest month	236
4.14	Monthly time series hydrography of Kampar in Zone C	237
4.15	Scatter plots to visualise R^2 linearity and data clustering patterns among studied zones	240
4.16	Stacked bar chart showing proportion of RPQI criteria rating results in each zone	242
4.17	Monthly bar chart profiles for comparing RPQI values between zones and individual sampling transect throughout the study period	243
4.18	Physical characteristics of the assessed zones	245
4.19	Stem plots for comparing IQI, WQI, RPQI and MyRII among the assessed zones. Zone A has the highest ratings since it was the most intact ecohydrological zone (i.e. reference site) while zone C scored the lowest ratings because it was a heavily disturbed segment of the Kampar River	246
4.20	Scatter plots show a noticeable clustering pattern among the zones and linear regression (R^2) values suggested that WQI has weak correlation with other indices in all zones assessed. This reinforces the notion that water chemistry assessment alone is not robust enough for determining the level of river integrity	248
4.21	The principal component analysis (PCA) loading plot, variable directions and zone clustering patterns. The variable directions show biological and physical metrics are strongly correlated. Values from zone A (reference site) are clearly distinguished while some values are overlapping between zone B and C.	254

4.22	The principal component analysis (PCA) loading plot, indices directions and zone clustering patterns. The variable directions show IQI and RPQI metrics are strongly correlated with MyRII. However, there is a departure in WQI's direction. This shows the WQI is not entirely reliable to reflect biological and physical qualities of river integrity	255
4.23	Cluster hierarchical plot by Ward's Method	256
4.24	Cluster hierarchical plot by Neighbour-Joining Method	257
4.25	Based on MyRII results presented on Figure 4.19, the MyRII data of zones A and B was combined to deduce the classification thresholds for reference site (left). Consequently, the "poor" classification was assigned to zones C and D (right) when benchmarked against the thresholds	260
4.26	Scatter plot diagram showing linear regression equation and correlation between surface water discharge (Q) and area (A). The equation may be referred to for forecasting surface water discharge volume if the watershed area size is known in the surrounding regions along Titiwangsa Mountain Range foothills	266
4.27	Comparison of historical mean monthly precipitation data with the mean monthly precipitation data of 2016	267
5.1	<i>Glyptothorax schmidti</i> 's "thoracic adhesive apparatus" (ventral view) is highly adapted to latching on smooth rocks and pebbles typically found in zone A's fast flowing river	272
5.2	Dissolved oxygen values in zone D reached hyperoxia level in April and September 2016. The hyperoxia occurrences were preceded by periods of low precipitation, i.e. extended sunlight period that promotes algal growth	281
5.3	Intense algal bloom observed in zone D's sampling point after the prolonged low precipitation period	282

5.4	Bar chart shows that the coefficient of variation (CV) for most indices was the lowest in zone A. This reflects the unmatched stability and suitability of zone A as a reference site	286
5.5	Comparison of water tariffs in USD per m ³ at domestic category between Malaysian states and other major cities in Southeast Asia at the time of this study. The study site of this research is located in Perak as indicated in black bar	291
5.6	Hydrograph plot of rivers during the period 20-29 December 2016 to show the differences between natural and heavily altered watersheds	294
5.7	Visual data providing a reference for locating high-risk erosion and landslide areas in the four tributary watersheds. Note that the Ulu Kampar watershed has reasonably more area with >25° slope (red) in the eastern region	308

LIST OF ABBREVIATIONS

AN	Ammoniacal Nitrogen
BCP	Biology, chemistry and physical
BOD	Biochemical Oxygen Demand
BPJ	Best professional judgment
COD	Chemical Oxygen Demand
CWA	Clean Water Act
DO	Dissolved Oxygen
DOE	Department of Environment
EHU	Eco-hydrological unit
ENSO	El Niño and Southern Oscillation
EPA	Environment Protection Agency
EPU	Economic Planning Unit
ES	Ecosystem services
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
IBI	Index of Biotic Integrity
ICZN	International Commission on Zoological Nomenclature
INWQS	Interim National Water Quality Standards
IQI	Ichthyofauna Quality Index
IRBM	Integrated River Basin Management
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
MEA	Millennium Ecosystem Assessment

MNRE	Ministry of Natural Resources and Environment, Malaysia
MPM	Market price method
MyRII	Malaysian River Integrity Index
NRCS	Natural Resources Conservation Service, US
NGO	Non-government organization
NOAA	National Oceanic and Atmospheric Administration
NWRC	National Water Resources Council
NWRP	National Water Resource Policy
OECD	Organisation for Economic Co-operation and Development
ONI	Oceanic Niño Index
PFC	Proper Functioning Condition
pH	Acidity value
PWB	Perak Water Board
PWES	Payment for Watershed Ecosystem Services
RPQI	River Physical Quality Index
SVAP2	Stream Visual Assessment Protocol Version 2
TEEB	The Economics of Ecosystems and Biodiversity
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WFD	Water Framework Directive
WQI	Water Quality Index
WTP	Water treatment plant

CHAPTER 1

INTRODUCTION

"Water is to the world what blood is to our bodies"

- Leonardo Da Vinci,

Codex Atlanticus, 1478-1519

Da Vinci used the term "*vetturale di natura*", literally meaning "the vehicle of nature", to describe water's role in intersecting, connecting and conveying nutriment to life on earth. Indeed, water is indispensable, and yet, it is often undervalued by modern society and economy systems (Luck et al., 2009; Robertson, 2012; Hill et al., 2014). Despite our essential dependence on the freshwater fluvial ecosystem for food, water, climatic and other socio-economic ecosystem services, the current situation speaks otherwise. Many freshwater riverine ecosystems are already ailing (Spangenberg and Settele, 2010; Thorp et al., 2010; Robertson, 2012; Hill et al., 2014). Literature and the news are currently filled with reports highlighting degradation and pollution occurring in many rivers and watersheds in Malaysia (Chan, 2004; Chan, 2005; Kamarudzaman et al., 2011). In 2013 alone, the Department of Environment (DOE) detected 1,475,444 pollution sources of water (DOE, 2013). A serious problem is already prevalent.

We are presently witnessing an era when Malaysia is undergoing a dramatic geohydrologic changes due to unsustainable land development

activities. Considering the national population has grown from 26.5% in 1957 to 62% in 2000 of the total population (Masron et al., 2012), the country need more portable freshwater. And yet, methodical conservation and management initiative is minimal as suggested by literature review. Inevitably, the setback is expected to become more severe. Without the appropriate assessment and monitoring protocol to inform corrective measures, Malaysia stands to lose its freshwater-based socio-economic assets and environmental services at an unprecedented pace.

At present, conventional assessment of river quality in Malaysia only calls for the assessment of water chemical parameters (MNRE, 2012). Other scientific components are subjects that science knows very little about in the country. Many researchers have defined and agreed that a river's resilience comprises of three overlapping dynamic components of physical, chemical and biological integrity (Karr and Dudley, 1981; Angermeier and Karr, 1994; Rapport, 1995; Schofield and Davies, 1996; Barbour et al, 1999; Campbell, 2000; Wiens, 2002; Coles et al., 2004; Wang et al., 2014). Although the Malaysian government acknowledged the deficiency in the existing approach (MNRE, 2012), a wholesome assessment system has yet to emerge. Here lies the critical gap that prompted this study.

Besides chemistry elements, this study presents an approach to justify why biological and physical measures are also critical elements that should be included to monitor the quality of river ecosystem in Malaysia in a holistic

manner. Correspondingly, a strong emphasis was given to adopt fish species as a key biological indicator.

1.1 Problem statement

News of freshwater shortages and pollution are becoming common in Malaysia. Wedged between 1) increasing point and non-point pollution being discharged into the rivers, and 2) rapid population growth and development that will drive rising water demand, the government was compelled to launch the National Water Resource Policy (MNRE, 2012). One of the policy objectives is to;

"... provide means and measures to complement existing policy directions related to water resources so as to ensure their sustainable and equitable use, as well as protect the integrity of the environment, ecosystems and natural heritage"

Nonetheless, besides water physico-chemistry properties, other "means and measures" are subjects that science knows very little about in Malaysia. A wholesome watershed assessment system has yet to emerge in the country. Although database and riverine ecosystem assessment approaches from temperate developed countries such as the United States and Europe are available, they are not readily valid in Malaysian context due to ecological,

geomorphological and climatic differences. Hence this research was chiefly motivated by the government's water policy mentioned above and it was aimed to address the gap.

1.2 Hypothesis and research questions

In the light of problems and deficiencies highlighted earlier, this research was deployed to test the hypothesis that biology, chemistry and physical (BCP) metrics can be collectively applied to assess the rivers to monitor their integrity. Thus the research question was – How can the biological, chemical and physical (BCP) metrics be explicitly integrated to form a systematic index to reflect river integrity in Malaysia?

1.3 Main objective and breakdowns

To address the research question, the main objective of this study was to carry out the development of a composite index that adopts the biological, chemical and physical multi-metrics for assessing river integrity. This composite index was to be termed as the Malaysian River Integrity Index, or MyRII.

To support and achieve the main objectives highlighted, four sub-objectives were projected. The first sub-objective objective was to conduct a

comprehensive literature review to understand the deficiency of conventional river assessment practice in Malaysia. The review also covered the latest schools of thought on the subject of river integrity and how it is empirically examined.

Informed by the literature review findings, the second sub-objective was to select a series of quantitative and qualitative BCP metrics to be integrated to systematically form the multi-disciplinary Malaysian River Integrity Index, or MyRII. Additionally, the method for assessing the economic value of the studied site was to be established to provide the baseline to underpin the importance of this study for socio-economic well-being. To support the baseline research, methods for assessing climatic forcing, river volumetric flow and geomorphological characteristics also need to be determined to enrich the research.

The third sub-objective was to test the MyRII protocol on four eco-hydrological zones in the selected study site Kampar River, Perak, Malaysia, to unveil its strengths and weaknesses. The trial process has to be carried out over 18 months to detect sporadic and episodic disturbances caused by natural and anthropogenic factors. Coincidentally, a peak El Niño-Southern Oscillation (ENSO) event had occurred during the trial period and the study managed to obtain first data and some valuable insights on how abnormal dry weather has affected the study site's water physico-chemistry properties.

The fourth and final sub-objective of this research was to analyse the empirical data collected and discuss the anomalies, field observations, implications, limitations and application challenges of the MyRII protocol to inform users, stakeholders and policymakers in a broader context.

CHAPTER 2

LITERATURE REVIEW

Since this study focuses on assessing the biological, chemical and physical (BCP) properties of the riverine ecosystem, a preliminary literature review to scope the research design was first carried out in mid-2015 to identify the availability of information, gaps and possible difficulties that may be encountered by the study as a precaution. It was discovered that the body of knowledge for assessing water physico-chemistry and river physical properties is fairly well defined and developed in Malaysia and elsewhere for reference. However, surprisingly, the information on Malaysian ichthyology body of knowledge was markedly lacking.

This chapter begins by rounding up the water concerns and issues in Malaysia that motivated this study. The latest literature is presented herein to describe trends and issues affecting the country's hydrologic cycle, pollution and the impending problems if no potential resolution is determined. The socio-economic value and ecosystem services (ES) of rivers and watersheds are also highlighted. This sets the tone for the need of a robust assessment system for monitoring and managing the riverine ecosystem.

Subsequently, the chapter proceeds to review the latest schools of thought and components in the riverine ecosystem in relation to chemical and physical qualities to underpin and set the direction for proposing and constructing a multi-disciplinary assessment system. Adequate foundation in the mentioned disciplines is required to develop a sensible assessment system that suits the Malaysian riverine ecosystem.

Lastly, since this study favours the utilization of fish as a key biological indicator, a substantial portion of this chapter is focused on reviewing the literatures that highlight the latest status on ichthyology, and especially fish biogeography related to peninsular Malaysia. It is essential to investigate and elaborate the ichthyology and fish taxonomy disciplines extensively during the literature review process as the disciplines are considered lagging and undeveloped by the experts. Thus a strong understanding of ichthyology and taxonomy is essential to inform this study for ensuring proper biological assessment and accurate interpretation of the fish-based metrics results.

Multi-disciplinary assessment such as one attempt by this study is not a common science in Malaysia. So far there is very little information published about the subject in Asia, and much less in Malaysia. As most literatures originated from the temperate countries, namely from North America and Europe, precaution is taken when interpreting them. Some information in these literatures may not be valid to in the Malaysian context.

2.1 Water resource status and trend in Malaysia

Malaysia as a country receives 990 billion m³ of annual rainfall over its land mass, where 566 billion m³ end up as surface runoff and the rest is transferred back to the atmosphere through evapotranspiration or retained as groundwater (Keizrul and Mohamed, 1998). With a yearly average rainfall of more than 2,500 mm in Peninsula Malaysia alone, surface runoff accounts to 147 billion m³ annually (Toriman and Mokhtar, 2012) and it is obvious that the country is not short of freshwater at time of this writing. However, is this enough for the future?

In the advent of economic and population growth, certainly, water demand for industry and household consumption is expected to increase (Academy of Sciences Malaysia, 2016). As it is, the agriculture industry has already become that highest consumer at 9 billion m³ and this is roughly 75% of total water expended from the country's various water stocking infrastructures such as dams and irrigation canals (Mohd Azhar, 2000). With rice planting, food crop and livestock farming intensification to feed the growing population and to reduce imports, a higher water demand can be expected in years to come to support food security.

There are also the concerns over energy security and climate change that forces the country to explore renewable energy options (Gerbens-Leenes

et al., 2012). The transportation and logistics sectors are poised to replace fossil fuel with higher portion of biofuel options. Cultivating more crops like oil palms and processing fatty acids into biofuel requires more water too. In a study, Kittithammavong et al. (2014) reported that 23.64 m³ of water is needed to produce 1 litre of biodiesel. By analysing data of water footprint (WF) and correlating them with countries' energy policy, Gerbens-Leenes et al. (2012) forecast that by 2030, Malaysia would become the largest bio-diesel consumer in the world (Figure 2.1). They also estimated that the WF would have to be increased by tenfold to meet the projections from 2005 to 2030.

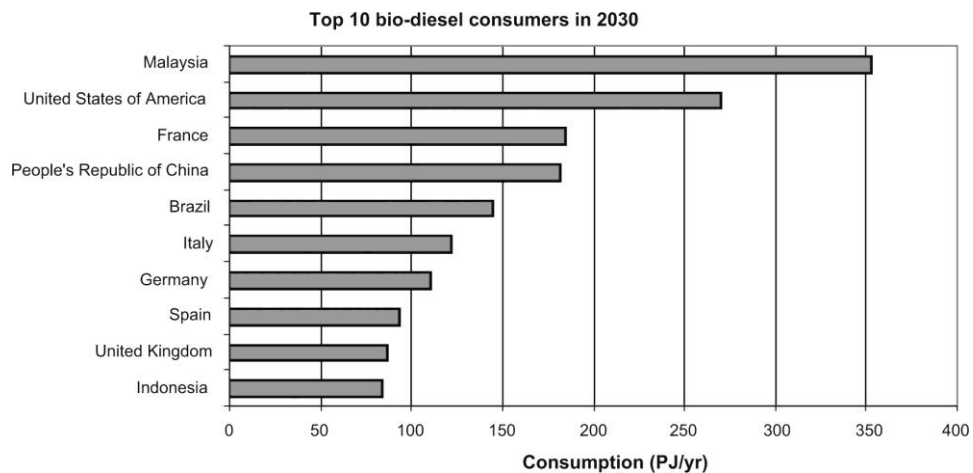


Figure 2.1: Ranking of biodiesel consumers by 2030 based on IEA APS projected scenario (Gerbens-Leenes et al., 2012)

In addition to the push for biodiesel usage by the National Biofuel Policy 2006, non-consumptive sector such as hydroelectric dams, aquaculture, ecotourism and river transportation are also specifically affected by water availability. Lest we forget, every Malaysian citizen is the major stakeholder of water resource too. To sustain a reasonable quality of life, portable water for

household use is essential. With the population expected to increase from 29.7 million in 2013 to 34.9 million by 2025 (United Nations, 2013, p.58), serious pressure will be put on the country's water resource.

As pointed out, the presence and wellbeing freshwater resource has a wide and critical implication to the economic, social and environmental wellbeing. Unfortunately, so far, there is no single body that bears overall responsibility for planning and management of water resource in Malaysia (IEM, 2014). Fundamentally, water resource usage, planning and management are treated separately, sometimes overlapping, according to each federal and state government agency's interest and jurisdiction (Table 2.1). Under such disarrayed circumstances, inter-agency coordination is expected to be challenging.

Table 2.1: Responsibility differs and overlaps among federal and state agencies in terms of water resource management (Chan, 2004; Rahman and Khalid, 2009; Saimy and Yusof, 2013; Academy of Sciences Malaysia, 2016; Khalid, 2018).

Federal and state agency	Functions / Responsibilities
Department of Irrigation and Drainage (DID)	Integrity of river, riparian, flood mitigation, coastal management and storm water management
Public Works Department (PWD)	Distribution of domestic and industrial water supply
Town and Country Planning Department	Planning of integrated land-use including watershed, river and drainage development in urban and rural areas
Department of Environment (DOE)	Environmental integrity of rivers, reservoirs and watersheds
Ministry of Health (MOH)	Quality of potable water supply for human consumption
Ministry of Water, Land and Natural Resources	National federal policies for water supply and sanitation
State Land Department	State land-use policy and administration (including watershed and protected forest reserves)
State Forestry Department	Environment integrity of watersheds and rivers in protected forest reserves
State Public Works Department	Water treatment and distribution in Kedah, Perlis, Labuan and Sarawak (except Miri, Bintulu and Limbang district)
State Water Supply Department	Water treatment and distribution in Negeri Sembilan, Sabah and Pahang
State Water Supply Board	Water treatment and distribution in Melaka, Perak, Kuching and Sibul
State-owned companies and private consessionaires	Water treatment and distribution in Penang, Kelantan, Johor, Selangor (including Kuala Lumpur), Terengganu and Sarawak (i.e. Miri, Bintulu, Limbang).

Apart from the uncertainties expected from water demand surge and disconcerted management, this begs another fundamental question – How clean is the existing hydrologic cycle?

The hydrologic cycle is a perpetual movement of water between atmosphere, land, sea and underground (Hornbeck and Swank, 1992; Kuchment, 2004). If at any part of the natural circulation is contaminated by pollution, the problem will be manifested into any other areas of the cycle (Luck et al., 2009; Li et al., 2015). Many causes of water pollution are now well understood, but they could not be easily addressed. As mentioned in earlier section, rivers are “receptors” of land-use changes (Postle and Barton, 2005; Chang et al., 2009). Therefore, it is apparent that any socio-economic activities imposed onto the landscape at spatial level will result in pollution being washed down into the streams and rivers, and this is where the complexity begins.

A competitive economy like Malaysia’s requires revenue to fund development and pay national debts. State governments sell logging and oil palm planting land concessions to raise funds (Gaveau et al., 2014; NEPcon, 2016). This causes deforestation and exposed soil can cause massive siltation in rivers thereon causes imbalance to the fluvial ecosystem. At the local community level, farmers of large and small scale often clear land to raise

crops for economic gains and to ensure food security for the country (Wiens, 2002; Vote et al., 2015). When the ground is degraded after numerous cycles of intensive harvest, chemicals are used to treat the soil or farmers would seek out other fertile areas to clear. The construction of more human settlements and industrial districts to cater for socio-economic development also constitutes a part of landscape changes. Naturally, with such intensive anthropogenic-driven landscape changes and certain unsustainable practices occurring in the country, many watersheds end up taking the brunt. According to the latest 2013 International Union for Conservation of Nature's Red List (IUCN, 2013), 71 species of fish are already listed as threatened and this speaks volume of fluvial ecosystem degradation in Malaysia. Correspondingly, the river water quality trend also paints a grim outlook (Figure 2.2).

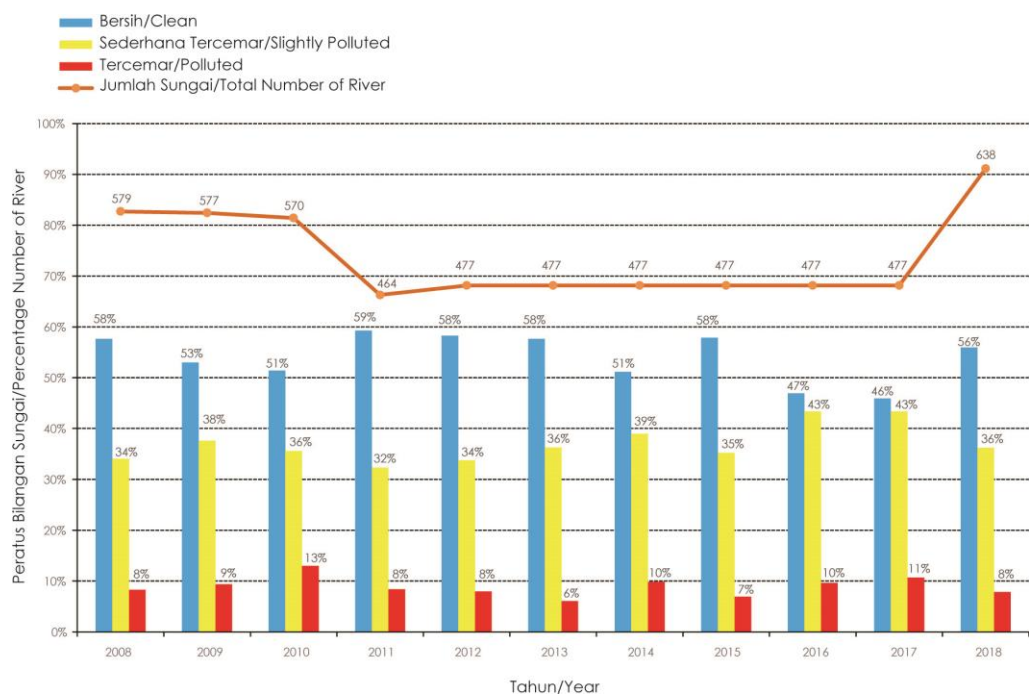


Figure 2.2. Annual trend of Water Quality Index (WQI) classification of rivers showing the percentage of “slightly polluted” and “polluted” rivers (Department of Environment, 2018)

In 2013 alone, the Department of Environment (DOE) found 1,475,444 point sources of water pollution (DOE, 2013). As the fluvial ecosystem is becoming more polluted, at some point, clean water scarcity will become the next cause of concern. This would be unprecedented for a tropical country that is endowed by heavy rainfall. From literature review, it is evident that the current “business-as-usual” approach has devastated many rivers in the country. Water resource is not conserved in tandem with the country’s rising water demand and the situation is serious.

Underpinned by water demand and watershed degradation issues, since 1998, a National Water Resources Council (NWRC) was set up to coordinate inter-state water resource management. Subsequently, based on concerns and feedbacks from various stakeholders, the National Water Resource Policy 2012 (NWRP) was also adopted under the Tenth Malaysia Plan (2011-2015) as the countermeasure to guide and outline action plans to ensure there is long-term water security. It is driven by 4 principles, namely 1) water for people, 2) water for food and rural development, 3) water for economic development, and 4) water for the environment.

NWRP is facilitated by the Ministry of Water, Land and Natural Resources and decision making is conducted collectively among multiple stakeholders. The policy also aims to adopt spatial best practices such as Integrated River Basin Management (IRBM) and Integrated Water Resources

Management (IWRM). Although the NWRP is coordinated through NWRC that is chaired by the Deputy Prime Minister, however, as shown on Table 2.1 earlier, water resource management in Malaysia is still largely a complicated task between the federal and state government agencies. To implement the NWRP appropriately in the upcoming years, the challenge now lies on how soon all agencies can be streamlined effectively through the NWRC for solving problems affecting the polluted rivers and watersheds.

From the literature review findings, it is clear the policymakers and custodians are not adopting any multi-disciplinary assessment standards. As indicated, there are 18 agencies entrusted to manage water-related functions (Table 2.1). Therefore, any assessment system endeavoured by this study must be cost effective, practical and easily understood in order to gain support from all stakeholders, including the public.

2.1.1 Economical value of water safety and security

What is the worth of natural water resource? Indeed it is a million dollar question that all who are concerned with water security around the world would like to uncover. In an era when the population growth and water demand increases are inevitable, watersheds are valuable national assets. According to Dunne and Leopold (1978), a watershed is defined as a spatially delineated landscape that drains water, sediment, and dissolved materials in to

a common channel. A watershed may contain a water body network of littoral, lentic, lotic and limnetic environments, depending on its natural or anthropogenically disturbed landscape (Hynes 1975) which demonstrate heterogeneity, hierarchy, directionality and process dynamics, either continuous or patchy, and occurring across spatio-temporal scales (Poole 2002; Vidal-Abarca et al. 2014). In terms of hydrology, a watershed's output is primarily influenced by the morphological characteristics such as the size, shape, complexity and the geometry of the riverine network (Eagleson 1970; Rodríguez-Iturbe and Valdés 1979; Brass 1990). Such physical attributes, or geomorphology, are critical for the rivers and watersheds' ecological function and quality to store, regulate and provide freshwater to the human population. These qualities are commonly known as ecosystem services (ES) (MEA 2005).

The Millennium Ecosystem Assessment (MEA) defines ecosystem services (ES) basically as “the benefits that people obtain from ecosystems” (MEA 2005). The ES term was conceptualized when a global initiative was deployed in 1999 to assess how disturbances in ecosystems would affect human wellness. It covers four broad categories, namely 1) supporting services; 2) provisioning services; 3) regulating services; and 4) cultural services (UNEP 2010; TEEB 2010; Wunder 2013; Kallis et al. 2013; Wunder 2015). In the context of a watershed, its ES provides the critical support for socio-economic components of the human society and recognizing its monetary value is often essential in influencing the stakeholders and policy-makers to take watershed conservation seriously (Elosegi and Sabater 2013; Everard and Quinn 2015). Consequently, when the watershed characters, river

outputs and monetary implications are overlooked, unaccounted for or not maintained, the society stands to experience a direct loss of ecosystem service (TEEB 2010).

Like many countries located in the tropics, Malaysia is blessed with high levels of precipitation, especially during the monsoon seasons (Wong et al., 2009). Most of its water intake points along the rivers for portable water production were established many decades ago when the watersheds were largely undisturbed. However, presently, with rapid economic development and population growth, anthropogenic disturbances to the watersheds supporting the intake points have increased progressively (Chan, 2009). Consequently, worsening environmental problems in and around the watersheds have become more severe and unpredictable. This has translated into recurring water shortage events in various parts of the country (Khor and Lee 1993; Abdullah 2002; Zainal Abidin 2004; Chan, 2009; Malek et al. 2013; Ewing and Domondon 2016; Chan and Ghani, 2016). Moreover, Malaysia and many countries located in the western Pacific are also susceptible to the El Niño and Southern Oscillation (ENSO) forcings which typically reduces the annual frequency of precipitation (Juneng and Tangang 2008; Ng et al. 2018). Under such constraints, one would expect that the watersheds would be sensibly conserved and managed. However, evidence shows that watershed ES values are currently being undermined by the monetary gains from other land-based activities (TEEB 2010). Land managers and policymakers are tilting towards mining, timber extractions, industrial agriculture and other activities which compromised many watersheds because these enterprises are deemed

more profitable (Postle and Barton 2005; Wunder et al. 2008; Spangenberg and Settele 2010).

The variability of river flow rate and volume is readily determined by the characteristics of the watershed it drains through (Ritter et al. 2002; Thorndycroft et al. 2008; Thorp et al. 2010). Expressing the characteristics quantitatively is essential and it is not surprising that researchers have applied spatial analysis techniques to investigate watershed geomorphology for more than a half a century (Horton 1945; Chorley et al. 1984; Everard and Quinn 2015).

Geomorphometry is defined as the measurement and mathematical analysis of the landscape's surface, shape and dimension of its landforms (Clarke 1966). Over the past decades, interest in this discipline has grown exponentially due to global water safety and security issues and there is a growing consensus that support the necessity of watershed-scale perspective to drive river conservation policies (Logan and Furze 2002; Kondolf et al. 2007; Nilsson et al. 2007). Gathering watershed baseline data is the first step for planning and managing the water resources as it provides the stakeholders a basis for formulating development or conservation strategies (Nilsson et al. 2007; Chang et al. 2009; Flotemersch et al. 2015). However, surprisingly, at the time of this study the author could not identify any report or publication in Malaysia and Southeast Asia that compile watershed geomorphological data or translates watershed or the riverine system's ES into the appropriate accounting unit to address the knowledge gaps highlighted. This has arguably hindered the

recognition of watershed importance although the ES concept has become more influential to drive management and conservation efforts globally (Wunder 2015).

Watershed areas and rivers are often perceived and studied on a large-scale approach. However, in reality, recent evidence shows that small watersheds may in fact make a disproportionately large contribution to the rivers (Postle et al. 2005; Nilsson et al. 2007; Elozegi and Sabater 2013; Ewing and Domondon 2016). Small watersheds should not be overlooked because collectively they play a major role in ensuring the main rivers can sustain a natural flow regime and supply raw water to the water treatment plants. This implies that they are likely to warrant a higher priority in terms of conservation. Moreover, small watersheds are more manageable and practical for the local communities if any conservation initiative is to be implemented (Davenport et al. 2007; Ghazoul 2007; Vote et al. 2015; Feng et al. 2018; Suhardiman et al. 2018).

2.2 Characteristics of the river ecosystem and integrity

In this study, the term "fluvial ecosystem" is defined as an array of littoral, lentic, lotic and limnetic environments that demonstrate heterogeneity, hierarchy, directionality and process dynamics, either continuous or patchy, and occurring across spatio-temporal scales (Naiman et al., 1993; Poole, 2002; Vidal-Abarca et al., 2014). Collectively, the fluvial ecosystem is typically

characterised as a waterway network, or riverine continuum, of longitudinal and lateral grade that integrates biological, chemical and physical interactions (Hornbeck and Swank, 1992) as it cuts across various landscapes.

Normally "drainage", "catchment" and "watershed" are terms synonymous and interchangeably used when deliberating the multitude of fluvial ecosystem. In this thesis, the "watershed" term is applied. At its simplest, collectively, they can be defined as a landform which receives natural precipitation from the hydrologic cycle (Hornbeck and Swank, 1992; Kuchment, 2004). Nonetheless, the pooling of precipitation alone is not the key interest of this study. More than that, this research is keen to investigate streams and rivers as receptors and sensors of positive or negative occurrences in their terrestrial surrounding.

The riverine ecosystem typically includes biotic and abiotic components along water margin, partially submerged or in substrate bottom such as fallen trees, sand, pebbles and rocks (Edwards and Meyer, 1987; Church, 2002). It can also consist of unnatural imprints such as engineered drainage, dams, jetties, aqua-culture ponds and ex-tin mining wetlands (Death, 2010; EPA, 2016). Therefore it should be recognized that a riverine ecology is not entirely aquatic as it may contain terrestrial metrics from natural and anthropogenic landscape far away from the water bodies (Elosegi and Pozo, 2016). In modern times, most landscape would certainly include some subtle and obvious evidences of anthropogenic interference. Clearly, any landscape

modification for human social and economic activities has dramatic effects on water quality (Karr, 1987; Barbour et al., 1999; Weaver & Garman, 1994; Walsh, 2000; Wang et al., 2001). In a severely degraded riverine ecosystem, it has less natural components and as a result provides less benefit to human.

In essence, the riverine ecosystem is a part of the hydrological cycle powered by solar energy (Kuchment, 2004). This cycle moves water perpetually back and forth between atmosphere and earth through the process of 1) precipitation 2) infiltration 3) interception 4) detention 5) evaporation, and 6) transpiration (Magaña and Conde, 2000; Kuchment, 2004). In precipitation, rain falls over the terrestrial surface and subsequently freshwater is retained or flowed across various riverine geomorphological routes by gravity force, such as over steep slopes or meander gently across flat valleys.

While it slowly finds its way into the lowest geographically point, mainly the ocean, water may not be perfectly transparent all the time. Water that flows in the riverine ecosystem may also exhibit the colour of tea due to high concentration of dissolved organic matter; usually termed as "blackish" water (Meyer and Edwards, 1990). This is a natural occurrence in waterways that flow across the Malaysian tropical rainforest where high loads of organic debris are released into the water (Abdullah, 2002). As mentioned earlier, there are also manmade influences that cause variances in physico-chemistry property of water (MNRE, 2009). On the plains where human settlements are typically located, river substrates usually consist of silt and mud. The water

velocity decreases while turbidity increases. The process of transfer and deposition of sediments received from eroded banks or exposed land due to deforestation may also render the water murky (Zalewski et al., 1997; Abdul Rahim, 1998). As urbanization becomes more widespread, the receiving waters can be increasingly contaminated by anthropogenic point and non-point pollution (Zainudin et al., 2013; Vidal-Abarca et al., 2014). Among a wide array of pollution, these can include industrial waste and bacterial sewage load discharged into the rivers (Brinley, 1942; Wittig et al., 2007).

The riverine ecosystem functions at its full aptitude when there is spatial and temporal fluctuation in hydrology and areal coverage of water (Poole, 2002; Everard and Quinn, 2015). Flow magnitude and changeability through fluvial geomorphological patterns (Figure 2.3), alluvial landforms, riverbed texture and vegetation are meticulously inter-related, hence these form the biophysical components of the system (Lord et al., 2009; NRCS, 2010).

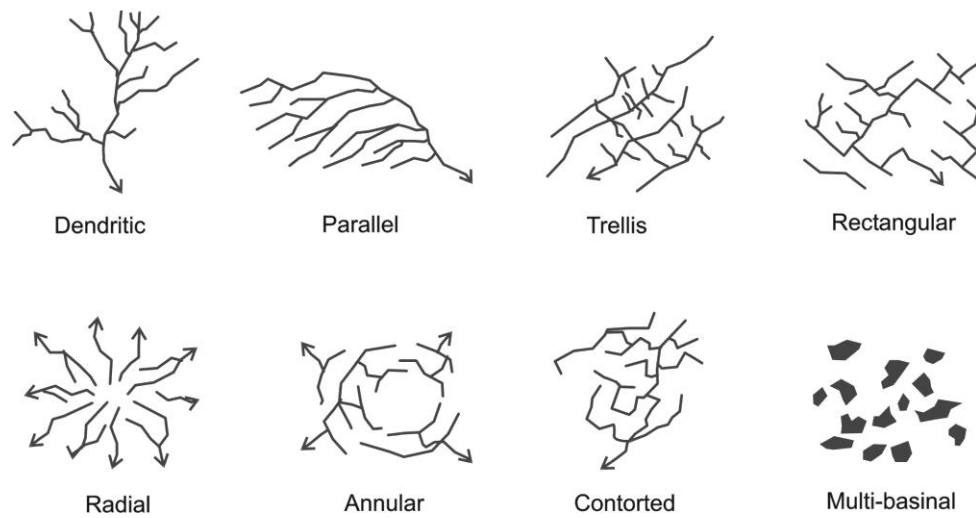


Figure 2.3: Typical spatial fluvial geomorphological patterns that sustain the riverine ecosystems (Morisawa, 1968)

They are typically directed downriver although linkages within the system can shuffle in lateral, longitudinal, vertical and temporal vectors which may be significantly affect its patterns and processes (Ward, 1989). The riverine ecosystem can also expand with seasonal flooding (Poole, 2002). Different durations of flooding or ponding cause natural decrease and increase of habitat for fish species. In turn, such phenomenon creates unique patterns and processes at different scale along each hydraulic vector (Thorndycroft et al., 2008). Obviously, every water body or linkage is likely to be individual in terms of dynamism (Hynes, 1975).

Water's directional system can be articulated as hierarchical linkages and every link, not matter how small or big, is likely to be distinctive, patchy and strongly hierarchical. This is known as “metastructure” and the theory postulates that configuration and juxtaposition of streams, rivers and complex tributaries are critical influences of each segment within a riverine ecosystem (Poole, 2002). Such trans-scale composition was observed as early as 1945 by Horton and subsequently in 1957, Strahler proposed a classification method (Figure 2.4) which became the standard today.

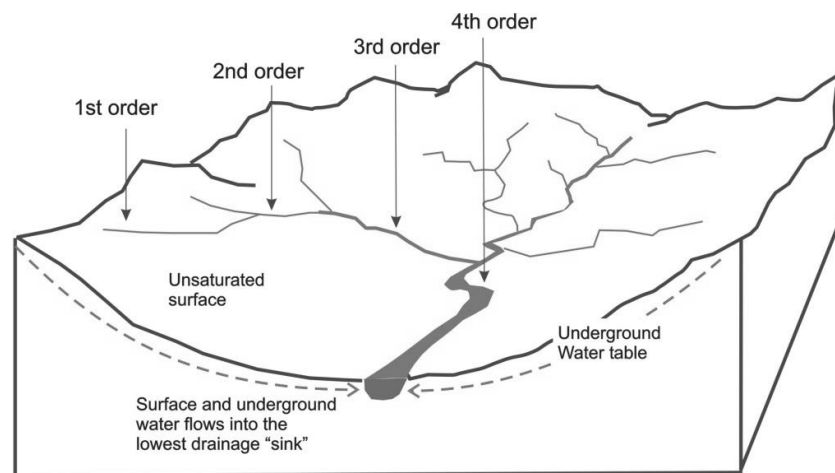


Figure 2.4: Strahler's concept of stream orders. Not all precipitation will eventually reach the watershed outflow because there is an amount that is transferred back to the atmosphere by evaporation (Strahler, 1957)

It must be stressed that there is a form of fluvial system without a stream or river component and the lacking cannot be construed as an anomaly or ecologically flawed. In Malaysia, especially in tin-tailing areas, although imperfect, these systems are somewhat capable of operating in a state of equilibrium. As a result of intense tin ore mining since 1800s, in some western peninsula regions, namely Kinta and Klang valley, water logged ex-mining

land covers approximately 113,700 hectares (Ang and Ho, 2002). As long as limiting thresholds are not breached, the systems can continue to maintain dynamic lateral and longitudinal coherence in a multi-basinal manner, especially during the tropical monsoon season when these autonomous still water bodies are connected to running water bodies momentarily (Morisawa, 1968).

2.3 Biological, chemical and physical (BCP) concept of multi-metrics assessment

Many authoritative researchers define and agree that the overall fluvial ecosystem integrity is an ability to support and adapt to three overlapping dynamic components of biological, chemical and physical integrity (Karr and Dudley, 1981; Angermeier and Karr, 1994; Rapport et al., 1995; Schofield and Davies, 1996; Barbour et al, 1999; Campbell, 2000; Wiens, 2002; Coles et al., 2004; Wang et al., 2014) (Figure 2.5). They also tell us that the integrity of an ecosystem should also include vigour, resilience to disturbances imposed by natural stresses and alterations induced by humans.

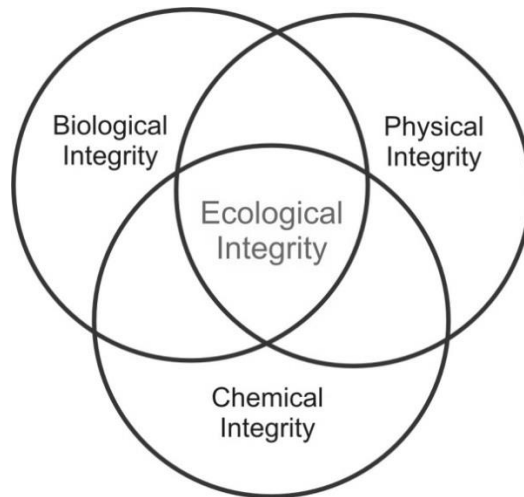


Figure 2.5: Fluvial ecosystem integrity is an overlap of biological, chemical and physical component (Barbour et al., 1999)

The importance of biological, chemical and physical (BCP) three dimensional property was first recognized and associated with the fluvial ecosystems when the United States Environmental Protection Agency (USEPA) introduced the 1972 Clean Water Act. With regards to “integrity”, the act envisions to “convey a concept that refers to a condition in which the natural structure and function of ecosystems is maintained”. Under the Act, states are expected to assess, monitor and impose objectives to restore and maintain biological, chemical and physical integrity of watershed at the ecosystem level. This also goes to point out that assessing water chemical properties alone is deemed insufficient because it does not consider the dynamism of biological communities and landscape physical characteristics that also affect water quality.

In diverse demographics, geohydrological and climatic variances in USA, the act allows individual states to develop their own assessment and restoration projects as long as the concept of BCP is adhered to. Such approach also generally compels each state to produce assessment results that can be compared across the country for benchmarking.

Table 2.2: Examples of prominent assessment systems that applied the BCP approach

Author(s)	Publication Title
Clingenpeel, J.A. and Cochran, B.G. (1992).	Using Physical, Chemical and Biological Indicators To Assess Water Quality On The Ouachita National Forest Utilizing Basin Area Stream Survey Methods
Coles, J.F., Cuffney, T.F., McMahon, G. and Beaulieu, K.M. (2004).	The Effects of Urbanization on the Biological, Physical, and Chemical Characteristics of Coastal New England Streams.
Oliveira, S.V. and Cortes R.M.V. (2006).	Environmental indicators of ecological integrity and their development for running waters in northern Portugal
Paretti, N.V. and Robinson, A.T. (2007).	Ecological Assessment of Streams in the Little Colorado River Watershed, Arizona.
United States Environment Protection Agency. (2010).	National Rivers and Streams Assessment, 2008-2009, A Collaborative Survey
N.J. Wentz, N.J., Henderson, N.D. and Christian, A.D. (2011).	Assessment and Characterization of Physical Habitat, Water Quality, and Biotic Assemblages of the Tyronza River, Arkansas
Lee, J.H., Han, J.O., Kumar, H.K., Choi, J.K., Byeon, H.K., Choi, J., Kim, J.K., Jang, M.H., Park, H.K. and An, K.G. (2011).	National-level integrative ecological health assessments based on the index of biological integrity, water quality, and qualitative habitat evaluation index, in Korean rivers

As show on Table 2.2, in the advent of USA's Clean Water Act 1972, many watershed assessment systems have emerged, and similarly, the European Commission has also enacted Water Framework Directive (WFD) to assess, monitor and manage European river basins using the BCP model.

Currently, there are 1,055 monitoring stations located in 570 rivers in Malaysia (Amneera et al., 2013). Unfortunately, there is a gap because the country is still far from applying the BCP approach for monitoring the rivers. In Malaysia, river integrity is conventionally and almost exclusively based on water chemistry analyses alone. Water chemistry parameters required by Water Quality Index (WQI), which stemmed from the Interim National Water Quality Standards (INWQS), are assessed to quantify the level of pollution in the context of water supply to household, aquaculture, agriculture and recreational use.

At time of this writing, literature review indicates that is no integration of BCP parameters into any Malaysian or Southeast Asian conventional assessment system for comparisons among various regional riverine ecosystems. Therefore this study is an attempt to fill the gap and takes up the challenge of developing a unified BCP assessment system for Malaysia. It does so by drawing lessons from best practices adopted by other countries and constructing an assessment approach that is acceptable to most stakeholders in water resource conservation. Certainly, there is a need also recognise that there

are a great number of assessment methods from all over the world that range from relatively simple algorithms or indexes to complex multivariate methods. The key is to compile a system that is cost-effective, practical and explicitly sensitive to the BCP variances in the Malaysian tropical riverine ecosystem.

2.4 Water physico-chemistry assessment

Peninsula Malaysia typically receives 324 billion m³ of rainwater annually and the current water demand is only 11 billion m³ (EPU, 2000). With just roughly 3.4% of total rainfall used to satisfy demand, freshwater shortage is not a common concern in Malaysia (MNRE, 2009). The problem lies on the fact that rainfall is not uniformly disseminated annually, temporally and spatially. This is compounded by increasing logging and deforestation activities that render many watersheds with less capacity to store water (Abdul Rahim, 1998; NEPcon, 2016). Moreover, with increasing anthropogenic influences via urbanization, agriculture, mining and other economic landuse activities, rivers are consequently tainted by point and non-point source pollution compounded by various types of pollutant (e.g. Klang River; Figure 2.6 and Figure 2.7). This speaks volume of the multitude of pollutants that make their way to the rivers.

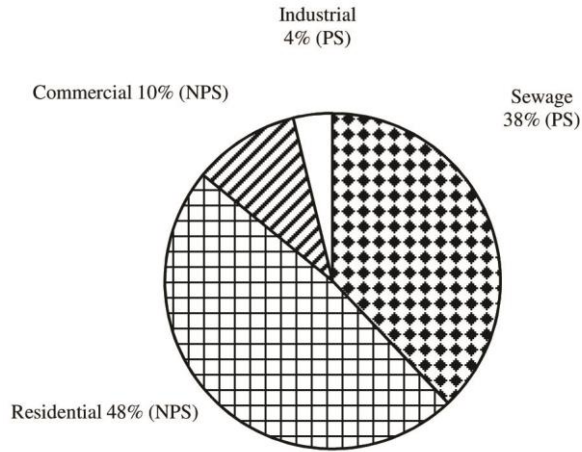


Figure 2.6: Biochemical Oxygen Demand (BOD) loading in Klang River basin (Mamun and Zainudin, 2013)

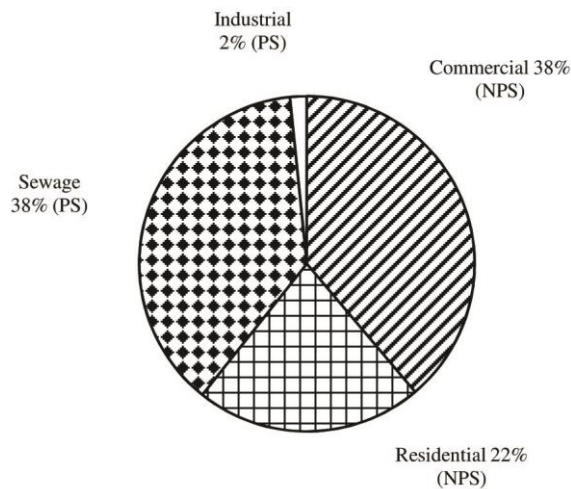


Figure 2.7: Ammoniacal Nitrogen loading in Klang River basin (Mamun and Zainudin, 2013)

There are roughly 468 water treatment plants (WTP) in Malaysia (Mamun and Zainuddin, 2013) and most employ conventional technology to treat raw water for potable use from intake points, generally from dams or rivers. To monitor raw water quality from dams and rivers, currently, Malaysia

has a well-developed physicochemical assessment system in the form of Water Quality Index (WQI) method (MNRE, 2009).

The WQI is basically a mathematical reductionist technique that summarizes a series of chemical test data into a single numerical composite rating, or index, to indicate the degree of water quality. The index is deemed the simplest term for reporting to the Malaysian authorities and public in a consistent manner. Key parameters that influence the calculation of WQI are;

1. Ammoniacal Nitrogen (AN)
2. Biochemical Oxygen Demand (BOD)
3. Chemical Oxygen Demand (COD)
4. Dissolved Oxygen (DO)
5. Total Suspended Solids (TSS)
6. pH

Correspondingly, the WQI can be correlated with classes (Table 2.3) to determine the level of acceptance for use. Class I indicates water of excellent quality and it shows that the environment is natural. Class II also indicate water of good quality and it is good enough to be extracted and treated by WTP for human consumption. It is also deemed suitable for recreational use which involves body contact. When water quality can only meet Class III limits, it is considered moderately polluted and advanced technology in WTP

is required to treat it for water supply. Class IV water quality is only suitable for agriculture irrigation use. Lastly at Class V, the water is considered heavily polluted. Like all indicative indices, WQI main objective is to summarize complex scientific data into a benchmark that can be easily understood by non-scientists. By comparing WQI benchmarks of various watersheds and rivers in the country, water authority and decisionmakers can be informed in a systematic manner on which locality should be prioritize for conservation and management.

Table 2.3: Water parameter thresholds, Water Quality Index (WQI) and class designation specified in National Water Quality Standards (NWQS) of Malaysia (Department of Irrigation and Drainage, 2009)

Metric / Class	I	IIA and IIB	III	IV	V
DO (mg/L)	> 7.0	5.0-7.0	3.0-5.0	1.0-3.0	< 1
BOD ₅ (mg/L)	< 1.0	1.0-3.0	3.0-6.0	6.0-12.0	> 12
COD (mg/L)	< 10.0	10-25	25-50	50-100	> 100
AN (mg/L)	< 0.1	0.1-0.3	0.3-0.9	0.9-2.7	> 2.7
TSS (mg/L)	< 25.0	25-50	50-150	> 300	> 300
pH	6.5-8.5	6.0-9.0	5.0-9.0	5.0-9.0	-
WQI Score	> 92.7	76.5-92.7	51.9-76.5	31.0-51.9	< 31.0

The Malaysian WQI system is not new. Since Horton (1965) first introduced a scientifically defensible and yet simple form of WQI, many similar techniques have been adopted all over the world, such as the well-established US's National Sanitation Foundation Water Quality Index (NSF WQI), Canadian Water Quality Index (CWQI), British Columbia Water Quality Index (BC WQI) and UNEP Global Drinking Water Quality Index.

Referring to Table 2.3, it brings up the question – Why is the Malaysian WQI method narrowed down to selecting and analysing only six water physico-chemistry parameters? What is the significance of each parameter in the context of tropical riverine ecosystem?

It is common knowledge that contaminated water is always a mixture of many organic and inorganic compounds. It is often too costly and impractical to run a complete range of chemical analysis. And for such reason, only some key indicative parameters are evaluated to represent the overall quality of water sample in question. In the context of WQI, there is a good rationale on why special attention is given to Ammoniacal Nitrogen (AN), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Total Suspended Solids (TSS) and pH.

Ammoniacal nitrogen ($\text{NH}_3\text{-N}$), is a pollutant that originates from domestic, industrial or agricultural, mainly from fertilizers, biowaste or fecal matter (Chen et al., 2018). It is water soluble and excessive $\text{NH}_3\text{-N}$ presence in

the waterways is a sign that it is contaminated with organic waste. Alasbaster and Lloyd (1982) inform us that fish tolerance to $\text{NH}_3\text{-N}$ content in water is only up to 2.2 mg/L. Besides being lethal when consumed by humans, high concentration of $\text{NH}_3\text{-N}$ can also cause pH variance in water thus negatively affect overall biological population.

Biochemical Oxygen Demand (BOD) is a parameter test to determine the amount of biodegradable waste present in water. Alternatively, it is also a measure of how much “food” there is in the water for aquatic microbes (Jouanneau et al., 2014). Dissolved oxygen is “demanded” by aerobic microbial metabolism to decompose and breakdown biowaste at a certain temperature over a period of time (Zainudin, 2008). Thus the test is commonly conducted over five days of incubation at 20°C as a representation of the level of organic pollution in water (MNRE, 2009). When the BOD level is high, low Dissolved Oxygen in the water can be expected. With acute shortage of dissolved oxygen, fish and other aquatic species will not survive (O’Connell et al., 2000).

Not all dissolved oxygen is entirely consumed by microbial metabolism in the process of decomposition. Oxygen is also depleted during the chemical reaction (oxidation) of water borne chemicals such as ammonia, nitrite and other inorganic pollutants (Chen et al., 2018). Therefore, Chemical Oxygen Demand (COD) is a test that measures overall oxygen demand of biodegradable and non-biodegradable substances in water sample. One can expect the typical COD results to be higher than BOD values in the same water

sample (Jouanneau et al., 2014). There are conditions when lethal levels of chemical substances such as pesticides and industrial waste poison all microbes. When there are no microbes to decompose organic waste, the BOD test becomes an ineffective assessment of pollution. Hence, the COD test by itself is more reliable and comprehensive (Jouanneau et al., 2014).

In both BOD and COD tests, dissolved oxygen is a key concern because the integrity of a fluvial ecosystem is inherently dependent on the availability oxygen to sustain life (O'Connell et al., 2000). Oxygen can be present in aquatic system by direct aeration when water is churned by waterfalls and riffles. It can also be introduced into water by algae and other aquatic plants as a by-product of photosynthesis (Ng et al., 2018). Geographical condition such as altitude, temperature and salinity may also affect oxygen content. When temperature and salinity increase, oxygen solubility in the water tends to decrease. Oxygen deficiency in water is known as hypoxia and it causes asphyxiation in fish (Lakani et al., 2013). When there are massive fish kills, the organic waste loading in the water with also be increased thus inevitably increasing BOD in the water and leaves the ecosystem in an imbalanced state (Jouanneau et al., 2014).

“pH” is an a mathematical scale that combines “p” (power or exponent) and “H” (hydrogen ion H^+ concentration) to rate acidity or basicity of water or liquid (MNRE, 2009). An increase of one pH unit represents a ten-fold increase in hydrogen ion H^+ concentration. The scale ranges from 0 to 14 and a pH of 7.0 at 25°C is taken as neutral point. Obviously, the pH of water in

streams and rivers can vary considerably within daily, weekly, monthly and seasonal timeframes but most aquatic species have evolved to tolerate the fluctuations. However, in very high or very low pH conditions, species will be stressed and die off (Melcher and et al., 2007). Water exposed to air has mild acidic tendency because diluted carbon dioxide from air in water produces carbonic acid. Correspondingly, in the advent of chemical reactions between carbon dioxide, hydrogen ions, anions and soil chemistry, alkalinity buffer is introduced to the water. Also, pH levels can also be influenced by photosynthesis of aquatic plants and respiration by aquatic species when they produce or use carbon dioxide, depending on population size, growth, decomposition, hydrology and climatic conditions (Mamun and Zainudin, 2013). Therefore, as mentioned earlier, biological dynamism play an important role in regulating the carbonic cycle and delivering balanced pH to a healthy ecosystem.

To obtain an overview of the typical pH range in the context of Malaysia, a study by Toriman et al. (2012) informs us that upper river water in forested area of Gunung Benum Forest Reserve has a pH range of 6.27-6.68. On the extreme end, Gasim et al. (2007) report that water from the South-East Pahang peat swamp forests with high organic content has a pH range of 3.53 to 4.55. From 52 monitoring stations in Sg Buloh, Selangor, which are typically located among urbanized areas, it was also reported that a high pH of 7.63 was detected (Rowshon et al., 2014) (Table 2.4). This demonstrates the significance of water pH in reflecting land character.

Table 2.4: Results of water quality parameter from Sg Buloh, Selangor watershed (Rowshon et al., 2014)

Parameter	Unit	Maximum	Average	Minimum
pH	-	7.63	6.69	5.05
Dissolved Oxygen (DO)	mg/L	7.32	4.16	1.00
Biochemical Oyygen Demand (BOD)	mg/L	583.00	39.09	2.00
Chemical Oxygen Demand (COD)	mg/L	598.00	70.36	2.00
Total Suspended Solids (TSS)	mg/L	1705.00	56.2	2.00

Last but not least, the Total suspended solid (TSS) in WQI is a parameter crucial to reflect fine particulates in water. Not only it is a concern of aesthetic point of view, high level of suspended particles in water can clog water treatment plants and interfere with the respiratory system in aquatic species (Wittig et al., 2007; Sujaul et al., 2013; Authman et al., 2015). The condition also prevents sunlight from reaching river and stream beds, therefore interrupts the process of photosynthesis in aquatic plants and affects fish's vision (Brinley, 1942).

Bear in mind, in water quality chemical assessment, the validity of results can be inaccurate if temporal and spatial influences are not taken into consideration at the point of time when a water sample was taken. As a measure of basic precaution, water sample should not be taken in the first hour of rainfall. Heavy loading of pollutants are known to be flushed into streams and rivers in the first hour of storm, also known as “first-flush phenomenon” or “shock loading” (Choe et al., 2002; Lee et al., 2004; Rad et al., 2014), and water tainted by initial runoff cannot be regarded as a representative sample. Such shocks are also commonly blamed for creating a momentary toxic condition that kills aquatic life in an instant.

2.5 Physical assessment

Streams and rivers are regarded as “ecologically sensitive receptors” (DOE, 2012) and riparian buffer zones where land interfaces with water are key

safeguards for bank stability and fluvial ecosystem integrity. According to National Research Council, US (2002), riparian is also defined as an intermediary area between aquatic and terrestrial ecosystem that significantly affect exchanges of energy and matter with aquatic ecosystems. This transitional area regulates and adapts to the dynamism of key hydrological events such as flooding, drought, channel expansion or shrinkage and sediment transport (Gregory et al., 1991; Gonzalez and Garcia, 2011). On a larger fluvial ecosystem context, the geomorphic structure of a river channel morphology and riparian area are the result of responses from climatic, hydrology, and loadings of inorganic and organic matter from adjacent landscapes and vegetation (Naiman et al., 1993; Chellaiah and Yule, 2018). For example, the profusion and richness of riparian vegetation depart greatly in successional junctures (Zainudin et al., 2013). Moreover, in rivers with good riparian quality, the intensity, intervals and duration of floods weaken laterally away from the active channel (Fennessy et al., 1998; NRC, 2002). In the author's personal observation, niche riparian tree species such as *Saraca caudiflora* and *Tristaniaopsis whiteana* in Malaysia have extensive root network capable of withstand the forces of flood are normally present along the waterline. Areas farther from the active channel may contain older and larger trees as there are usually unaffected by the frequency of flooding. In any cases, hydrology is the master shaper of riparian zones and Prichard et al. (1998) deduce riparian areas can only function properly where there is adequate vegetation, landform and large wood debris is present to 1) disperse high water flow energy which lessens soil erosion, 2) detain bedload, sieve sediment and support floodplain development, 3) enhance flood-water holding capacity and ground-water

recharge, 4) increase root masses that stabilizes banks, 5) form wide-ranging ponding and channel properties to provide habitats of various depths and timeframe for aquatic and semi-aquatic species, and 6) support biodiversity. The perimeter of riparian corridor typically broadens outwards to the highest floodline and upward encompassing the canopy of riverbank vegetation (Gregory et al., 1991). Therefore, as interfacing and three-dimensional ecotones, riparians present sharp contrasts of geomorphic, hydrologic, edaphic, and vegetative changes. According to Ministry of Natural Resource and Environment Malaysia (MNRE, ND), a riparian corridor is classified in accordance to Table 2.5.

Table 2.5: Width designation of riparian reserve

River/stream width (m)	Riparian reserve width (m)
>40	50
20-40	40
10-20	20
5-10	10
<5	5

Recognizing that what happens inside and outside the river channel may affect its biological and chemical processes, there is certainly a need for river physical assessment methods to inform planning and management strategies. Unfortunately, so far in Malaysia, literature review found no evidence of official and unified riparian assessment protocol adopted as part of

its national initiative to safeguard the watersheds. However, in contrast, there is a lengthy list of physical assessment protocols employed by many countries around the world. In this sense, Malaysia is falling behind and there is an urgency to start developing a protocol that incorporates the best practices. It should also be practical in tropical fluvial ecosystem environment.

In setting out to identify the best methods and metrics, firstly, there is a need to review existing assessment criteria. In most countries, assessments are generally conducted through a mix of quantitative, qualitative and semi-quantitative protocols (Fennessy et al., 1998; Bartoldus, 1999; Burglund, 1999; Karr, 1999; Fennessy et al., 2004; Carletti et al., 2004; OHIO EPA, 2006; Tanago and Jalon, 2011; Valero et al., 2015). There no evidence of a dominant assessment system, and clearly, rapid methods are the favourites because they require less time. Also they can lead to significant cost savings. As such, rapid methods are increasingly becoming popular and central to implementation by most authorities and government agencies in charge of water resources and forestry management.

From a critical review of 40 assessment methods conducted by Fennessy et al. (2007), they found that effective and practical methods generally offer the following qualities, namely, 1) clear scope of assessment area, 2) procedures to collect empirical data, 3) final outcome that produces a single integrative score, or index, 4) includes on-site evaluation, 5) low cost to carry out, and 6) truly rapid. USEPA (2004) also defines the term “rapid” as

taking no more than two persons in half a day total in the field and not more than another half day of desktop analysis to finalize the result. Many poor methods were found to be too lengthy, contain up to 72 measurables and no reasoning was provided to support complex formulas used to calculate the final scores, or indices (Roth et al. 1996).

So far, the author has an *a priori* reason to believe that the literature review also shows another key weakness is that physical assessment methods are commonly blind to the seasonal dynamism's relationship among biological, chemical and physical elements in the tropics. This can be expected because majority of the assessment methods originated from developed countries of temperate weather. For example, although organic matter decomposition in northern-temperate and tropical streams experiences the same processes, the differences in intensity between them are conspicuous. It is a common knowledge that riparian vegetation in temperate latitudes often sparse and species poor compared to Malaysia's where vascular plant abundance and diversity is high. Their leaves' chemical properties such as phenolic and tannin content contribute greatly to water acidity when shed from terrestrial and riparian plants (Stout, 1989; Abelho, 2001). Other less apparent items that make their way into waterbodies include fruits, seeds, flowers and pollen. These allochthonous organic inputs affect water chemical greatly and some items are consumed by aquatic life which in turn influences the local biological composition and integrity (Janzen, 1974; Dudgeon, 1994; Wantzen et al., 2008).

Additionally, most assessment systems accord high rating to physical components that depict perfect conditions although the fact is, the river banks and channels suffer erosion and destruction during flooding all the time. Such event is even more prevalent in Malaysia which is affected by heavy monsoonal rainfall. The healthiest riverine physical system is expected to experience a constant flux of inundation and drying i.e. flood pulse (Junk et al., 1989). Repetitive cycles of flooding provide the ecological conveyance to aquatic population dispersal and recharge the lowlands with soil nutrient (Winemiller and Jepsen, 1998; Haase, 1999). It is widely recognised that such lateral exchange of water and organic materials between upriver and downriver is the driving force of nutrient dynamism that sustains habitats and species in an eco-hydrological unit.

Certainly, some signs of physical destruction, or disturbance, can be expected and the “Proper Functioning Condition” (PFC) (Prichard et al., 1998) approach should be ingrained into some components of a practical assessment method. A proper and functional physical river is always changing to adjust to the regional geomorphological and hydro-geomorphological processes. An assessment method should therefore be adaptive enough to recognize such dynamic equilibrium and accord the appropriate fair assessment.

2.5.1 Hydro-morphological variances

In attempting to diagnose features of a particular riverine ecosystem, qualitative or quantitative study deployed must always be preceded with some exercises to understand the range of eco-hydrological units (EHU) contain within the river continuum. As mentioned earlier, a riverine ecosystem can consist of many individualistic zones depending of the regional geomorphology and hydromorphology in question. Each is very likely to express a particular countenance and niche. In the context of flooding which typically occurs at lowland, subdividing a study site into sensible EHUs stands to produce a better result fidelity.

Besides patch coverage and linkage, there is a need to scrutinize how hydro-morphological dynamism behaves on a smaller scale for a better understanding. In any open landscape, the potential energy of water starts as precipitation falls on high grounds. Water as it flows downward has the ability to carve its own “trails” with kinetic energy into various forms of stream and rivers. Thereon the fluvial ecosystem would attain a stable equilibrium in acquiring and using energy to adjust path geometry used by water to reach the lowland. Such steady state is known as dynamic-equilibrium (Wiens, 2002) and it explains that all flow lines in a basin affect the main line. Disturbance in any flow line would stimulate a response from the main line and subsequently to other flow lines. Possibly the most significant example to visualize responses of the main and flow lines with each other are how rivers meander.

Straight natural rivers are rare. With the passage of time and variation in flow intensity caused by fluxes in tributaries and downriver, bank erosion and sedimentation becomes the response in the main line. It is easy to observe that in a natural riverine system, flow can happen laterally and longitudinally. Erosion usually occurs at areas where the flow changes direction, no matter how slightly, due to topography. Such “bends” would eventually be eroded into the meandering pattern. Flow intensity from tributaries lines is influenced by seasonal climatic and geologic factors. Corresponding, meandering pattern in the river channel tend to expand, shrink and reshape itself continuously back and forth across the EH unit on a smaller scale, and the fluvial ecosystem at a broad scale. Indeed, such three dimensional interdependence and self-adjustment hydro-geomorphological ability makes the riverine ecosystem an exceeding complex area to examine. Nonetheless, it is an interesting one especially in the context of this study which also seeks to understand fish meta-population responses to aquatic habitat destruction, creation and reformation.

2.5.2 Meteorological disturbances

The rainy season is often associated with flood catastrophe and destruction. Understandably, it is difficult to accept flooding as a natural event with an ecological goodness. In the context of this study, precipitation shock and flooding make interest subjects as the sporadic and episodic hydro-

morphological dynamism may cleanse, rejuvenate or realign the riverine system to become more resilient. Large dead biomass like fallen trees are washed into stream and organic debris provides important food and habitat to aquatic species. Fertile soil directed downriver and deposited along the banks and floodplains rich terrestrial habitats and farms in the lowland. Periodical flood flashiness (rate of change) and spillage also creates new habitat and provide irrigation to normally drier area to flourish.

In limnology interpretation, the occurrence of flood is categorised under two premises, 1) the ecology of disturbance and 2) the ecology of land-water subsidy (Pickett and White 1985; Odum et al., 1979). In 1989, Junk et al. proposed the theory of “flood pulse” to conceptualize the seasonal hydrological and biological disruption. It is hypothesised that spatial and temporal inundation mechanism is necessary to maintain fish population persistency, dynamics and resilience (Agostinho et al. 2005) within an ecohydrological unit (Zalewski et al., 1997; Schiemer et al., 2007). In times of active flooding, one can expect deterministic sorting and stochastic dispersal to occur among biological taxa. Water retained on land surface after flooding provides a new fluid habitat for additional interactions of living and non-living matter.

Peninsular Malaysia which typically receives 324 billion cubic metres of rainwater annually and the current water demand is only 11 billion cubic metres (EPU 2000). With just roughly 3.4% of total precipitation used to satisfy

demand, freshwater shortage is not a common concern in Malaysia. However, the problem lies in the fact that precipitation is not uniformly distributed in yearly, decadal and century time scales. This is compounded by anthropogenic disturbances such as increasing forest impairment that have rendered many watersheds with less capacity to store and discharge freshwater in a consistent manner (Chan and Ghani 2016). This situation may become more acute when there is abnormal prolonged dry weather and high temperature shock due to meteorological forcings such as the El Niño-Southern Oscillation (ENSO).

Studies have found that a strong El Niño event threatens water quality and security in many regions such as Africa and Latin America (Magaña and Conde 2000; Wittig et al. 2007; Rojas et al. 2014; Maeda et al. 2015; Veldkamp et al. 2015; Degefu and Bewket 2017). And yet, a reduced level of precipitation may not have the same effect all over the world. At the time of this writing, no study has so far been conducted to investigate the effects of prolonged dry weather on river water quality in Malaysia or other Southeast Asian neighbouring countries.

The period of 2015–2016 which coincided with this study period has been regarded as strong El Niño years by many experts (Rembold et al. 2015; Jiménez-Muñoz et al. 2016; Varotsos et al. 2016). A strong El Niño event is typically unfavourably viewed, but such a worst-case scenario is a good opportunity to measure pollutant concentrations induced by water volume reduction and possibly reveal other emerging issues from the prolonged dry weather in water bodies.

2.6 Biological assessment

Biological assessment and monitoring, or biomonitoring, is a process that determines the ultimate consequences of environmental strain by appraising selected biota. The results of biota metrics may vary in response to anthropogenic influences, and together, the process can give an overall situation of an ecosystem. However, a bio-monitoring process must be carried out not only with practicality and precision, it must also be sensitive enough to detect nuances.

In 1981, James R. Karr provided the world with the first protocol of a fish-based bio-monitoring process; now widely known as Index of Biotic Integrity (IBI). The protocol was favourably welcomed and widely utilized because of its practicality and multi-metric approach. Since then, Renata and Gubiani (2013) report that 734 papers published in 207 journals have cited "Karr, 1981" and this speaks volume of Karr's contribution to the development and evolution of various aquatic ecosystem assessment many countries are adopting today (Figure 2.8).

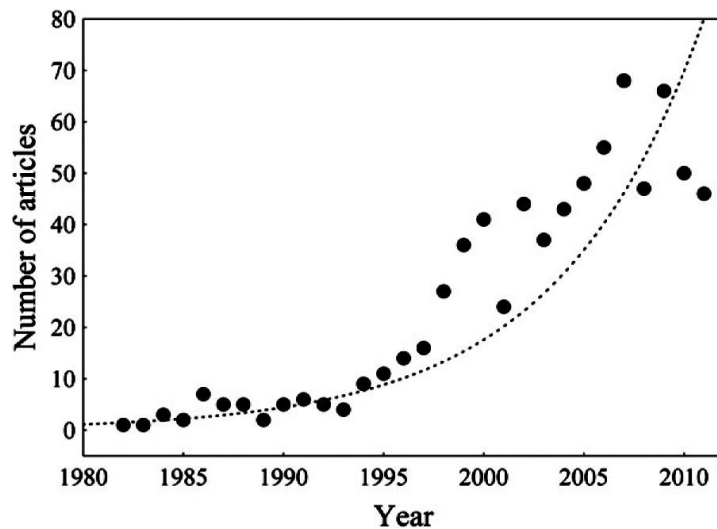


Figure 2.8: Temporal trend of papers that cited "Karr, 1981" (Renata and Gubiani, 2013)

However, unfortunately, there is still a low level of citations from Latin America, Africa, Asia and many other tropical environments which host a large portion of freshwater networks and species that by far are most negatively impacted by human settlements (Schindler, 2007). Other shortcomings will be discussed later in this section.

To objectively detect perturbations within a complex aquatic ecosystem, the original IBI assesses 12 biological metrics, with each metric to be rated between 1, 3 and 5. The ratings are sensitive and take into consideration of:

1. Level of abundance and diversity of species
2. Number of species of eco-morphology guild grouping
3. Number and percentage of species that is tolerant and intolerant

4. Percentage of species of feeding guild grouping
5. Percentage of hybrids, and species with deformities and diseases

Table 2.6: IBI scoring criteria (Karr, 1981)

Attribute category and metric	Scoring criteria		
	5	3	1
Species richness and composition			
Total number of fish species	Expectations vary with stream size, region, and basin		
Number and identity of darter species			
Number and identity of sunfish species			
Number and identity of sucker species			
Number and identity of intolerant species			
Percent individuals as tolerant	<5%	5–20%	>20%
Trophic composition			
Percent individuals as omnivores	<20%	20–45%	>45%
Percent individuals as insectivorous cyprinids	>45%	20–45%	<20%
Percent individuals as piscivores	>5%	1–5%	<1%
Fish abundance and condition			
Number of individuals sampled	Expectations vary with stream size, region, and basin		
Percent individuals as hybrids	0	>0–1%	>1%
Percent individuals diseased or with anomalies	0–2%	>2–5%	>5%
Total IBI score (sum of 12 metrics)	60 ←————→ 12		
Integrity class	Excellent – Good – Fair – Poor – Very Poor		

The IBI final score that may range from minimum 12 to maximum 60 is subsequently generalized and expressed in "integrity class" between 5 classes, namely "excellent", "good", "fair", "poor" and "very poor" (Table 2.6). Bear in mind, the rating is deduced against a least-disturbed "reference site" because IBI recognizes that each region is unique. A reference site is considered the best natural site of a particular geographic and eco-region. Therefore, before any IBI program can be initiated, it must be preceded by a study of reference sites to set the foundation and benchmark for comparison to site being assessed (Scardi et al., 2010).

IBI is basically a system to quantify the metrics with an assessor's best professional judgment (BPJ). According to Marcot (1989), BPJ of an assessor consists of a comprehension of concepts, theory, consequences as well as local environmental knowledge. Through heuristic learning process, the assessor is expected to conduct a biomonitoring process to the best of his/her knowledge and make educated conclusions. The assessor may not be a qualified ichthyologist, but in a predetermined and systematic manner, IBI imposes upon the assessor to employ quantitative standards to derive BPJ conclusions.

From its humble beginnings, when it was first used to assess streams in Illinois by James R. Karr, today IBI is now widely adopted and adapted by water resource management agencies in the United States as well as countries in the European Union (EU). It enjoyed a sudden surge of interest when the Clean Water Act (CWA) and the Water Framework Directive (WFD) legislation came into force in 2000 in EU. At that time, many member countries in the EU have not established any fish-based assessment methods and could not comply with WFD requirements (Murphy et al., 2005). Thus, IBI became the most sought after ready-to-use standard for assessing the ecological status of European riverine ecosystems. Eventually, based on IBI theoretical concept, many countries have improvised and produced some new country-specific integrity indices. Also, a project by the codename FAME (<http://fame.boku.ac.at>) under the European Commission had pushed for the implementation and harmonization of fish-based methods to assist all countries classify their water bodies from 1 (excellent) to 5 (very poor) by 2015. It

should be noted that the EU's 1 to 5 classification bears an uncanny resemblance to IBI's "integrity classes" of 1 (very poor) to 5 (excellent) in a reversed manner.

While the objective of FAME is commendable because it requires all EU members to adopt more or less a standard approach to riverine ecosystem assessment and pushes every country to set a high standard for watershed management, it begs the question of whether a one-size-fits-all system can really provide for widely varying eco-regions at spatial and continent scale. Certainly, this exposes some weaknesses in adopting IBI-like standardized protocols and assumptions. Although IBI-based approaches is widely adopted, literature review shows many researchers are still deliberating and trying to refine the metrics, whether by modifying or deleting certain aspects (Simon and Lyons, 1995; Hughes and Oberdorff, 1999; Oberdorff et al., 2002; Pont et al., 2006).

Wan et al., (2010) point out that IBI-based protocols have so far neglected the role of rare species as indicators of well-functioning ecosystem. A scoring system cannot only depend on common species because there are niche habitats within a drainage which may be inhabited by niche species. They argue that a larger sampling scale stands to capture rare species than smaller drainage areas. Therefore, with consideration to cost and resource, they suggest that the largest possible area should be assessed and the finding of rare species must add some weight to any IBI-based scorings. Additionally, sampling timing can also strongly affect assessment (Peterson and Rabeni

1996; Grossman et al. 1998). Many species migrate seasonally and seek refuge in hidden habitats during severe occurrence such as flood or drought. Such cases are certainly worth taken into consideration when establishing and conducting fish-based assessment in Malaysia where there is a pronounced annual monsoon season.

IBI-based assessment is also commonly criticised for diluting and generalizing field data into numerical scores. Some researchers argue that complex information and variation details deserve more attention (Harrison & Whitfield, 2004; Darwall et al., 2007; Oliveira et al., 2011; Clavel et al., 2013; Renata and Gubiani, 2013). However, the author of this study views argument put forward by the previous studies as a matter of opinion because the fish-based assessment is originally intended to serve as an overview, or summary, of riverine integrity in a rapid manner. Essentially, the IBI-based assessment's main aim is to simplify the results, to a certain extent, for effective communication. After the index result is obtained, details at a finer scale can be pursued separately by specialists and other interested parties at some later stages.

Another challenge highlighted by some researchers is the unavailability of reference sites, or least-disturbed places, for the benchmarking (Kwak and Peterson, 2007) as required by, IBI-based assessment. Admittedly, in times of modernity when human influence has permeated across most terrestrial and fluvial regions of the planet, it is increasingly difficult to find any reference sites that are relatively pristine. Over the last several decades, primary forests

have been cleared and degraded at an accelerating rate for human social and economic activities, and this affects regional watershed ecosystems (FAO, 2011). In Asia, there are already less than 20% of primary forests left and they are mainly found in highlands and inaccessible terrain (Figure 2.9).

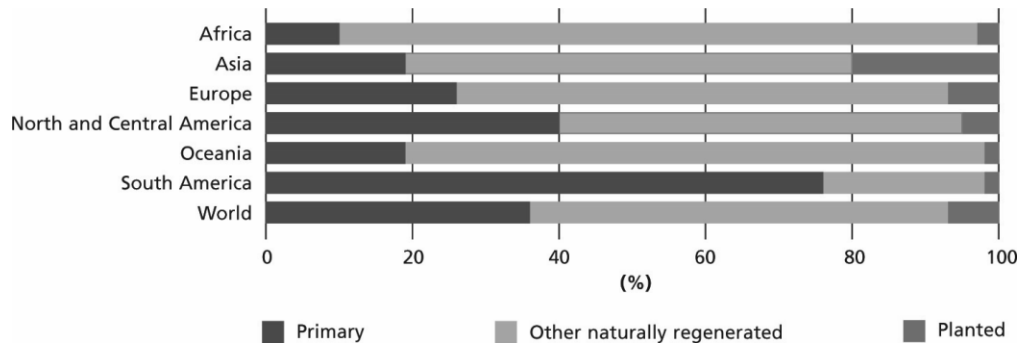


Figure 2.9: Characteristics of the world's forests in 2010 (Food and Agriculture Organization of the United Nations, 2011)

In the context of Malaysia, Giree et al. (2013) deployed satellite remote sensing technology to conclude that there was a continuous loss of forest cover at a rate of 0.64 Mha/yr (SE=0.055, CI=95%) between 1990 to 2005. This is certainly a glooming outlook because primary reference sites are decreasing at an alarming rate. Thus it may be fair to ask, will the country run out of reference sites for the effective implementation of fish-based assessment? Malaysia is still far from managing its forests and watersheds sustainably (Abdul Rahim, 1998; FAO, 2010; Chimeli et al., 2011; Giree et al., 2013; Gaveau et al., 2014; Garcia-Chevesich et al., 2017) and the possibility of losing more reference sites is high.

All species-driven assessments are still evolving and generally they are currently undergoing expansions, changes and improvement according to the following themes, namely 1) extending assessment to countries beyond United States and Europe 2) testing of new metrics and reference concepts to improve sensitivity to detect environment stressors 3) improving ecomorphological guild classification of regional fish species 4) standardizing sampling protocols and monitoring reporting, and 5) formulating tools for prioritizing ecosystem restoration (Beier et al., 2007; Degerman et al., 2007; Grenouillet et al., 2007; Melcher et al., 2007; Virbickas and Kesminas, 2007; Herlihy et al., 2008; Scardi et al., 2010; Oliveira et al., 2011; Renata and Gubiani, 2013).

As reductionist systems, species-driven assessments have opponents because of their inherent weaknesses in detecting fine-scale stressors in complex ecosystems. But, it is not short of proponents either. There are those who appreciate the straight-forward simplicity it offers and literature review shows species-driven assessments have stood the test of time. Moving forward, the following sections describe the challenges highlighted by the latest literature on adopting fish as bio-indicator in Malaysia and the discipline of fish taxonomy and systematics. The review is essential for avoiding pitfalls and reinforces this study with a strong foundation in assessing and interpreting fish-based metrics.

2.6.1 Freshwater fish biogeography

Among vertebrate animals which totalled approximately 54,711 recognized species, by far, fishes form the largest category. Their numbers are expected to reach more than 32,500 valid marine and freshwater species within 515 families (Nelson, 2006). In general, roughly 11,952 species, or about 40% of fish species, occur exclusively in or most often in freshwater (Helfman et al., 2009).

Freshwater species is a typical term used to describe fishes that are found in inland streams, rivers, lakes and regions of weak brackish water. The term may also encompass diadromous species such as sturgeons which often spend their lifecycle between inland freshwater and the ocean. Among them, some can be classified as anadromous (e.g. salmon, herrings), which means they usually migrate at incredible distances to the rivers and spawn in freshwater although they spend most of their adulthood at sea. In contrast, there are some 225 species which are catadromous (e.g. *Anguilla* eels) (Nelson, 2006) and they spawn in the ocean but live in freshwater. There is also a group of fish species that can live freely between waters of various levels of salinity and they are classified as euryhaline species.

Many hypotheses have been proposed to rationalise species diversity at a wide range of habitats on spatial scales and they can be categorized into three major hypotheses. Firstly, MacArthur's (1969) "area" hypothesis suggests that

species diversity increases when there are more surface areas to accommodate habitats and speciation processes. Secondly, Wright et al. (2003) and Evans and Gaston (2005) proposed a “productivity” hypothesis that expects species richness to increase when there is more energy available. “Energy” in this context refers to the productive energy of solar that translates to the volume of plants and biomass resources available to species to feed on and inhabit. In general, the hypothesis proposes that energy variability in the environment affects the rates of metabolism, speciation and molecular evolution in species. Consequently, high energy areas promote faster speciation and evolution, thus more species can occur. Thirdly, Ricklefs (2004) proposed the “historical” hypothesis which explains that competition, predation and mutualism relationship among species over ecological time provides the drive for diversity patterns.

With regards to freshwater fishes, the “area” hypothesis seems to be plausible for explaining richness variability, namely species richness tends to increase in proportion to the size of the basin area (Eadie et al., 1986; Rosenzweig 1995; Hugueny et al., 2010). Biogeographically, larger freshwater areas appear to host more genera and species, namely the Neotropical region (705 genera, 4,035 species), Oriental (440 genera, 2,345 species), Afrotropical (390 genera, 2,938 species), Palaearctic (380 genera, 1,844 species), Nearctic (298 genera, 1,411 species) and Australian (94 genera, 261 species) regions (Leveque et al., 2008) (Figure 2.10).

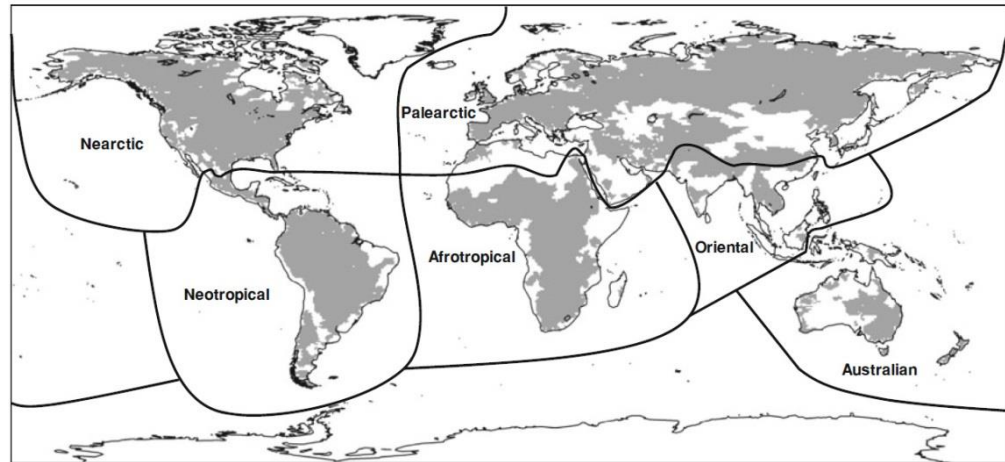


Figure 2.10: Major freshwater fish ecoregions encompassing 1,054 rivers as classified by the Fish-SPRICH database. Malaysia is located in the Oriental ecoregion (Brosse et al., 2012)

2.6.2 Taxonomic of freshwater fishes in Malaysia

Species richness increases with decreasing latitude and it is commonly known that there is a high level of endemism in the tropics. Malaysia is located in the Oriental tropical ecoregion that encompasses the east, south and southeast Asia regions. When combined, an estimated 3,500 freshwater fish species are present and high diversity occurs mostly in the equatorial countries with Indochina, India, Indonesia and Malaysia taking the lead. In comparison to Africa's 50 families and Latin America's 55 families, tropical Asia harbours a staggering 121 families within inland waters with cyprinids as the dominant group. The Mekong River basin hosts the highest diversity with 1,200 species followed by the Yangtze River basin in China and the Kapuas River in Indonesia with approximately 320 species each (Kottelat and Whitten, 1996).

Currently, the website <http://ffish.asia/> website (Kano et al., 2016) reports that there are 765 freshwater fish species found in Southeast Asia. In Malaysia, which encompasses peninsular and Sabah-Sarawak provinces, the online database FishBase (<http://www.fishbase.org/search.php>) (Froese and Pauly, 2016) has records for 634 species in Malaysia alone which are grouped into 68 families.

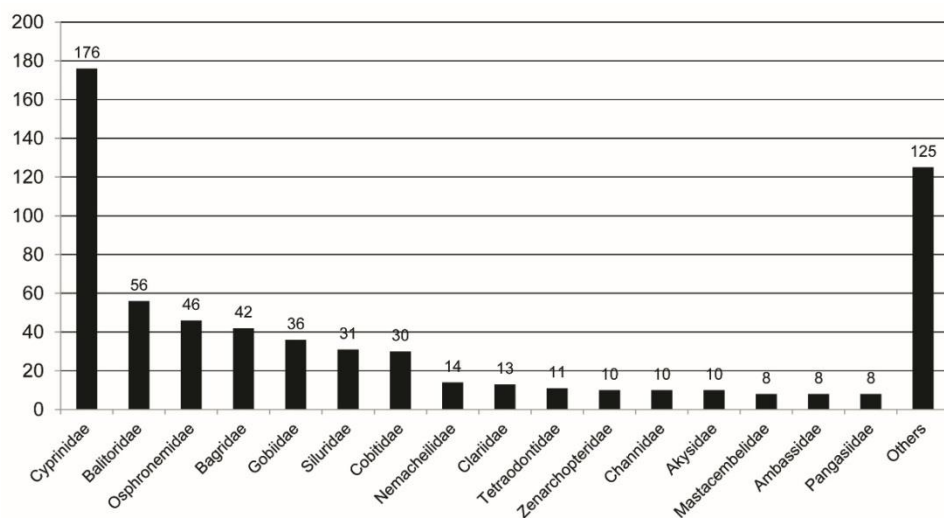


Figure 2.11: Major freshwater ichthyofaunal families in Malaysia (Froese and Pauly, 2016)

As indicated, the Cyprinidae family is the largest group (Figure 2.11). The family encompasses 27.8% of fish species composition in Malaysia and with 33 species, *Rasbora* is the largest genus in the family (Froese and Pauly, 2016). Siluriformes is the most diverse order with 8 families of catfish and the *Hemibagrus* is the largest genus (Zakaria-Ismail, 1992). This numerical information can be taken as a guide when conducting field sampling in the freshwater habitats in Malaysia.

Also, to infer how many species can be hosted and typically found in a particular freshwater hydro-ecological unit, Ng and Tan (1999) reported that 108 species in 26 families were recorded in the Endau basin, which is located in the state of Johore. Such a large diversity is not unusual and this was observed by Johnson as early as 1967. He speculated that there is a pronounced difference in the fish distribution patterns between the north and south of Peninsular Malaysia (Figure 2.12). Johnson observed that fish diversity is greater in the southern freshwater regions. He argued that the south has more acidic ($\text{pH} < 4$) or brackish meso-habitats that harbour specialized tolerant species such as *Betta persephone*, *Parosphromenus tweediei* and *Desmopuntius johorensis*. In the north, there are less brackish meso-habitats because they are typically dried out by the annual distinct dry weather during the period between December to February (Wong et al., 2009).

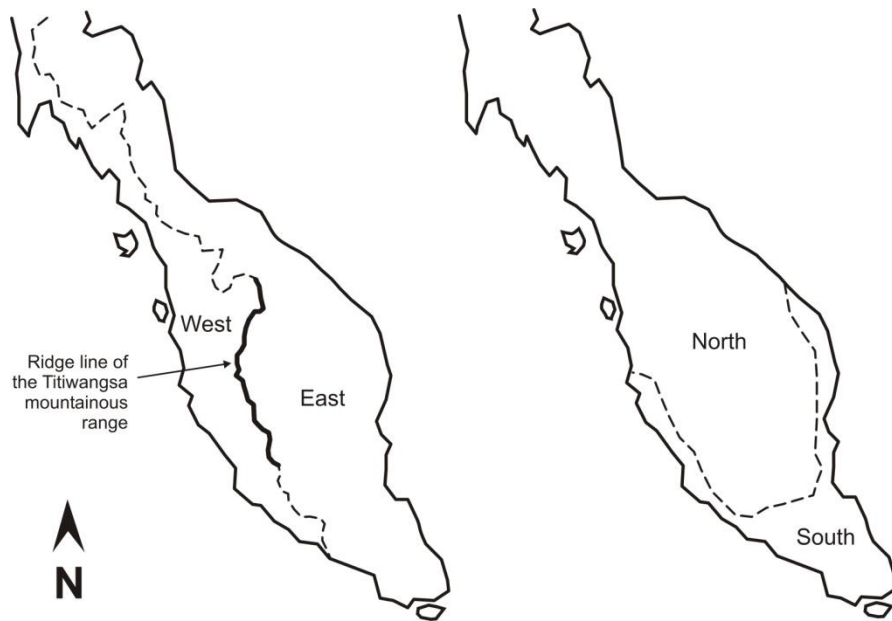


Figure 2.12: Comparing the east-west faunal line postulated by Abell et al. (2008) (left) with north-southern crescent faunal line suggested by Johnson (1967) (right)

Another observation reported by Johnson (1967) is the dispersal pattern of cyprinids. In Malaysia, genera from the Cyprinidae family are diverse and productive in peat swamp and brackish waters such as *Rasbora* spp. and *Osteochilus* spp. However, in the Europe, cyprinids such as *Blicca bjoerkna*, *Pseudorasbora parva* and *Scardinius erythrophthalmus* typically populate hard waters (calcium content > 60 mg/l) and leave acidic waters (pH < 4) to other families (Johnson, 1967).

2.6.3 Ichthyofaunal biogeography pattern in Malaysia

Biogeography is a science that is concerned with species vicariance (Wiley, 1988). Nelson and Paltnick (1981) describe it as "comparative biology of space, time and form". No matter how small a present watershed is, first and foremost, the broadest outlook of "space, time and form" should be investigated to understand ichthyofauna composition and niches for making decisions when conducting fish-based studies. Watersheds that are occurred in the past but no longer exist at present day, typically known as paleo-drainage basins (Abell et al., 2008), and how they link the freshwater habitats at the alpha, beta and gamma diversity levels in the past should be also investigated (Jurasinski et al., 2009). Alpha diversity is a term used to describe local diversity such as fish species composition in a stream or a river. The beta diversity encompasses fish diversity along a gradient for example, fish composition from the highland headwater to the lowland river. At the largest scale, gamma diversity refers to fish diversity at regional or watershed level. Regrettably, fish biogeography is not an active field of study in Malaysia. The subject is markedly riddled with knowledge gaps and literature is scarce. As mentioned earlier, politically Malaysia comprises the west (peninsular) and the east (Sabah and Sarawak) which are separated by the South China Sea. Any freshwater fish study in the country should include some local and regional fish biogeography investigation as part of the analysis process in order to produce a species presence or absence forecast in a particular target site. Such approach would increase the robustness of study (Abell et al., 2008).

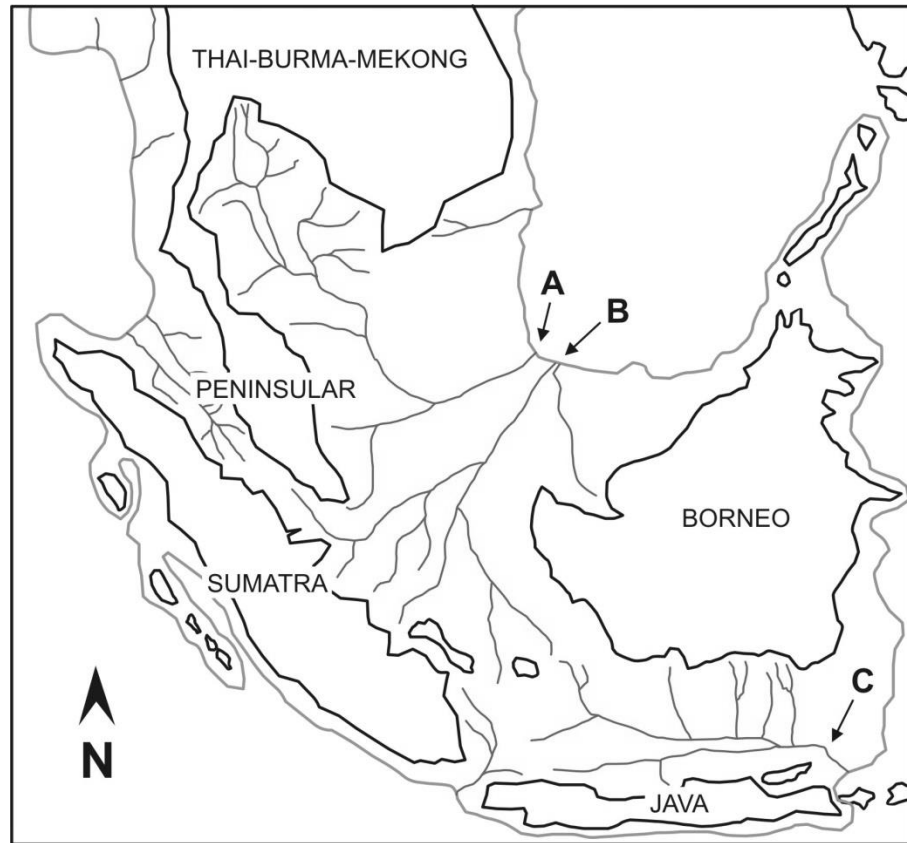


Figure 2.13: Major river networks in southeast Asia during the Pleistocene era, namely East Sunda River (A), West Sunda River (B) and North Sunda River (C) (Rainboth, 1991)

During the Pleistocene epoch which occurred between 2,588,000 to 11,700 years ago, the northern peninsular has a historical biogeographical link with the Thai-Burma-Mekong watershed systems and the watersheds in southern peninsular has a relationship with Sabah, Sarawak, Kalimantan, Sumatra and Java (Figure 2.13) (Zakaria-Ismail, 1994; Voris, 2000; Bird et al., 2005; Abell et al., 2008; Hall, 2013). In a phylogeographic study where geographic distribution of species in southeast Asia were correlated with population genetics, Lohman et al. (2011) concluded that the Thai-Malay peninsula is the transition zone linking the Indo-Burmese and Sundaic regions.

They also highlighted that Corner (1960) found that fishes in Riau-Palembang (Sumatra), Kapuas (western Borneo) and Johore River (southern peninsular Malaysia) to share the same haplotypes.

Haplotype is a simplified term used to describe "haploid genotype". "Haploid" refers to cells with only one set of chromosomes and "genotype" refers to genetic makeup of a species (Kapusinski and Miller, 2007). In fish species distribution studies, haplotypes offer important clues to reveal genetic similarity of individuals from different locations (Danzmann and Gharbi, 2001). Haplotype analysis by Kamaruddin and Esa (2009) who studied *Barbonymus schwanenfeldii* and Tan et al. (2012) who studied *Channa striata* population also supported the theory of historical biogeographical connection between the Thai-Burma-Mekong watershed systems in northern peninsular and that southern peninsular has a biogeographical linkage with Sabah, Sarawak, Kalimantan, Sumatra and Java.

In the context of peninsular Malaysia, Abell et al. (2008) took another approach to study fish biogeography. They established faunal lines in accordance to watershed delineation along the Titiwangsa mountainous range that runs from the northwest to the southeast of the peninsular (Figure 2.12). Abell et al. (2008) suggested that drainages that flow to the direction of Malacca Straits and South China Sea exhibit dissimilarity in fish composition. Correspondingly, they estimated that there are 150 species and 33 families in the west side of Titiwangsa mountainous range which generally encompasses the inland and coastal plains of Perlis, Kedah, Perak, Selangor, Negeri

Sembilan and Melaka state. For the east side of Titiwangsa mountainous range that generally covers Kelantan, Terengganu, Pahang and Johore state which is associated to Thai-Burma-Mekong ecoregion, an exceptional 320 species and 43 families was estimated by them. The high species diversity is stark and this is demonstrated by examples such as *Labiobarbus festivus*, *Pseudomystus fumosus*, *Nanobagrus lemniscatus* and *Betta pi* which can only be found in the eastern side of Titiwangsa mountainous range (Roberts, 1993; Ng and Lim, 2005; Ng, 2010; Lee et al., 2012).

Since Borneo Island is typically regarded as a singular ichthyofauna biogeographical region, the fish diversity in Sabah and Sarawak is expected to be rather similar to other regions in the 745,567 km² island. In Sarawak, Atack (2006) proposed that there are 254 species and in Sabah, Inger and Chin (2002) deduced that 168 species are present. Comparatively, a total of 263 species from 40 families and 120 genera were found in the Kapuas basin, Kalimantan (Roberts, 1989).

The freshwater biogeography boundary and subdivisions are still subjected to debates, primarily arising from the scarcity of data. As highlighted earlier, it is unfortunate that freshwater fish biogeography and the identification of fish species are not active fields of study in Malaysia as they are considered fundamental research with no economic returns.

2.6.4 Conservation and management status

Although ichthyofauna studies have been supposedly conducted for more than 160 years since Cantor (1849), freshwater fish conservation and taxonomy management in Malaysia is still considered in the discovery and exploratory stage (Zakaria-Ismail, 1992; Lim et al., 1993; Zakaria-Ismail, 1994; Ahmad and Khairul-Adha, 2005; Chong et al., 2010; Khairul, 2011). The lack of interest and funding constraint has also acutely affected ichthyological studies in the country although there are many unresolved taxonomic problems (Ahmad and Khairul-Adha, 2005). For instance, the Cyprinidae family is the largest in Malaysia but its systematic has been historically convoluted especially those under the subfamily Cyprininae which is generally divided into four groups, namely barbines, cyprinines, labeonines and oreinines (Moghaddam et al., 2012). Within the barbin group alone, for example, *Puntius* which is the "catch-all" genus (Kottelat, 1999) is still problematic. In the past, a substantial number of small barbs have been assigned to the genus. Subsequently the species were taxonomically debated, revised and transferred to the *Barbodes*, *Barbonymus*, *Barbus*, *Capoeta*, *Hypsibarbus* and *Systemus* genera by the authorities progressively (Chen et al., 1984; Shantakumar and Vishwanath, 2006; Chen and Mayden, 2009; Kottelat and Tan, 2011; Collin et al., 2012; Kottelat, 2013). Since the *Puntius* genus encompasses a diverse range of species in Asian tropics and there are many researchers in various countries working with morphological and molecular methods, their nomenclatural validity is expected to remain unstable for a period of time (Pethiyagoda et al., 2012; Rajasekaran and Sivakumar, 2016).

Correspondingly, the status of the *Tor* genus under the Cyprinidae family is also somewhat unresolved for species that occur in Malaysia. According to various studies, the researchers have treated *T. douronensis*, *Tor tambra*, *T. tambroides*, and *T. soro* as valid species (Atack, 2006; Esa et al., 2006; Haryono, 2006; Ingram et al., 2007; Esa et al., 2008; Nguyen, 2008; Esa et al., 2012). At the time of this writing, the California Academy of Science's Catalog of Fishes website recognizes *T. douronensis*, *Tor tambra* and *T. tambroides* as valid species. However, authorities such as Roberts (1999) and Kottelat (2013) noted that they could not explicitly distinguish morphological markers between the species. Therefore Kottelat (2013) has so far proposed that *Tor tambra* is the only valid species in peninsular, Sabah and Sarawak. The debate is expected to be prolonged as the taxonomic issue is complex.

Depository centres are the hearts of ichthyological science as obviously voucher specimens are needed for a solid foundation in conservation to ensure reproducibility in scientific method. Researchers are encouraged to preserve organism representatives in officially recognized and publicly accessible depositories so that these are available to peers at any time for examination, identification or when doubts arise. The permanent records or voucher specimens are also strictly labelled with geographical location and time they were collected to increase their value as scientific evidence. Nonetheless, for a country that hosts exceedingly rich biodiversity, it is unfortunate that Malaysia

has yet to set up a national repository centre. At present, fish voucher specimens are scattered around the country (Table 2.7).

Table 2.7: Fish voucher specimen depositories in Malaysia

Institution	Location and state
Fisheries Research Institute (Freshwater Division)	Gelami Lemi, Negeri Sembilan
Universiti Kebangsaan Malaysia (UKM)	Bangi, Selangor
Kolej Universiti Sains dan Teknologi Malaysia (KUSTEM)	Kuala Terengganu, Terengganu
Universiti Malaya (UM)	Kuala Lumpur
Universiti Putra Malaysia (UPM)	Serdang, Selangor
Universiti Sains Malaysia	Pulau Pinang
Universiti Malaysia Sarawak (UNIMAS), Fish Museum	Kuching, Sarawak
Natural History Museum	Kuching, Sarawak
Likas Fisheries Research Center	Kota Kinabalu, Sabah
Universiti Malaysia Sabah (UMS)	Kota Kinabalu, Sabah
Sabah Parks	Kundasang, Sabah

Apart from the absence of a national repository as mentioned earlier, the predicament is compounded by frequent taxonomic revisions and there are insufficient ichthyologists in the country to work on resolving taxonomic issues (Zakaria-Ismail, 1992). Ahmad and Khairul-Adha (2005) also highlighted the scarcity of practising ichthyologists and that although many

students are trained in the universities, they did not end up as active fish researchers.

In a comprehensive study of literature over a period of 20 years since 1987, Chong et al. (2010) estimate that 76% species are being threatened mainly by habitat degradation, loss and modification. These include Blackskin catfish (*Clarias meladerma*), Pearl gourami (*Trichogaster leerii*) and all endemic species from the *Betta* genus. The Bala shark (*Balantiocheilos melanopterus*), *Encheloclarias kelioides* and *Neobarynotus microlepis* which are typically found in pristine rivers and wetlands are considered extinct in the wild. They also estimate that there are 144 threatened/extinct species, 81 endemic species and 26 introduced species in Malaysian brackish and freshwater habitats.

Rahim et al. (2013) highlight that there is also no serious attempt to study and manage the negative impacts of non-native species on native species composition although the non-native species such as Mayan cichlid (*Mayaheros urophthalmus*), Nile tilapia (*Oreochromis niloticus*) and Vermiculated sailfin catfish (*Pterygoplichthys disjunctivus*) has been recorded by many researchers for more than a few decades ago. It is also unfortunate that the production and releases of fries of non-native species such as Java barb (*Barbonymus gonionotus*), Sutchi catfish (*Pangasianodon hypophthalmus*) and Grass carp (*Ctenopharyngodon idella*) into rivers and wetlands were significantly higher than native species in the past 40 years and ironically this

was mainly carried out by the Department of Fisheries Malaysia (Khairul, 2011) as a measure to increase inland fishery productivity.

From literature review, it is evident that the current “business-as-usual” approach has devastated many rivers in the country. The trend and evidence show that water-based habitats and natural resources are not managed and conserved in tandem with the country’s rising fishery and freshwater security needs, and the situation is acute. Since there is also a lack of interest in fish taxonomy, species accounting in Malaysia is still very much in discovery phase. Urgent countermeasures are needed to address the downslide of ichthyology in the country.

2.6.5 Definition of fish and species concept

The term “fish” is usually a convenient description for a group of poikilothermic (cold-blooded) aquatic vertebrates under the Chordata phylum that breathe with gills (Nelson, 2006). Scientifically, the collective term of “fish” primarily refers to Agnatha (jawless fishes), Chondrichthyes (sharks and rays), Sarcopterygii (lobe-finned fishes), and Actinopterygii (ray-finned fishes). Actinopterygians, the bony or ray-finned fishes, are without a doubt the majority of fishes found in freshwaters. Actinopterygians have lepidotrichia which are characterized by fins of membranous webs held together by bony spines, or rays. This niche character differentiates

Actinopterygians from Sarcopterygians which possess lepidotrichia that are fleshy.

Although in early 20th century, the ichthyologist Regan (1910) defined a fish species as a product of interrelated communities with common morphological features (today this is termed as “morphospecies”), it should be noted that the species classification concept differs among scientists. While authorities such as Nelson (2006) and Mayr (1942) accept the “biological species” concept, others like Simpson (1951) promotes the “evolutionary species” concept. Then there is Cracraft (1983) who prefers to adopt the “phylogenetic” or “cladistic” species concept.

The oldest and most widely practised “biological species” concept postulates that species are part of a group composition that breed or can potentially interbreed in natural conditions. In the “evolutionary species” concept, a species is a representative of a lineage having its own evolutionary affinity and historical destiny. As for the “phylogenetic species” concept, species is viewed as a monophyletic set of organism with common ancestors. In practice, each of these major concepts is prone to some level of subjectivity. Regardless of concept, wildlife scientists, especially ichthyologists, typically identify and name fishes by either by their consistency in morphological, and more recently, molecular characteristics. Such species identification process is typically addressed by the taxonomy discipline.

2.6.6 Overview of trends in the taxonomy discipline

While most researchers are concerned with fishes as a food source and their work involves enriching the body of aquaculture knowledge, there are some who are interested in their diversity, distribution patterns, ecology and functional physiology. Recently, there has also been an overwhelming interest in the molecular constitution of fishes (Wong et al., 2011; Pereira et al., 2013; Rakshit et al., 2015 Quraishia et al., 2015) and their function as biological indicators to monitor waterbody pollution (Fonge et al., 2011; Khodadoust et al., 2013; Authman et al., 2015). Correspondingly, the interest in fish has expanded exponentially, and the ichthyology discipline is often sought to contribute to many other fields of studies (Padilla and Williams, 2004; Lauder et al., 2007; Feist and Longshaw, 2008; Rudkowska et al., 2010). Generally, species is the basic unit in these studies and sound taxonomy is a prerequisite to prevent confusion and misinterpretation.

However, researchers who wish to adopt fish as a major or minor component of their studies will be discouraged when they discover that ichthyology is not an easy subject, more so fish taxonomy. Also, it is a common knowledge that there is already an acute shortage of fish taxonomists and finding a fish taxonomist to assist in a study is often difficult. Such is the same case with many other taxa. Since fish diversity can be high, especially in tropical countries, a taxonomist is typically overwhelmed with constant scientific name revisions, field collection expeditions and managing a

museum. Moreover, taxonomy cannot be commercialized and it sees very little funding in many countries. Thus, the discipline rarely attracts students or can sustain career taxonomists in the universities. Such a problem has caused taxonomic errors in published papers and the condition is now widely known as the “taxonomy impediment” (Wheeler et al., 2004; de Carvalho et al., 2007). It is often said that the discipline of taxonomy would be extinct earlier than most endangered species.

On the hindsight, the advancement of molecular, computerized and statistical techniques have led many to believe that “species” can be easily characterized by nucleotide sequences, software and mathematical calculations, and the knowledge in taxonomy is no longer needed. Ebach and Holdrege (2005) warn us that there are a growing number of researchers who have never wet their feet in the rivers to observe species or build competency in applying nomenclature rules, and yet set out to conduct fish based studies and publish papers. Since they lack field experiences, many are unaware of distinctive fish characteristics such as phenotypic polymorphisms, sexual dimorphism and behavioural divergence due to the regional speciation process (Waugh, 2007). Failing to recognize such exceptions can lead to wrong species diagnosis. Some researchers restrict themselves to laboratories, ornamental fish and aquaculture farms, and their specimens may look very different from the wild type which the scientific name was derived from. Ideally, it is advisable to treat a selective bred variety raised in artificial conditions differently. Otherwise, publication with nomenclature errors will be perpetuated through

citation and cause a chaotic situation. In lieu of concerns highlighted, it is apparent that the taxonomy discipline is complex, but an important field.

2.6.7 Why are there so many species?

Teleost species form the largest category among vertebrate animals and their numbers have reached more than 32,500 valid marine and freshwater species under 515 families (Nelson, 2006). In the global context, there are roughly 11,952 of freshwater species (Helfman et al., 2009). Ricklefs (2004) suggests that competition and mutualism among species have an effect on species abundance while Wright et al. (2003) speculate that species diversity is the result of productivity from available “energy” in a particular region. If a region lacks energy (e.g., low food availability in the desert), species richness is typically low. However, in the case of fish, MacArthur’s (1969) hypothesis seems to be the most probable as he suggests that species diversity is accelerated if there are more areas to host suitable habitats. The hypothesis corresponds with the reality today as large freshwater regions seem to demonstrate more genera and species, for example the Neotropical region (705 genera, 4,035 species) compared to the Australian region (94 genera, 261 species) (Leveque et al., 2008) (Figure 2.14).



Figure 2.14: Comparison between Neotropical and Australian fish genera and species richness (Leveque et al., 2008; Brosse et al., 2012)

Early taxonomists, namely Linnaeus and Darwin, had started cataloguing and clustering species that looked similar because they believed that these species share a common biological lineage. In the mid-18th century, the evolution hypothesis was a new and strange concept. Eventually this was proven to be factual in the advent of modern molecular and genetic assessment technologies. In general, today, there is a consensus among scientists that all species on Earth are interlinked with a hierarchical and evolutionary tree with millions of branches. Each branch itself is a representation of the natural history of a particular species and its pedigree. But why did the branches have to extend and multiply in the first place? What causes the divergence?

When gene flow among populations is interrupted by natural (e.g., geographic barriers created by earthquakes) or artificial means (e.g., man-made barriers in aquaculture farms and dams), two types of speciation will occur,

namely allopatric speciation and sympatric speciation (Butlin et al., 2016) (Figure 2.15). Allopatric speciation occurs when a population is separated by a barrier and such isolation prevents the two or more sub-populations from mating. Given time, the lack of gene flow among the sub-populations will cause biological incompatibility and divergence would be triggered (Mayr, 1959; Turelli et al., 2001; Singh, 2012).

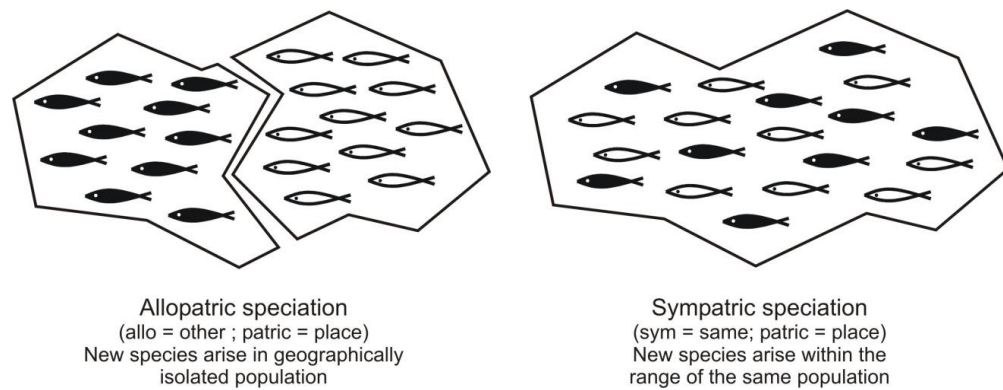


Figure 2.15: Modes of speciation

In sympatric speciation, biologists highlight that ecological shift and resource competition are the key drivers (Mayr, 1947; Dieckmann and Doebeli, 1999; Bolnick and Fitzpatrick, 2007; Mallet et al., 2009). They reasoned that new species may arise within a population from biological reproductive barriers between mutants that are better adapted and parent populations. Nonetheless, despite further speciation in both space and time, and regardless of allopatric or sympatric speciation, species within a branch would still maintain a certain degree of morphological similarity (Butlin et al., 2016).

2.6.8 Taxonomy and systematics

The word taxonomy originated for Greek word *taxis*, meaning arrangement, and *nomos*, meaning law. The science of biological taxonomy is responsible for discovering, describing, classifying, naming and treating each species as the basic unit. Species are given names in accordance to the protocol set by Linnaeus' binomial nomenclature system (Enghoff, 2009).

Systematics on the other hand is the science of distinguishing orderliness and classification of a taxon into hierarchical series to emphasize their interrelationships (Mayr, 1942; GuerraGracia *et al.*, 2008). The word systematics stems from Greek word *systema*. Nelson (2006) tells us that a systematist seeks the broadest outlook to resolve family, relative, order or grouping orderliness. Taxonomy and systematics are not entirely different schools of thought, but rather overlapping fields (Wilson, 1985; Lincoln *et al.*, 1998). Kapoor (1998) and Wägele (2005) also highlight that the term “systematics” is often used synonymously with taxonomy. It must be clarified that this review adopts Nelson's (2006) argument that biological classification is based on systematic studies and taxonomy is part of systematics.

A proper taxonomy is a first-hand and exhaustive undertaking. Whether one adopts the “biological species” concept (Mayr, 1942; Nelson, 2006), “evolutionary species” concept (Simpson, 1951) or the “phylogenetic species” concept (Cracraft, 1983) as explained earlier, all identification processes start

which examining morphotypes at the earliest stage of discovery. Specimens are physically scrutinized from small microscopic configuration of scales to large membrane patterns of the caudal fin. Each physical variance, no matter how small, on a fish body is useful information. Naturally, all fish-based studies require considerable identification skills, experiences and familiarity with local species. Nonetheless, this may not be as complex as it sounds because each species is normally distinctive in appearance and has a certain “look” (Figure 2.16).

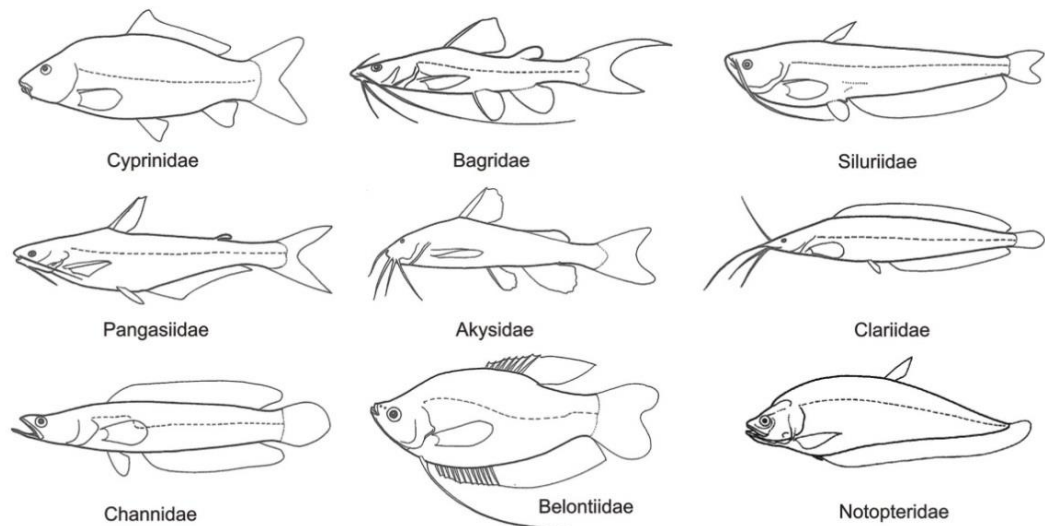


Figure 2.16: Species from each family have a similar morphological profile to provide identification clues (Rainboth, 1996)

At a higher level and broader perspective, systematists are experts who examine historical discrepancies, ambiguities, errors and variant names of species, genus and family. For example, there is the problem with regards to whether Eleotridae or Eleotrididae should be used for the members of sleeper

fishes (Robins, 1991). Thankfully, species classification and naming consistency is slowly being resolved and currently governed by the International Commission on Zoological Nomenclature (ICZN). However, fish taxonomic problems cannot be resolved quickly as desired because ICZN also has to address issues affecting other taxa. For the fish taxon, appreciatively, there are dedicated ichthyologists who take it upon themselves to diligently keep track of the latest development and progressively publish the most updated information.

Every species belongs to a genus (plural: genera), every genus to a family, every family to an order, every order to a class, every class to a phylum (plural: phyla) and finally all phyla are placed under an overarching kingdom (Figure 2.17). Each phylum is regarded as a representation of a large grouping of species that shares a common ancestor in evolution.

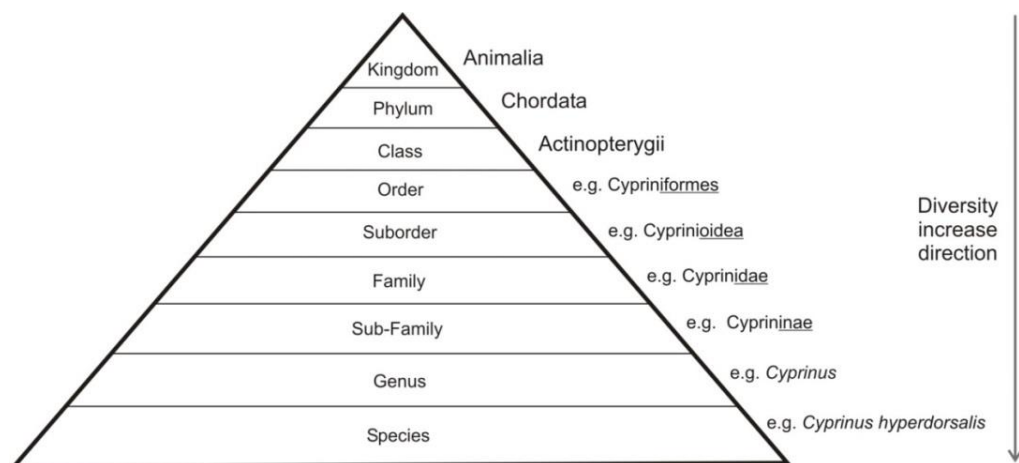


Figure 2.17: Taxonomic ranking and naming convention

Ray-finned fish which is reviewed in this study belongs to the Actinopterygii class under the Chordata phylum in the Animalia kingdom. Such is the ranking and principle of taxonomy practice used to organize all biological units. At time of this writing, some experts have arrived at some agreement and the “Family-group Names of Recent Fishes” published by Van der Laan et al. (2014) seems to be the most updated for family naming.

In fish taxonomy, there are established conventions for expressing taxonomic ranking. According to ICZN regulation, the family-group name must always end with the “idae” suffix (e.g., Cyprinidae) and the subfamily-group name must end with the “inae” suffix (e.g., Cyprininae). At a higher level, the order-group name should end with the “iformes” suffix (e.g., Cypriniformes) and the suborder-group name must end with the “oidea” suffix (e.g., Cyprinioidea). The family names are always capitalized but never italicized.

2.6.9 How species are named and why

In Latin, species means “a kind, appearance and quality”. Depending on locality, people have various vernacular and common names for a fish species. For example, the common names Pearl Gourami, Diamond Gourami and Mosaic Gourami all refer to the same species. Therefore, the use of common names can be confusing and misleading. However, its scientific name *Trichogaster leeri* is a unique name and there is no chance that the name may

be mistaken with other species. Ideally, a scientific name may even tell something about the species' key characteristics (Figure 2.18), its habit, discoverer and perhaps the location where it was first found.



Figure 2.18: The species name *Leptobarbus rubripinna* is derived from Greek word “leptós” which means thin or slender, and the Latin word “barbus” meaning barbel. Rubripinna originates from the Latin words “ruber” and “pinna” which mean red and fin, respectively

Another interesting example is the fighting fish species, *Betta persephone*, which is named after Persephone the daughter of Zeus in Greek mythology. Also known as the princess of darkness because she is said to rule the underworld, Persephone was the perfect epithet for *B. persephone* which typically inhabits the black water in peat-swamp habitats of Southeast Asia. Another fighting fish species the *Betta gladiator* need no further explanation as to why the epithet was given.

The *Kottelatia* genus (with only one recognized cyprinid species, *Kottelatia brittani*) was named after a prominent ichthyologist Maurice Kottelat, and a species that is named *Anguilla borneensis* tells us that it was first described from specimens found in Borneo Island. Those familiar with Latin or Greek, the traditional language used in scientific names, would also be able to tell that the catfish *Clarias leiacanthus* should have pectoral spines with smooth anterior edge; in Greek, “leios” means smooth and “akathos” means thorn.

The *Bihunichthys monopteroides* was named after a popular food in Southeast Asia; “bihun” is a local name for rice noodle and “ichtys” means fish in Greek. Sure enough, it is a very small and thin spineless eel that resembles rice noodles. From examples mentioned, a scientific name can be communicative and gives species stable and universal designations for easy retrieval.

The scientific naming that we practice today would not be possible without the foundation laid by Carl Linnaeus (1707-1778). Often confused by the many dialectal names during his specimen collection work in various countries, Linnaeus was convinced that species names must be standardized. In 1735, he published a small pamphlet titled *Systema Naturae* (The System of Nature) to introduce his new system of giving and organizing species names. Linnaeus also decided that species names should be given in Latin or Greek in two parts. Thus the binomial nomenclature system was conceived. Although

the Systema Naturae was meant for naming plants, it soon gained popularity due to its practicality and it was quickly adopted by taxonomists of various taxa.

The rule of binomial nomenclature dictates that the first part of species name comprises of its genus (noun) and it is always capitalized (e.g., *Cyprinus*). The second part is used to describe the species' attribute or epithet (adjective) and it is never capitalized (e.g., *Cyprinus hyperdorsalis*; “hyper” meaning “over” in Greek and “dorsalis” meaning the back part of the body in Latin). The first and second part is always italicized. However, if the neighbouring texts are italicized, then the first and second name would be non-italicized (e.g., *in mesohabitat that hosts an isolated Channa gachua population ...*). This is to ensure that the species name is outstanding and can be easily singled out during reading. When handwritten, species name should be underlined for the same reason. The first part may be used alone but the second part is never used by itself.

A species name must be written in full the first time it is expressed in a manuscript (e.g., *Cyprinus hyperdorsalis*) and thereafter the first part, or genus name, can be abbreviated with initial capital letter (e.g., *C. hyperdorsalis*) on the condition that there is no misconstruing with other genera (i.e., bearing in mind “C.” can also mean *Channa* or *Clarias* if these genera appear on the same paper). In cases where an abbreviated initial capital letter may cause confusion, two letters may be used (e.g., *Ch.* for *Channa* or *Cl.* for *Clarias*). There is no absolute rule and the objective is to avoid misinterpretation.

Additionally, “sp.” (singular) or “spp.” (plural) may be used to represent “species” to indicate partially identified species with the genus known. For example, when a specimen is recorded as *Cyprinus* sp. it denotes that a specimen of the *Cyprinus* genus cannot be identified to species level, possibly due to it being a small juvenile which makes positive identification difficult. For species with problematic identification, it may also be recorded with the term “cf.” added between the scientific names. It is simply a short term for “confer” or “compare with”.

For example, when a species is referred as *Rasbora* cf. *elegans*, it implies the species it most likely belongs to but the designation is still marred by unresolved taxonomic issues or more work is needed to be completely sure. Alternatively, the term “aff.” is sometimes added between the scientific name when a specimen cannot be matched to any species known to science, or it is a new species that is yet to be named. The term is a short form of “affinis” in Latin which means “akin to”. The insertion of “aff.” is to associate the possibility of a new species with the closest species (e.g., *Rasbora* aff. *elegans*).

It would be advisable to describe the genus, species, author and year in full when a species name is expressed as part of a manuscript title, or the first time it is written in the manuscript. The author(s)’ name(s) who first coined the binomial name and year of publication should be included (e.g., *Cyprinus*

hyperdorsalis Nguyen, 1991) because it is a good practice to ensure the manuscript author is explicitly referring to a species described by a particular taxonomist in a particular year. The author's name is typically enclosed in parentheses when the genus is no longer the original one used. Alternatively, the author's name is enclosed within parenthesis when a species has been transferred from the original genus in which it was first described; e.g. *Cyprinus melanes* (Mai, 1978). This puts the author and the reader in a safer position because literature that adopts fish as a subject can be flawed by synonyms and obsolete species' names. It should be noted that the author citation is treated differently in various taxa. Also, when submitting a manuscript for peer review, it would be wise to countercheck the journal's submission instructions on how to quote the target species.

2.6.10 Species identification at the morphological level

Since humans learnt how to hunt fish, species were identified based on some simple anatomical features. Observation of specimen anatomy and differentiating fish species based on their morphological features is the most practical, rapid and low cost method. Besides experienced local fisherman and fish mongers, people who live by the river or wetland would learn to identify fishes at a young age. This is due to knowledge and memory acquired from long-term observation or through oral tradition maintained by elders. Such traditional knowledge has been interweaved into modern ichthyology by many researchers (Calamia, 1999; Drew, 2005; Stacey et al., 2008; MacLean et al.,

2009; Ferreira et al., 2014), and the term for it is “traditional ecological knowledge” (TEK) (Berkes et al., 2000). For those keen in taxonomy, however, there is a need to adopt a more precise and sound approach.

Fish identification is the most important component in any fish-based study and acquiring reasonable competency always begins with the study of fish anatomy. Fundamentally, fish species have to “go with the flow”. It is apparent that the anatomy of fish is shaped by the physical properties of water, the essential liquefied medium in which the fish adopts as habitat. Water is dense but holds relatively small amounts of oxygen which affects fish respiratory function. Water also absorbs light in higher intensity than air which affects fish visual capacity. Water can flow fast or not at all, and this affects how fishes manoeuvre in water. Such a complex and fluid environment calls for special adaptations to live in and fishes have evolved precisely to fit in.

In general, most biological adaptations in fish occur in the body, mouth, fins, skin coloration and reproductive traits. The body of a bony ray-finned fish comprises of three sections; the head, trunk and caudal or tail. The head is a region from the mouth tip to the posterior edge of the gill cover. The trunk contains the abdominal cavity and it forms the main body that lies between the head and caudal (Figure 2.19). In most species, the trunk is narrowed down at an area called the caudal peduncle where it is connected to the caudal fin, which is a prominent feature on the body of a fish.

Body flexure attained by contractions of the myomeres and thrust from fins is responsible for fish propulsion. Fin shapes and sizes vary tremendously and they are used for stabilizing, reversing, stopping, descending, ascending and manoeuvring. In morphometric (Figure 2.20 and Figure 2.21) and meristic identification of fishes, the positions of fins, numbers and types of ray or spine composition are useful (Figure 2.22, Figure 2.23 and Figure 2.24).

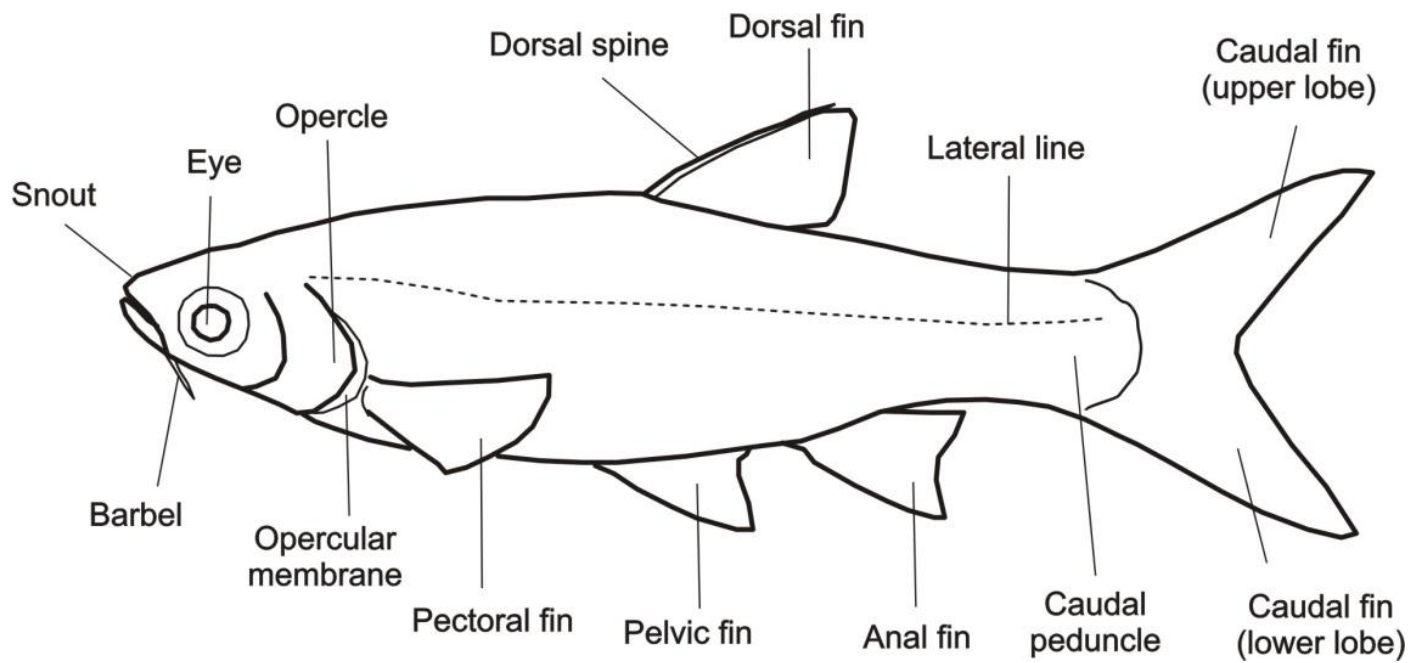


Figure 2.19: An example of key morphological features of a species from the Cyprinidae family (Rainboth, 1996)

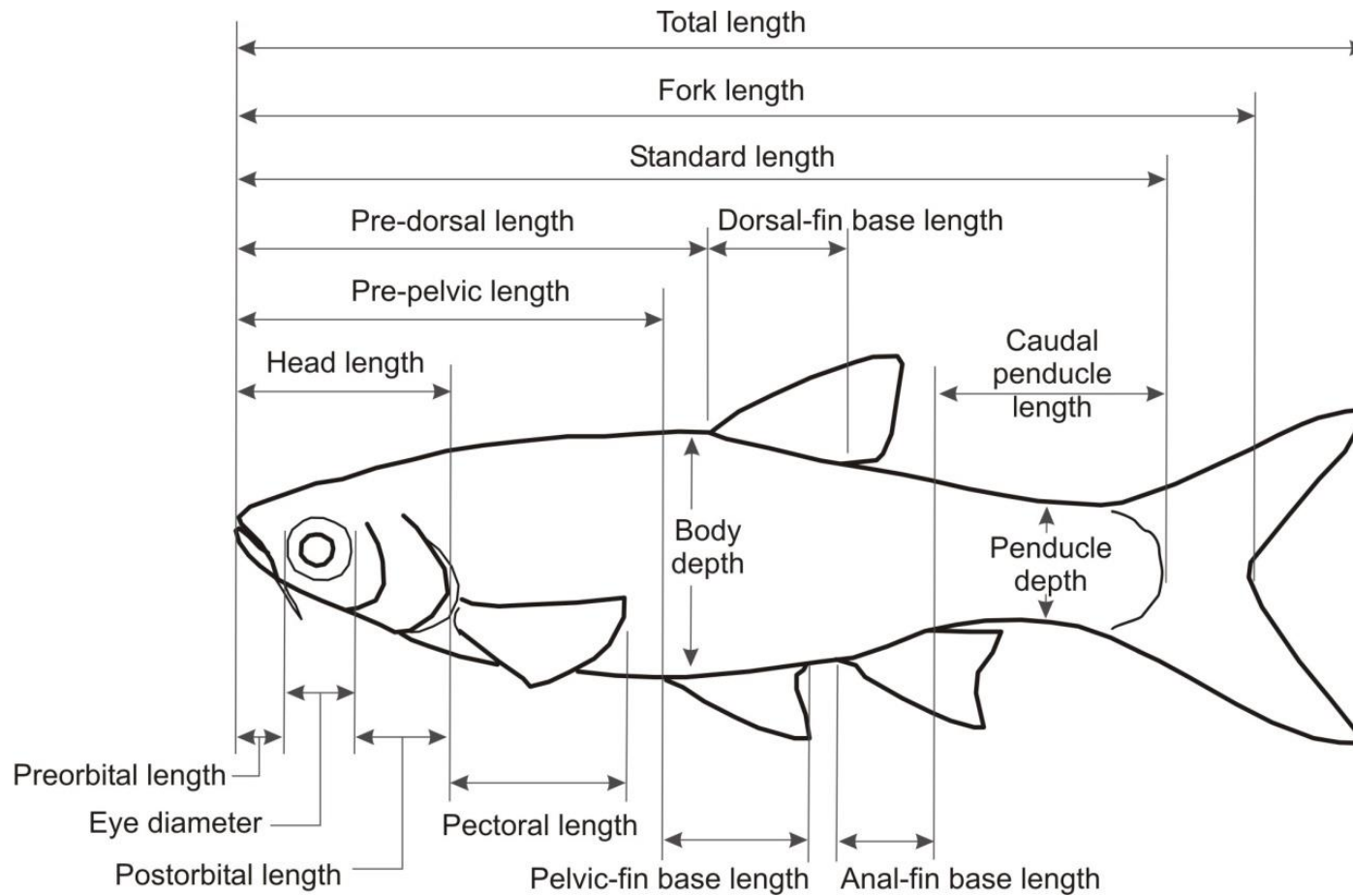


Figure 2.20: Common morphometric data collected for fish identification (Rainboth, 1996)

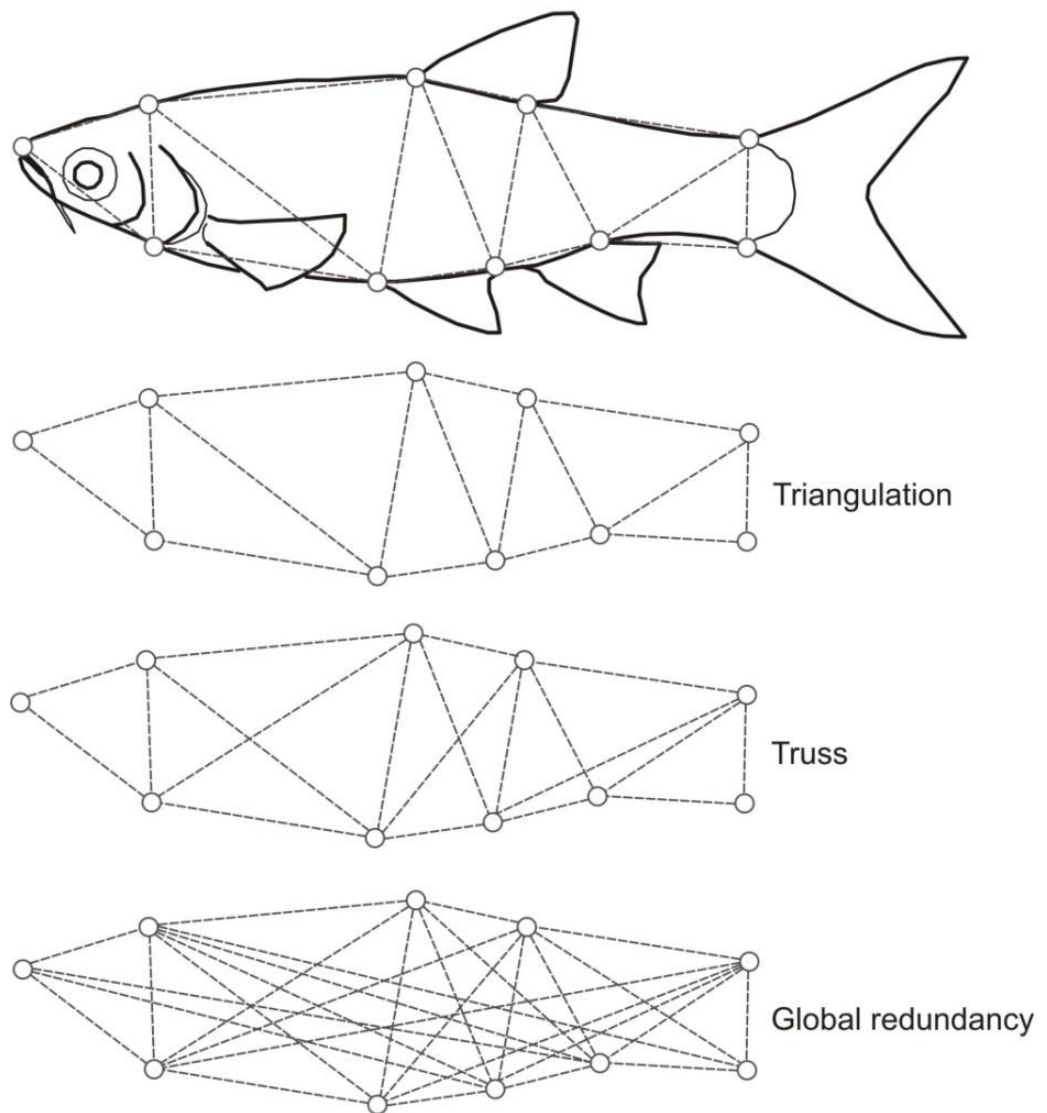


Figure 2.21: Common measurements between key points to construct patterns to quantify morphometric variance between species (Strauss and Bookstein, 1982)

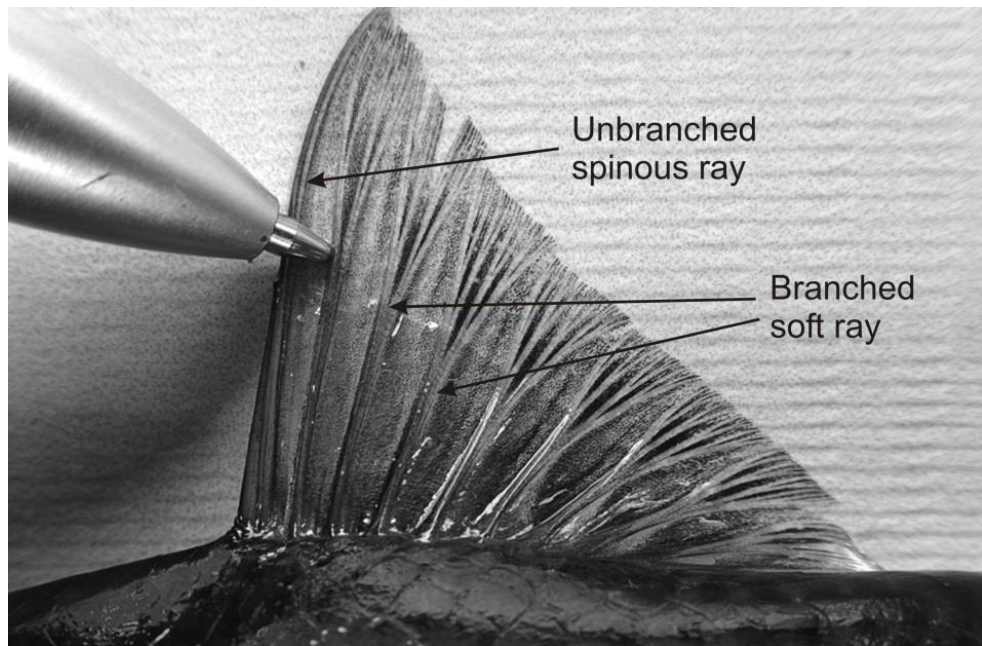


Figure 2.22: A close-up view of fin rays which epitomises fish under the Actinopterygii class

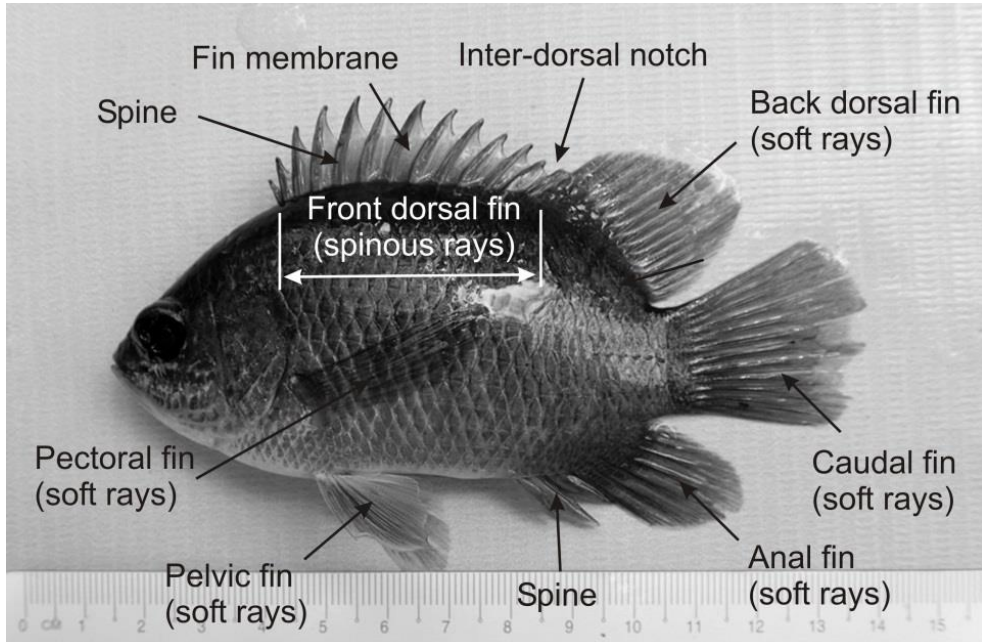


Figure 2.23: An example of fin positions and ray structures of a fish with a contiguous dorsal fin



Figure 2.24: A specimen from the *Gastromyzon* genus with specialized suctional pectoral fins and fused pelvic fins for adhering to substratum rocks in riffles

There are two fundamental types of fin rays, namely the true spinous rays and soft rays that form the framework for fins. Spinous rays are stiff and typically unbranched, and they are located in a single fin's anterior part while soft rays consist of longitudinal supports and are typically branched. Even so, there are exceptions. Some species like the *Silurichthys indragiriensis* and *Wallago attu* propel themselves forward or backward by wavelike flexure of long anal fins. Ichthyologists call these fins “ribbon-fins” (Curet et al., 2011), and what makes them so special is that the entire stretch of the anal fin is actuated by muscles along the body length. In eels, a ribbon-fin may be present but the caudal fin is almost absent and they rely mostly on snake-like rectilinear locomotion for swimming.

Most bony fishes have homocercal caudal fins that can be forked, rounded, truncated, and other symmetrical and non-symmetrical forms (Figure 2.25). Generally, fishes with tapered body and fins are proficient in high-speed propulsion in fast flowing waters while fish with rounded body and fins are associated with low speed movement in slow waters.

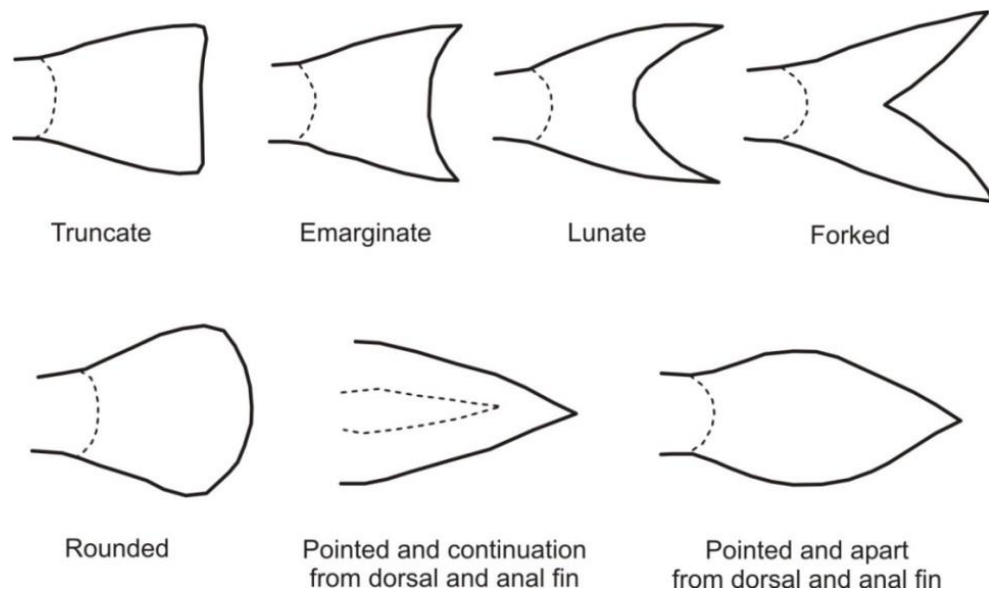


Figure 2.25: Common caudal fin shapes (Rainboth, 1996)

Mouth form and position also vary greatly among fishes (Figure 2.26). In most fishes, the mouth is located terminally at anterior tip of the head (e.g., *Pristolepis* spp. and *Oreochromis* spp.), but in some others it may be inferior (beneath the snout, e.g., *Pangio* spp.) or superior (upturned, e.g., *Belodontichthys dinema*) depending on their feeding habits. Generally, terminal mouths belong to species that prefer to bite or seize their prey while those with inferior mouths are bottom feeders. Insectivorous fishes

such as the archer fish (*Toxotes* spp.) typically have superior mouths and they feed on insects that fall on the water surface. Some freshwater species like the river pipefish of the genus *Doryichthys* have a tubular mouth to suck food from crevices.

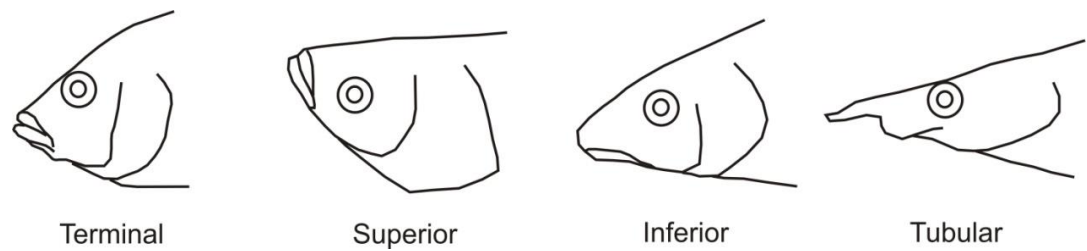


Figure 2.26: Common mouth types

Most fishes have protective scales which vary greatly in size, structure, squamation (scale coverage), arrangement, sequence and colouration. Scientifically, scales of teleost fishes can be classified into the placoid, cosmoid, elasmoid and ganoid categories (Sudo et al., 2002). Teleost scales possess outstanding hydrodynamic properties and provide a resistant layer to protect fishes from injury (Bruet et al., 2008). Scaled skin is also known to play a critical role in supporting fish locomotion by synchronizing wave propagation (Long et al., 1996), and by accumulating potential energy like tendons (Hebrank and Hebrank, 1986) for swimming efficiency. As expected, scale counts are crucial for fish identification (Figure 2.27). Some genera such as *Clarias*, *Mystus* and *Ompok* are without scales, but they are no less vulnerable. The skin of scaled and scaleless

fishes also secrete mucus to function as a sealant or protection against infection, and to reduce hydraulic friction while swimming.

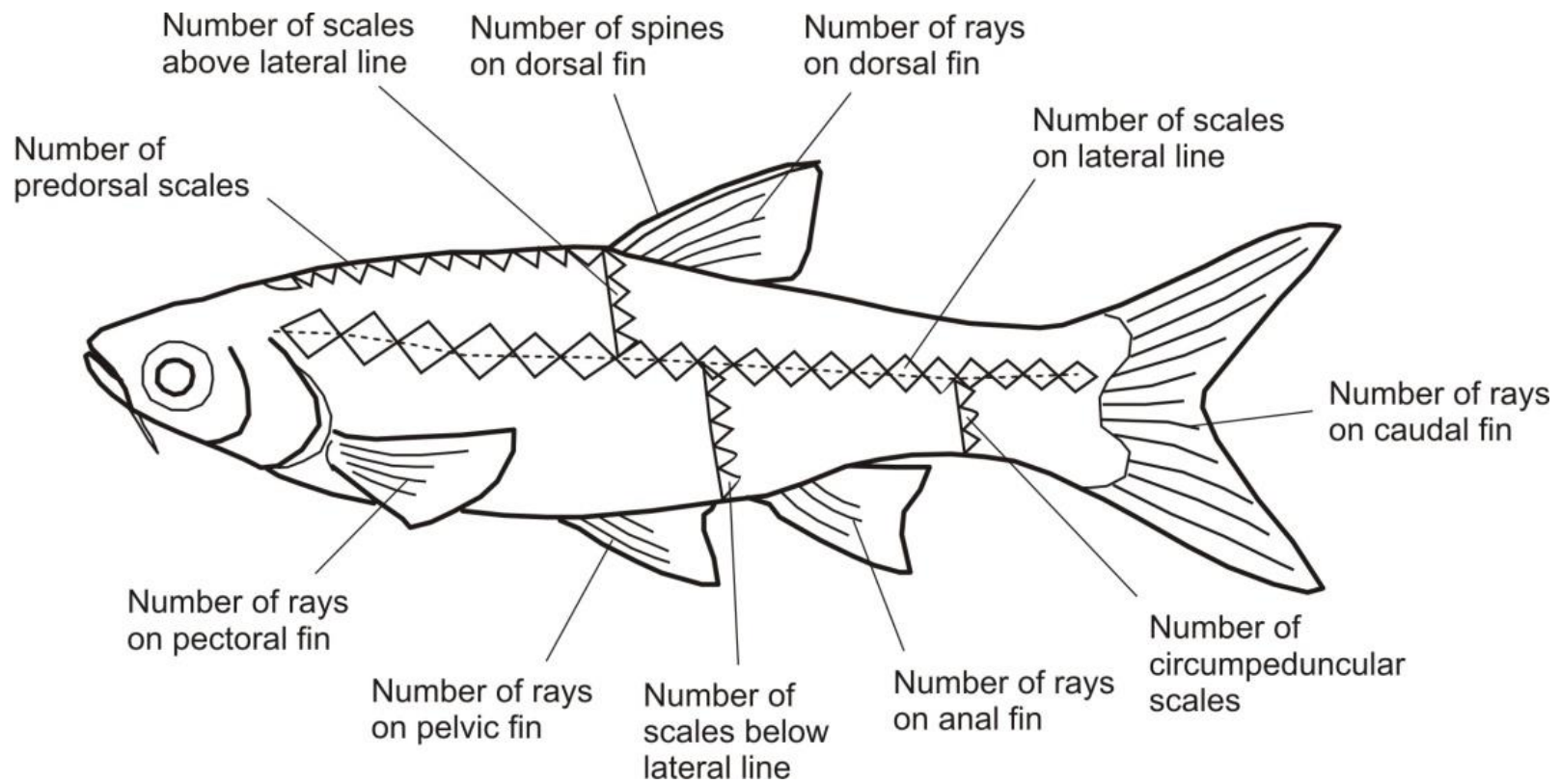


Figure 2.27: Common meristic data collected by taxonomists (Rainboth, 1996; Ambak, 2012)

Evidently, some of the most interesting features of fishes are their pigmentation patterns which can be used as critical references for taxonomic identification purposes (Figure 2.28). Body colouration is indeed an interesting subject in the context of fish as a biological indicator. Like all animals, fishes cannot synthesize pigments. They have to ingest colourant pigment like carotenoids from the food they consume within their habitats, and these can include fruits, insects and phytoplankton (Grether, 2000). This can reflect their foraging tendencies, habitat health and especially the presence of insect diversity as a rich source of pigments. Many studies have shown that fish mating behaviour is affected by pigment availability from feeding habitats and this, in turn, affects mate choice and population abundance (Endler, 1980; Basolo, 1990; Houde, 1997; Blount et al., 2003).

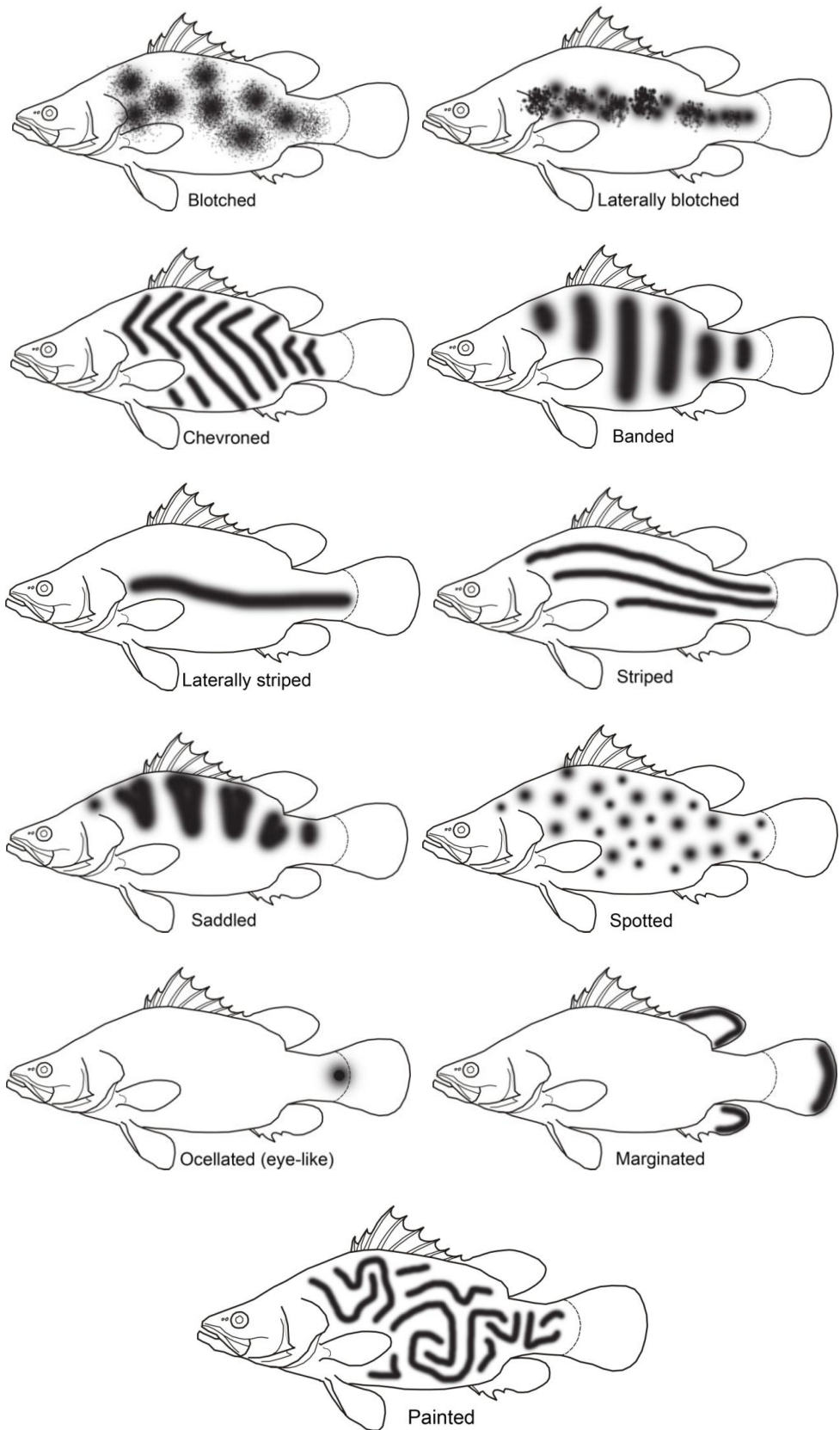


Figure 2.28: Common terms used to describe body markings and patterns on a representative teleost

The fundamental colour constituent in fishes is the dermal chromatophore unit (pigment cell) which consists of the: 1) melanophore which contains melanin (browns, blacks, and greys), 2) xanthophore and erythrophore which harbour carotenoids (yellows, orange and red), and 3) iridophore, or sometimes termed as iridocyte, which naturally reflects external light source and provides fishes their iridescence (Hawkes, 1974; Fujii et al., 1989; Metz et al., 2006). Chromatophores can naturally contract or expand to induce or change colours to blend into the aquatic environment for camouflaging purposes. In some cases, a combination of chromatophore units can produce interesting colours. For example, in the Siamese fighting fish (*Betta splendens*), a wide variety of bodily colours can be exhibited by the permutation of iridophores, melanophores, erythrophores and xanthophores (Khoo et al., 2012; Khoo et al., 2014).

It must be cautioned that identifying species by their body colouration and patterns alone is not entirely robust. In certain cases, individuals in a natural population may be affected by genetically inherited conditions that cause them to exhibit albinism, leucistic, melanistic and xanthic abnormalities. Albino individuals such as *Silurus glanis*, *Astyanax mexicanus*, *Hydrolagus colliei* and *Genidens planifrons* have been reported (Dingerkus et al., 1991; Jeffery, 2006; Reum et al., 2008; Leal et al., 2013) and these individuals are unable to synthesize tyrosine and melatonin hormones partially or fully (Slavík et al., 2016). Individuals affected by albinism are typically pale, light pink, white or yellow (Lechner and Ladich, 2010). Their eyes are generally pink because blood is seen through the colourless retina (Van Grouw, 2006).

Conversely, leucism is a condition characterized by the reduction or absence of most, if not all, of the pigment cell types. Leucotic individuals are generally pale, white or yellow but they exhibit normal retinal pigmentation (Quigley and Wallace, 2013). Melanism is the exact opposite of albinism where excessive development of dark-coloured pigment melanin occurs and the affected individual is typically dark brown or black (Regan, 1961). It is a form of polymorphism that is widespread in fishes, and it may be genetically determined and/or influenced by the environment (Price *et al.*, 2006). For example, melanin polymorphism has been reported in *Gambusia holbrooki*, *Siphateles bicolor mohavensis* and *Amphilophus labiatus* (Horth, 2002; Henkanaththegebara and Stockwell, 2011; Sowersby *et al.*, 2014). When an individual exhibits abnormal deep yellow, orange or reddish pigmentation on the body, this is attributed to excessive development of the xanthophores and erythrophores (Khoo *et al.*, 2012). Xanthic variety of the *Cyprinus carpio* and *Carassius auratus* with red, orange and yellow pigmentation were first reported and domesticated in China and Japan as ornamental species (Kajishima, 1977; Balon, 1995).

Wild individuals from species such as *Cyprinodon bifasciatus* have also been found to be xanthic (Carson 2011). On the other hand, an axanthic individual that lacks xanthophores may be black, white, and/or blue (Lewand *et al.*, 2013). For example, Parichy (2006) reported that axanthic individuals have been found in species from the *Danio* genus.

Being fully aquatic, fishes have vastly different sensory systems when compared to those of terrestrial vertebrates. In fact, they are endowed with more sensitive and complex sensory organs to detect vibration and sound. Fishes possess the cephalic-lateralis system (Nelson, 1972) that comprises a series of neuromast sensory cells that run across the outer layer of the head and body (Figure 2.29).

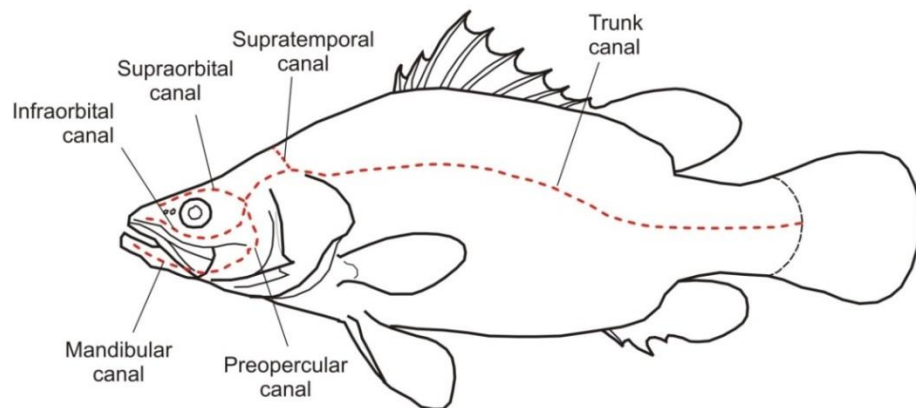


Figure 2.29: An illustration of the fish cephalic-lateralis system consisting of neuromast sensors that run across canals on the head and body (Nelson, 1972; Iwata and Jeon, 1995)

The neuromast contains fine hair cells oriented in a manner to detect the direction of vibration. Vibration signals are then transmitted through special canals and pits containing endolymphic fluid to amplify the signals and thereafter pass on to the brain. The location of the lateralis system in fish can reflect their feeding habits. Bottom feeders tend to have the lateralis system on top of the body to detect vibration from predators that are lurking above. Those which feed on the water surface normally have the system along the ventral margin of the body to track the presence of predators below. Studies have also

shown that the lateralis system is responsible for obstacle avoidance, triggering startle response and schooling synchronization (Partridge and Pitcher, 1979). The patterns and configuration of cephalic-lateralis system on fish bodies are sometimes used for fish identification such as those from the *Kryptoglanis*, *Pseudorasbora* and *Caecieleotri* genus (Moncey, 2012; Kawase and Hosoya, 2015; Walsh and Chakrabarty, 2015).

In the case of cryptic species when the species are too difficult to be differentiated because they show small external anatomical and morphological deviations between species in the same genus, ichthyologists have relied on the internal organs to characterise them (McCune, 1981).

Where necessary, gill rakers from the first gill arch on the left side of the body are also counted for meristic characterization such as species from the *Coregonus*, *Garra* and *Labeo* genus (Amundsen et al., 2004; Ayoade et al., 2004; Krupp and Budd, 2009). Correspondingly, in some species, the pharyngeal teeth found on the fifth gill arch are counted from left to right to assist in meristic identification of species such as those from the *Moxostoma*, *Cycleptus*, *Danio* and *Epalzeorhynchos* genus (Eastman 1977; Pasco-Viel et al., 2010).

All teleost fishes have an inner ear as an auditory system. Instead of bony ossicles, fishes have three pairs of calcareous “ear stones”, or scientifically termed as otoliths (Greek for “ear stones”). The lapillus (“little

stone” in Latin) functions in maintaining body balance and orientation, and the other two, namely asteriscus (“little star” in Latin) and sagittal (“arrow” in Latin), peruse acoustic reception. Otoliths are enclosed in a membranous sac together with sensory hair cells or ciliary bundles. Detection of mechanical signals will occur when there are dynamic interactions between otoliths and cilia (Assis, 2003; Campana, 2005). Since Koken (1884) reported that fish species can be characterised by having otoliths of different shapes and sizes, otolith morphometry is fast becoming a trend to identify fishes and some species such as *Netuma bilineata*, *Nuchequula nuchalis*, *Coilia dussumieri* and *Garra rufa* (Chen et al., 2011; Thuy et al., 2015; Salimi et al., 2016; Yedier et al., 2016). In 2006, the AFORO online database was launched (<http://www.cmima.csic.es/aforo/>) to archive and share Fourier spectrum (FFT), wavelet analysis (WT) and curvature scale space analysis (CSS) data of otoliths (Lombarte et al., 2006). At time of this writing, the AFORO archive contains 4,672 high resolution images of 1,441 species from 221 families for reference.

2.6.11 Species identification at the molecular level

Morphological characterization is not entirely robust. As mentioned earlier, the concept of “species” is still subjected to debate and not all taxonomists assign meaningful categories to organisms by morphotype. In many cases when certainty cannot be attained, researchers use terms like “subspecies”, “strain” or “variant”. These are highly subjective and confusing. In fish especially, morphological plasticity between individuals of the same species is inherent.

For example, body colour tones and polymorphism exhibited by individuals of the same species may vary considerably depending on the diet regime, habitat and season such as species from the *Betta*, *Poecilia* and *Danio* genus (Khoo *et al.*, 1997; Price *et al.*, 2008). And this is where molecular analysis has become a viable alternative.

Each organism is characterized by a unique set of biological attributes that enhance its fitness to survive in a niche environment. Correspondingly, to adjust to any changes in the environment, an organism is naturally subjected to genetic drift, mutation or variation (polymorphism) as a mechanism to adapt. Such natural phenomenon provides markers at molecular level to detect individual or species uniqueness (Sanger *et al.*, 1977). All molecular methods depend on DNA marker or protein sequence analysis and comparison to determine molecular divergence over evolutionary time based on the null hypothesis of molecular evolution, or better known as the “neutral theory” (Kimura, 1968). Essentially, all methods assume that individuals from the same species have specific DNA (or protein) sequences that vary, to a certain extent, from individuals that belong to other species. Nonetheless, the variance, or “signature” of speciation (Sbordoni, 2010), is dependent on time and space and subjected to biological productivity of individuals, dispersal pattern and natural genetic drift. Therefore, genetic variability also occurs among individuals of the same species. This means establishing a credible locus, or the position of a gene (Khoo *et al.*, 2011) from a phenotype is a prerequisite as master reference for comparison purposes.

DNA markers can be classified in two different types, namely type I which are markers associated with genes with known function and type II which are markers are with anonymous genomic segments (Chauhan and Rajiv, 2010). For example, allozyme markers are classified as type I protein markers and microsatellites and other neutral markers are considered type II (Hinsinger et al., 2015). The DNA in all organisms is a composition of four chemical bases – adenine (A), guanine (G), cystosine (C), and thymine (T) (Avisé, 1994). Their order or sequence in each gene is unique to every species. Since Razin and Rottem (1967) have successfully employed protein analysis for characterising microorganism species, modern advances have adapted the concept of analysing A-G-C-T bases in various DNA genetic markers. In fish identification, the common DNA analyses applied are length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), random amplified polymorphic DNA (RAPD), microsatellites or simple sequence repeat (SSR), single nucleotide polymorphism (SNP) and expressed sequence tag (EST) markers (O'Reilly and Wright, 1995; Khoo et al., 2003; Sampaio et al., 2003; Teletchea, 2009; Chauhan and Rajiv, 2010; Khoo et al., 2011; Kress et al., 2015).

Fish genome typically contains roughly a billion nucleotide pairs (Stepien and Kocher, 1997), and analysing all of them would be too tedious and the results would cause an information overload. Since Herbert et al. (2003) discovered a technique to amplify the mitochondrial cytochrome c oxidase subunit 1 (COI) gene, there is now a consensus to analyse a 648-base pair (bp) region of COI to rapidly identify a fish species (Cawthorn et al.,

2012). Such an approach is now known as DNA barcoding and it has gained widespread acceptance as a fast, cost effective and standardised technique. So far, the Fish Barcode of Life Initiative has barcoded 7,882 fish species, which is only approximately 25% of the estimated 31,220 species present globally (Jinbo et al., 2011).

It should be stressed that identified species through DNA barcode is only as good as the voucher specimen's DNA barcode made available and archived in platform such as GenBank. Hence, if a DNA barcode is inaccurate or compromised due to issues such as carryover DNA contamination, incomplete genotyping of loci throughout the genome, low/wrong quality DNA material, human errors, biases and some other critical risks (Bridge et al., 2003; Forster, 2003; Moritz and Cicero, 2004; Smith and Burgoyne, 2004; Ebach and Holdrege, 2005; Meyer and Paulay, 2005; Will et al., 2005), the identification process would be erroneous. Ross et al. (2008) proposed that reference sequences of at least five or more voucher specimens from various geographical sites should be acquired. Unfortunately, this also means that DNA analysis is not a one minute procedure. To conduct it properly, the process of acquiring exemplar genotypes is tedious and costly because some species are found over large regions and various countries.

In the recent years, DNA sequencing techniques have made substantial progress and they are able to analyse 30 to 1,500 nucleotides (nt) for hundreds of thousands to millions of DNA molecules in a single process within a complex or degraded DNA source (Davey and Blaxter, 2011; Mehinto et al.,

2012). These are classified as next-generation sequencing (NGS) technologies (Tillmar et al., 2013) and sometimes termed as "DNA metabarcoding" to refer to their ability to automatically identify multiple species from a single bulk sample (Taberlet et al., 2012). Because NGS technologies can extract massive numbers of reads, the results increase the chances of finding and annotating matches (Hemmer-Hansen et al., 2014). So far, technological platforms that are able to produce and analyse gigabases of DNA sequence include Illumina, Roche, AB SOLiD, 454 GS FLX, Ion Torrent, HeliScope, Starlight and PacBio (Rothberg and Leamon, 2008; Pandey et al., 2008; Davey and Blaxter, 2011; Hemmer-Hansen et al., 2014). They differ from each other based on amount of sequence information generation, chemistry protocol for sequencing and the length of sequence read (Mehinto et al., 2012).

2.6.12 Reference type and traceability

The hallmark of the taxonomy discipline is its persistency in collecting, preserving and managing specimens as essential physical references for species-level research. Although ecologists, conservationists, aquaculturists or researchers who adopt fish as a part of their studies need not master the specifics in specimen management, it is useful to briefly understand the ICZN zoological code and terms as a precaution against negligence when tracing the correct binomial nomenclature and description of fish.

Fundamentally, in taxonomy, a “type” is a specimen of a distinct species which is used as master reference (Krell and Wheeler, 2014). Each species or subspecies that is scientifically named by the original author (discoverer) is traceable to a name-bearing specimen which was first found and kept in a particular museum. A new species cannot be described and registered formally without depositing a single physical whole fish known as a “holotype” in the museum (Clemann et al., 2014; Kumar and Hassan, 2015). As sexual dimorphism occurs in many fish species, it is good practice to deposit an opposite sex specimen of the holotype and it is assigned as an “allotype” (Jorge et al., 2014). Also, polymorphisms may occur in certain fishes and a holotype is not expected to be a typical representative (Hulsey, 2005), although in an ideal case it should be. To mitigate this, morphotypes that show morphological variants of a species can be established, and molecular analysis is usually carried out to determine whether the variations are due to polymorphism or if it is a new species (Simonov, 2008).

A researcher may also designate a duplicate specimen of the holotype and such a specimen is termed as an “isotype”. When a better specimen is eventually deposited, the holotype is not superseded. According to the ICZN code, such a specimen which provides better clarity is known as an “epitype” and it may be deposited when the holotype is evidently imprecise. In the case when a holotype is lost or damaged, a “neotype” specimen may also be deposited as replacement. While there can only be one holotype, taxonomists can continue to deposit specimens in any museums around the world for the type series (a range of specimens showing variation in the species). These

comparable specimens are termed as “paratypes” and they have no name-bearing role.

In situations when the researcher fails to establish a holotype, the existing two or more specimens collected and deposited in the museums can be used to describe and name a species. These deposited specimens are known as “syntypes” although such practice is now rarely used in contemporary taxonomy. A master reference specimen selected from syntypes is termed as “lectotype” and when a lectotype is finally established, all other syntypes shall be, by default, reassigned as “paralectotypes”. Correspondingly, any duplicate specimen of the lectotype is called an “isolectotype”. Finally, specimens that have been erroneously described, named or labelled are annotated as “non-types”. All terminologies pertaining to types mentioned in this section are elaborated in detail by ICZN at the website <http://www.iczn.org/iczn/index.jsp>.

The responsibility rests on the taxonomist to maintain the specimens and make them accessible for current and future studies (Krell and Wheeler, 2014; Rocha et al., 2014). To consolidate a large quantity of voucher specimen database in a museum, the taxonomist is also expected to occasionally publish monographs that contain summarised information of all species in a group to update the scientific community (Grinnell, 1910; Pyke et al., 2010; Kottelat, 2013).

In the advent of technological advancement, non-destructive methods such as high-resolution photography, computerised tomography (CT) scan and radiography methods that can record the physical characteristics of specimens, the work of a taxonomist has expanded over the years. There are already attempts to digitalize specimens using these technologies. For example, Berquist et al. (2012) have progressively scanned specimens with the magnetic resonance imaging (MRI) technology and created an online digital archive called Digital Fish Library (DFL, <http://www.digitalfishlibrary.org>) to share high-resolution and high-contrast visual data. The Biovisualization Center at the University of Washington has also just initiated a program that applies the CT scanning technology and the captured 3D morphology data of fish specimens is shared through the Open Science Framework website (<https://osf.io/ecmz4/wiki/Fishes/>). Such innovations have the potential to replace pale and degraded voucher specimens that have been preserved for a long period of time in alcohol. Morphological and meristic database compilation can be instantly peer-reviewed and shared online with any amateurs or experts located anywhere around the world. This is an opportunity for scientists to engage more with the society and garner support from the public and policymakers for fish conservation.

2.6.13 Specimen collection and preservation

In principle, a scientific finding must be reproducible. When an author declares and publishes the description of a new species, a specimen (i.e. holotype) must be deposited permanently in the museum so that the author's claim can be

critically appraised and reappraised by others (Rocha et al., 2014). The specimen can be refuted or disputed by other ichthyologists to allow for revisions. Similarly, when a researcher conducts a fish inventory investigation that results in a scientific or journal report, it is a good practice (although not compulsory) to collect voucher specimens for future verification and to promote transparency. This approach also provides physical records that allow researchers to scrutinize the inter- and intraspecific variation of species collected at different periods of time and localities.

Specimens are typically acquired by various capturing methods as discussed widely elsewhere by literature such as by hand-nets, traps, seine nets, electrofishing and even by buying directly from fishermen or the local fresh markets. Once obtained, they must be immediately labelled with 1) serial number, 2) species name, 3) name of collector, 4) location, 5) date of collection, 6) GPS coordinates, and 7) some description of the specimens' colour and body markings in fresh should be recorded (Fischer, 2013; Motomura and Ishikawa, 2013). This may be supported by high resolution photographs of the whole fish and specific parts with distinctive characters (Figure 2.30, Figure 2.31 and Figure 2.32). Specimens should be cleaned and can either be frozen or immediately fixed in formalin or alcohol before being transferred to depositories.



Figure 2.30: Fresh specimen is photographed facing left together with a ruler to indicate scale



Figure 2.31: A live specimen is best photographed with high-resolution photography to record subtle details and colouration



Figure 2.32: Noticeable variations of the same species should be photographed for species-level studies. For example, in the case of *Tor tambra* (above), individuals in the same population may display differing forms of mental lobe and barbels

In fish taxonomy, the left side of the fish body is examined. Therefore if muscle tissue is required for molecular analysis, it should be dissected from the right side of the body. In small fishes where muscle tissues are difficult to excise, the right pelvic fin may be collected as an alternative (Shiozawa et al., 1992). Typically, 1.0 cm³ tissue from the fresh muscle contains enough genomic material for molecular study and it should be stored in 95% alcohol and then refrigerated at -20°C (Motomura and Ishikawa, 2013). Preferably, it should be free from fat and blood which may hamper the DNA purification process (Wong et al., 2012). Chakraborty et al. (2006) suggest that in the absence of refrigeration during field work, specimens fixed in 10% buffered formalin or 95% alcohol should be analyzed with DNA processes within one week to produce the best results.

In the museums and depositories, taxonomists are cautious when fixing and storing specimens (Figure 2.33) since any flaw in the process will devalue their academic significance. Specimens are usually fixed in 10% formalin solution and large sized specimens are incised on the right side to enable better absorption of formalin (Schander and Halanych, 2003; Garrigos et al., 2013). For the same purpose, formalin may also be injected into the abdomen by using a syringe (Motomura and Ishikawa, 2013).



Figure 2.33: Fixed specimens are usually stored in glass jars with heads pointing downwards. Note that specimens become pale and lose their colouration quality, which is why photography of live specimens is crucial as part of the data collection process

2.6.14 Taxonomic key

After fixing, labelling and cataloguing a specimen, a competent taxonomist would carry out the standard morphometrics, meristics and sometimes molecular analyses as mentioned earlier. As a minimum, the taxonomist would subsequently generate a report with the following information (Fischer, 2013) for each species;

1. Species name, author and year.
2. Material examined – description of type material and voucher specimen examined.
3. Diagnosis – description of the specimen's key markers or morphological features that differentiates it from nearest congeners from the same watershed and other watersheds. Diagrams may be included for clarity.
4. Description – description of major morphological and meristic data.
5. Pigmentation in life – description of colour, marking and patterns on the body and fins of a fresh specimen.
6. Colour in formalin or alcohol – description of colour, markings and patterns on the body and fins of the fixed specimen.
7. Distribution – description of location where the specimen and the species can be typically found according to published literature.

8. Etymology – description of the Greek/Latin word or rationale behind the scientific name (binomial nomenclature) assigned to the species.

9. Field notes – description of sympatric and syntonic species found in the same habitat when the specimen is collected.

10. Remarks or comments – description of precautions as a measure against misidentification and any other useful information for effective identification.

If a potential new species is encountered, the specimen and full-colour photographs are to be sent to an authority of the genus for further investigation. This shall be recorded in this section.

A competent taxonomist would update the field “taxonomic key” for the corresponding genus once a new species has been identified. It is a conventional tool meant for quick and practical identification based on the major morphological characters (Figure 2.34) of a species (Fischer, 2013).



Figure 2.34: The key characteristics of a genus are typically described at the start of the taxonomic key. For example, the *Glyptothorax* genus's key characteristic is the presence of a unique thoracic adhesive apparatus (arrow) that can only be observed in the ventral view

A typical taxonomic key is organized in a series diagnostic characteristic of a species that lead the user to the correct name of a given specimen. A taxonomic key is called a dichotomous key (in Latin “dichotomous” means in two parts) because only two marker options are offered in each step (Figure 2.35). The markers provided may be quantitative (e.g., scale count) or qualitative (e.g., body colour). Once created, the key can be continuously improved by taxonomists based on feedback from users.

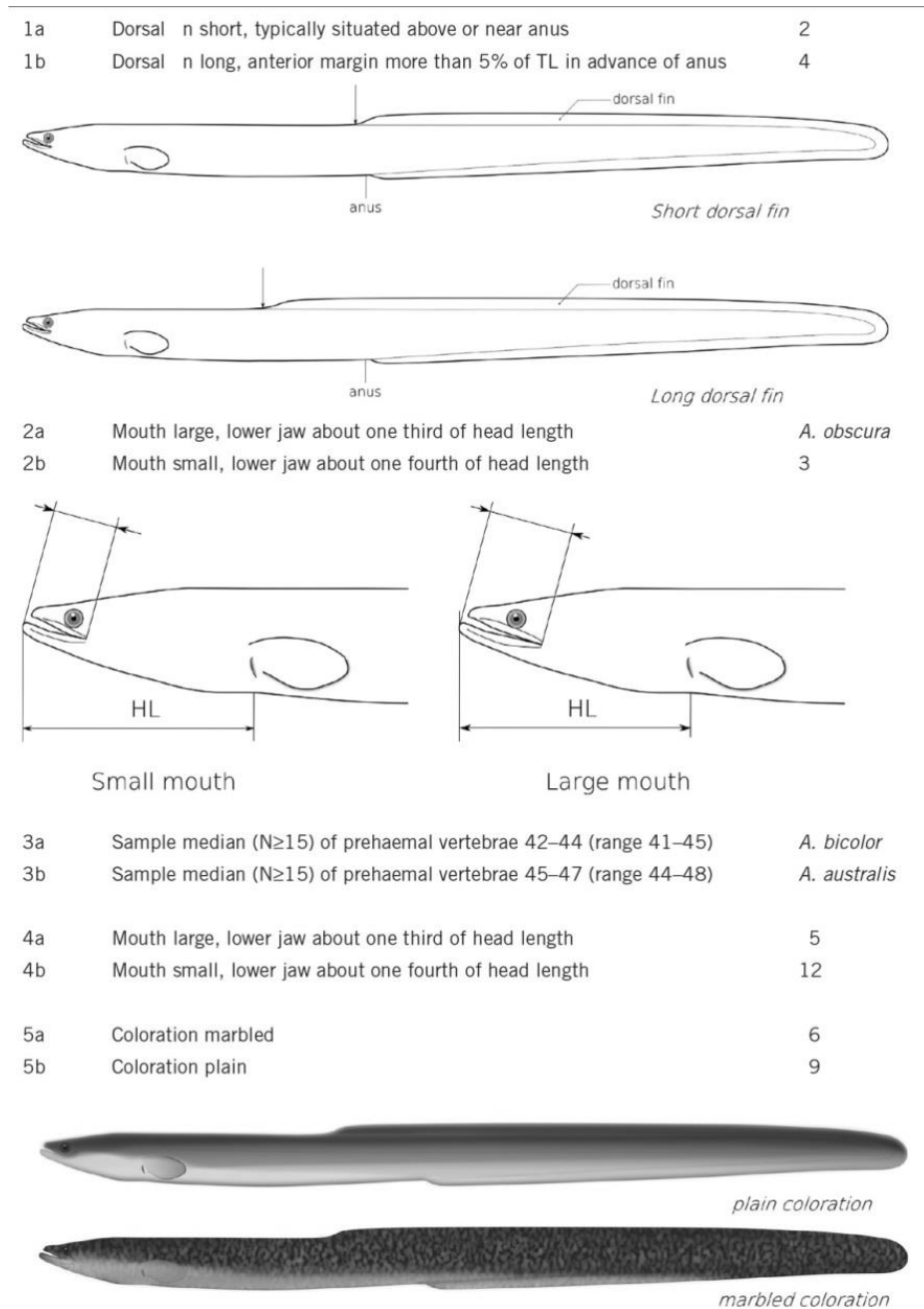


Figure 2.35: An example of a dichotomous key produced by Silfvergrip (2009, p.25) for the identification of freshwater eels from the Anguillidae family

2.6.15 Integrative taxonomy

There are species within the same genus that possess small variations that are not easy to discriminate. This is compounded by the unstable and convoluted taxonomic history of some species which can experience numerous revisions of species names because taxonomists may not share the same assumptions and approaches. Correspondingly, it is fair to expect that the science of taxonomy and systematics is constantly in flux and revisions may be frequent.

A classic example is the case of *Neolissochilus* spp. and *Tor* spp. found in Southeast Asia. These genera are typically prone to trophic polymorphism and display conspicuous oral morphology variation (Roberts and Khaironizam, 2008) that have confused even the most experienced ichthyologists. For example, in early 20th century, members of the *Neolissochilus* genus were placed in the *Barbus* genus (Boulenger, 1893; Duncker, 1904). Later they were reassigned respectively to *Labeobarbus*, *Crossochilus*, *Puntius* and *Acrossocheilus* (Weber and de Beaufort 1916; Ahl 1933; Fowler 1934; Herre and Myers 1937; Smith 1945) before being finalized as *Neolissochilus*, a new genus created by Rainboth (1996).

In cases when the taxonomy of a particular genus has stabilized, misidentification can still be common because small variations can be difficult to be distinguished. For example, in the past decades, there were numerous reports that highlighted misidentification of the freshwater eels from the

Anguillidae family due to species and subspecies from the family have sympatric distribution and the morphological characters among them are hard to distinguish (Castle and Williamson, 1974; Aoyama et al., 2000; Arai and Wong 2016). For example, Sugeha and Suharti (2009) found difficulty in distinguishing *Anguilla bicolor bicolor* and *Anguilla bicolor pacifica* based on morphological attributes alone. However, they were able to make a distinction between the species by their adult sizes. Generally, *A. bicolor bicolor* is longer and heavier than *A. bicolor pacifica*. They also found that *A. bicolor bicolor* tend to occur in Sumatra and Java region and *A. bicolor pacifica* is found in Sulawesi and New Guinea region of Indonesia. As such, they have proposed that the two subspecies can be distinguished by the geographic approach. Subsequently, Teng et al. (2009) resolved the issue by conducting a phylogenetic study and validated the notion that *Anguilla* species and subspecies can cluster regionally (Figure 2.36).

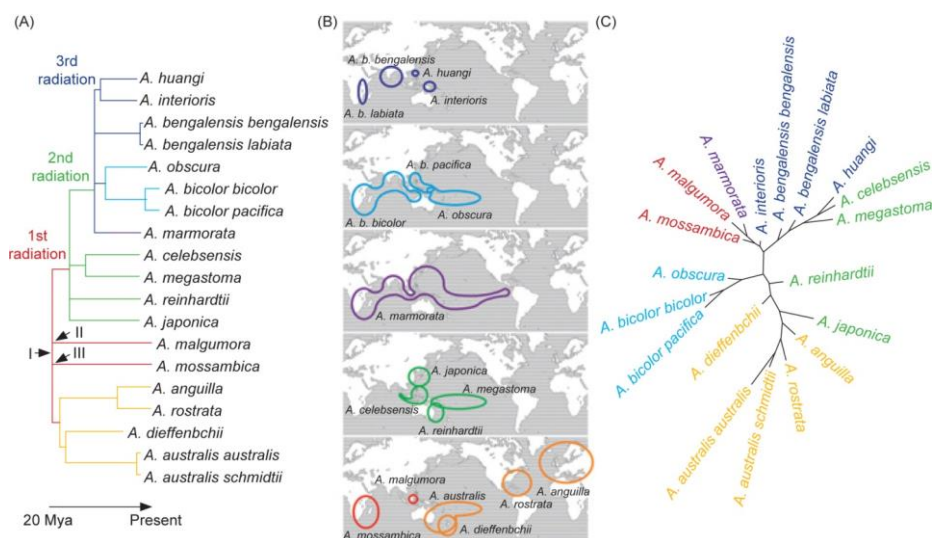


Figure 2.36: The morphological phylogenetic tree of the genus *Anguilla* showing correlation species occurrence in various regions (Teng et al., 2009)

The case of *Anguilla* genus is a classic example how the combination of morphological and molecular approaches, generally termed as integrative taxonomy (Goulding and Dayrat, 2016), are crucial in gaining and expanding the understanding of taxonomy and diversity in fish. This demonstrates that the broadest range of methods should be utilized to answer and solve taxonomic concerns.

CHAPTER 3

MATERIALS AND METHODS

This section describes all field and desktop materials and methods that were deployed to collect and analyse the raw data explicitly for biological, chemical and physical metrics in detail. Additionally, methods for assessing climatic, geomorphometric and economic values are also enumerated to underpin the importance of this study to the society in terms of freshwater provision ecosystem service value during the driest period in 2016 to reflect Kampar River's integrity and resilience. Since this study deals with the development of an assessment protocol, it is also obligated to describe the rationale behind metrics selected and justify how the assessment system was constructed and systemized into the MyRII. The rationale behind the selected ecohydrological units, or zones, as test areas and the corresponding sampling plan to ascertain MyRII's effectiveness is also elaborated.

For quick reference, all materials and methods deployed in this study is provided in Table 3.1.

Table 3.1: Summary of all materials and methods deployed in this study

No.	Metrics	Materials and methods
1	SAMPLING SITE	Sg Kampar, Perak, stratified to zone A, B, C and D
2	SAMPLING PLAN	Each zone with 4 transects, 800 m apart Each transect length 25 m
3	SAMPLING DURATION	October 2015 to March 2017 (18 months)
4	BIOLOGICAL SAMPLING	n = 18 for each zone
	Fish sampling	Specimens capture by handnet, castnet, hook and line along the transect
	Fish taxonomy and identification	Kottelat (2013); Van der Laan et al. (2014), Eschmeyer et al. (2018)
	Shannon and Pielou equation	Magurran (2004)
5	CHEMICAL SAMPLING	n = 36 for each zone
	Water sampling	Water samples extracted from the transect
	Water Quality Index (WQI) classification	Ministry of Natural Resources and Environment (2009)

No.	Metrics	Materials and methods
	Dissolved Oxygen (DO), Ammoniacal Nitrogen (AN) and Total Suspended Solids (TSS)	Portable colorimeter, HACH United States, model DR890
	pH	Benchtop pH meter, Mettler Toledo United States, model FE20-ATC
	Biochemical Oxygen Demand (BOD5) and Chemical Oxygen Demand (COD)	Kenep Laboratories (M) Sdn Bhd, MS ISO/IEC 17025 accredited laboratory
6	PHYSICAL SAMPLING	n = 18 for each zone
	Physical sampling	Visual assessment along the transect
	Channel Stability (ChnnStabl), Bank Stability (BankStabl), Hydrologic Continuity (HydCont), Riparian Quantity (RiprQuan), Riparian Quality (RiprQual), Canopy Cover (CanpyCov), Pools Availability (PoolAvail) and Riffle Embeddedness (RiffEmbed)	United States Natural Resources Conservation Service's Stream Visual Assessment Protocol Version 2 (SVAP2) (NRCS, 2009)
	Topography, watershed, river, stream delineation and digitization	QGIS® on digital elevation model (DEM) data downloaded from US Geological Survey's EROS Data Center, namely Shuttle Radar Terrain Mapper (SRTM) data projected on WGS 1984
	River volumetric discharge (Q)	Brodie et al. (2007), with correction factor of 0.8 for substrate with rocks and pebbles (EPA, 2016)

No.	Metrics	Materials and methods
	Watershed geomorphometrics analysis	GRASS GIS®, GDAL/OGR® and SAGA® geo-algorithm function
	Watershed geomorphometrics equations	Horton (1945); Miller (1953); Schumm (1956); Strahler (1957); Singh (1992); Suresh et al. (2004); Raghunath (2006); Al-Saud (2009); Anderson et al. (2014); Bello et al. (2014)
7	STATISTICAL ANALYSIS	IBM SPSS version 20; PAST version 3; BioDiversity Pro (McAleece et al., 1997)
8	OTHERS	
	Meteorological forecast	Oceanic Niño Index (ONI) dataset (NOAA, 2015)
	Economic value of water	Standard tariff of water in Perak state (PWB, 2016)

3.1 Core principle

In the context of Malaysia where a unified river assessment protocol has yet to emerge, it was determined that “reinventing the wheel” would be counterproductive. It would be more efficient to utilize the available accepted systems, metrics, and readapt them to the local environment where appropriate to ensure the widest acceptance and adoption. Correspondingly, from literature review and considering best practices adopted by advanced countries, the MyRII framework proposed herein is underpinned by the *a priori* hypothesis (Quine, 1953; Harman, 2002). *A priori* is a proposition that is “assumed prior to that inquiry”, or taken for granted, and it does not need experience, or sense, to be established to be true. In other words, it is already common knowledge and it clearly does not need testing or further studies to be accepted. Such approach has been widely accepted when developing assessment systems (Karr, 1981; Simon and Lyons, 1995; Deegan et al., 1997; Schmutz et al., 2000; Harrison and Whitfield, 2004; Breine et al., 2004; Melcher et al., 2007; Noble and Cowx, 2007; Clavel et al., 2013; Valero et al., 2015). In principle, the MyRII protocol requires data to be collected for three sets of *a priori* metrics for examining biological, chemical and physical characteristics of the study site (Figure 3.1).

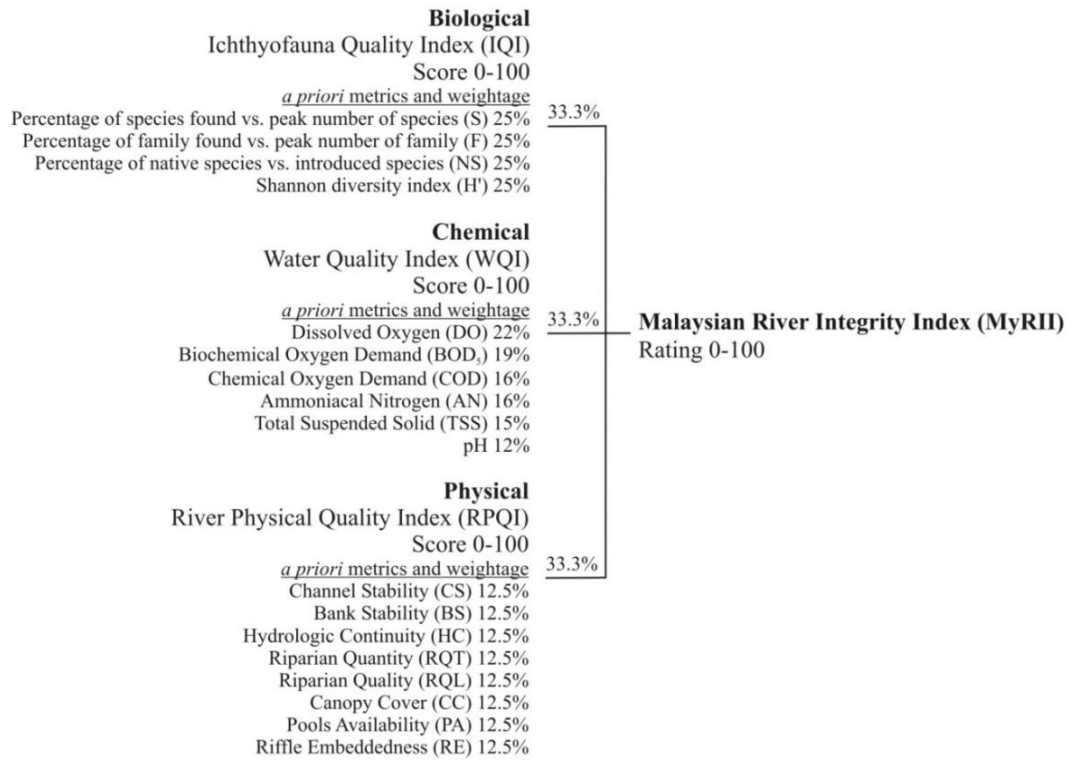


Figure 3.1: The multi-disciplinary metrics framework and algorithm of the MyRII assessment system. The IQI was developed in this study while the RPQI was adapted from the SVAP2 protocol (NRCS, 2009). The WQI was developed by the Ministry of Natural Resources and Environment, Malaysia (2009). Collectively, the three indices were integrated to form the MyRII

3.2 Biological metrics

In this study, a strong preference was given to fish community structure as a key biological indicator. Evolution has granted each species with biological aptitude to tolerate aquatic variances up to a certain degree. Therefore, the inclusion of fish-based metrics makes sense. Literature review indicates that fishes are practical bio-indicators as they are 1) inexpensive and convenient for

effective sampling, 2) ubiquitous across various aquatic systems, 3) easy to identify to species, or at least to genus level, 4) relatively long lived than most aquatic-based taxa and can reflect long-term aquatic degradation, and 5) sensitive to the effects of pollution and other environmental changes (Winemiller, 1992; Kottelat, 1995; Wheeler, 1995; Lundberg et al., 2000; Grabarkiewicz and Davies, 2008; Clavel et al., 2013). In this study, the resultant fish community structure, or ichthyofauna, assessment is termed as the Ichthyofaunal Quality Index, or IQI.

Fish sampling was carried out on monthly basis. Two man-hours (120 minutes) were spent on each transect using two circular 750 mm diameter dip nets with 2 mm mesh, one cast net with mesh size 15 mm and hooks-and-lines along the transects to reveal as many species and individuals as possible following Inger & Chin (2002) and Prudente et al. (2017). Along each transect, ten casts, 40 dips and five hooks-and-lines were applied during the 120 minutes sampling exercise. Each hook-and-line comprised type J-hook barbed point size 2/0 and 0.30 mm diameter monofilament nylon line of 10 m length. The hooks-and-lines were deployed at 5 m interval along the 25 m transect. Specimens caught were photographed for morphological characteristics, colour patterns and any other distinct variations to enable future reference and traceability before release. Publications by Kottelat (2013) and Eschmeyer et al. (2017) were consulted for identifying species' valid scientific names. Specimens that could not be confidently identified were recorded with open nomenclature terms "cf." at species level or "sp." at genus level. These were later referred to the literature for identification. Following Magurran (2004),

Shannon and Pielou indices were computed with software BioDiversity Pro (McAleece et al., 1997).

The Shannon index (H') was calculated as;

$$H' = -\sum(p_i \ln p_i)$$

where p_i is the ratio of individuals corresponding to the i th species and \ln is the natural logarithm function.

The Pielou index (J') was calculated as;

$$J' = H'/\ln S$$

where H' is the calculated Shannon index, S is the number of species and \ln is the natural logarithm function.

Based on the metrics and equal weighting (Table 3.2), the Ichthyofauna Quality Index (IQI) was calculated as;

$$IQI = 0.25*S + 0.25*F + 0.25*NS + 0.25*H'$$

Table 3.2: The metrics of Ichthyofaunal Quality Index (IQI). The peak number of species/families and percentage of native species is the highest number obtained during the study duration in the four zones

IQI metrics	Score	<i>A priori</i> hypothesis to stressors	Weightage
Percentage of species found vs. peak number of species (S)	0 - 100	Decrease	25%
Percentage of family found vs. peak number of family (F)	0 - 100	Decrease	25%
Percentage of native species vs. introduced species (NS)	0 - 100	Decrease	25%
Shannon diversity index (H')	0 - 100	Decrease	25%

3.3 Chemical metrics

As mentioned earlier, it would be more efficient to adopt existing practices that are already widely accepted by the local authorities and stakeholders. Therefore the MyRII has incorporated the metrics of Water Quality Index (WQI) established by the Ministry of Natural Resources and Environment, Malaysia (2009) into its framework (Table 3.3). In each month, two water samples were collected from the sampling transects for physico-chemistry assessment. A portable colorimeter (HACH United States, model DR890) was used for in-situ measuring of Dissolved Oxygen (DO), Ammoniacal Nitrogen (AN) and Total Suspended Solids (TSS) for WQI calculation in the sampling transects. The pH of the water sample was measured with a benchtop pH meter (Mettler Toledo United States, model FE20-ATC). Water samples were collected from the sampling transects for testing BOD₅ at 20°C for 5 days and COD parameter at Kenep Laboratories (M) Sdn Bhd, which is an MS ISO/IEC 17025 accredited laboratory. The WQI is calculated as;

$$\begin{aligned} \text{WQI} = & 0.22*\text{SIDO} + 0.19*\text{SIBOD}_5 + 0.16*\text{SICOD} \\ & + 0.16*\text{SITSS} + 0.15*\text{SIAN} + 0.12*\text{SIpH} \end{aligned}$$

where the sub-indices and the water quality classes were standardized in Table 3.4 and Table 3.5 respectively.

Table 3.3: The metrics of Water Quality Index (WQI) established by the Ministry of Natural Resources and environment, Malaysia (MNRE, 2009). The metrics are the standard parameters tested to determine river integrity in Malaysia

WQI metrics	<i>A priori</i> hypothesis to stressors	Weightage
Dissolved Oxygen (DO)	Decrease	22%
Biochemical Oxygen Demand (BOD ₅)	Increase	19%
Chemical Oxygen Demand (COD)	Increase	16%
Ammoniacal Nitrogen (AN)	Increase	16%
Total Suspended Solid (TSS)	Increase	15%
pH	(not applicable)	12%

Table 3.4: Sub-index (SI) of each metric established by the Ministry of Natural Resources and Environment, Malaysia, for calculating the WQI (MNRE, 2009)

Metric	Range	Sub-index
Dissolved Oxygen (DO) in %	DO < 8	SIDO = 0
	DO > 92	SIDO = 100
	8 < DO < 92	SIDO = $-0.395 + 0.03DO^2 - 0.0002DO^3$
Biochemical Oxygen Demand (BOD ₅) in mg/L	BOD ₅ < 5	SIBOD ₅ = 100.4 - 4.23BOD ₅
	BOD ₅ > 5	SIBOD ₅ = $108e^{-0.055BOD} - 0.1BOD_5$
Chemical Oxygen Demand (COD) in mg/L	COD < 20	SICOD = 1.33COD + 99.1
	COD > 20	SICOD = $103e^{-0.0157x} - 0.04COD$
Ammoniacal Nitrogen (AN) in mg/L	AN < 0.3	SIAN = 100.5 - 105AN
	0.3 < AN < 4	SIAN = $94e^{-0.573AN} - 5 AN - 2 $
	AN > 4	SIAN = 0
Total Suspended Solids (TSS) in mg/L	TSS < 100	SITSS = $94e^{-0.00676TSS} + 0.05TSS$
	100 < TSS < 1000	SITSS = $71e^{-0.0016TSS} + 0.015TSS$
	TSS > 1000	SITSS = 0
Acidity value (pH)	pH < 5.5	SIpH = 17.2 - 17.2pH + 5.02pH ²
	5.5 < pH < 7	SIpH = -242 + 95.5pH - 6.67pH ²
	7 < pH < 8.75	SIpH = -181 + 82.4pH - 6.05pH ²
	pH > 8.75	SIpH = 536 - 77.0pH + 2.76pH ²

Table 3.5: Standardized water quality classes in accordance to the Ministry of Natural Resources and Environment, Malaysia (MNRE, 2009)

Metric / Class	I	IIA and IIB	III	IV	V
DO (mg/L)	> 7.0	5.0-7.0	3.0-5.0	1.0-3.0	< 1
BOD ₅ (mg/L)	< 1.0	1.0-3.0	3.0-6.0	6.0-12.0	> 12
COD (mg/L)	< 10.0	10-25	25-50	50-100	> 100
AN (mg/L)	< 0.1	0.1-0.3	0.3-0.9	0.9-2.7	> 2.7
TSS (mg/L)	< 25.0	25-50	50-150	> 300	> 300
pH	6.5-8.5	6.0-9.0	5.0-9.0	5.0-9.0	-
WQI Score	> 92.7	76.5-92.7	51.9-76.5	31.0-51.9	< 31.0

Note: Class I denotes water can be used without any treatment; Class IIA denotes water that requires conventional treatment for human consumption and aquaculture; Class IIB denotes water that is suitable for recreational use with body contact; Class III denotes water that requires extensive treatment for aquaculture and livestock consumption; Class IV denotes water that is only suitable for agriculture irrigation; Class V denotes water that does not fall into any classes

3.4 Physical metrics

For assessing river physical quality, this study adopted and readapted the United States Natural Resources Conservation Service's Stream Visual Assessment Protocol Version 2 (SVAP2) (NRCS, 2009) which was an improvement from the 1998 pilot version. It was determined that “reinventing the wheel” was not necessary and the MyRII should readily incorporate an assessment system which was already widely accepted and has undergone thorough refinement. Along similar lines, Hughes et al. (2010) have also found significant agreement between SVAP2 and other widely practiced and prominent methods such as River Basin Planning (RBP), Quantitative Physical Habitat (QTPH) index and Qualitative Habitat Evaluation Index (QHEI). With the improvement in SVAP2 in 2009, the system was deemed to be more consistent, comprehensive and robust. Moreover, the SVAP2 originator NRCS recognizes and encourages modification of the SVAP2 protocol based on professional judgment, if necessary, to suit application in various regions and conditions (NRCS, 2009, subpart B-614, appendix C).

The original SVAP2 prescribes 16 qualitative criteria for rating biological, chemical and physical conditions. Since this study's objective was to produce a RPQI protocol for evaluating physical qualities of study site, the biological and chemical criteria are omitted. Physical criteria retained and the rating designation can be viewed in Table 3.6. The scoring criteria are outline in Table 3.7, Table 3.8, Table 3.9, Table 3.10, Table 3.11, Table 3.12, Table

3.13 and Table 3.14. Each criterion carries a weightage of 12.5% and may be rated from 0 to 10 in accordance to guidelines provided by SVAP2 (NRCS, 2009). With eight criteria, the RPQI would collectively sum up to 100% (i.e. the final index may range from 0 to 100).

Table 3.6: The metrics of River Physical Quality Index (RPQI). The rating criteria and score follow Stream Visual Assessment Protocol Version 2 (SVAP2) that originated from the Natural Resources Conservation Service, US (NRCS, 2009)

RPQI metrics	Score	<i>A priori</i> hypothesis to stressors	Weightage
Channel Stability (ChnnStabl)	0 – 10	Decrease	12.5%
Bank Stability (BankStabl)	0 – 10	Decrease	12.5%
Hydrologic Continuity (HydCont)	0 – 10	Decrease	12.5%
Riparian Quantity (RiprQuan)	0 – 10	Decrease	12.5%
Riparian Quality (RiprQual)	0 – 10	Decrease	12.5%
Canopy Cover (CanpyCov)	0 – 10	Decrease	12.5%
Pools Availability (PoolAvail)	0 – 10	Decrease	12.5%
Riffle Embeddedness (RiffEmbed)	0 – 10	Decrease	12.5%

Table 3.7: Criteria for Channel Stability (NRCS, 2009)

Criteria 1. Channel stability											
Rating	10	9	8	7	6	5	4	3	2	1	0
Natural, stable channel with established bank vegetation	If channel is incising (appears to be downcutting or degrading), score this element based on the descriptions in the upper section of the matrix										
No discernible signs of incision (such as vertical banks) or aggradation (such as very shallow multiple channels)	Evidence of past incision and some recovery; some bank erosion possible.			Active incision evident; plants are stressed, dying or falling in channel			Headcuts or surface cracks on banks; active incision; vegetation very sparse				
Active channel and flood plain are connected throughout reach, and flooded at natural intervals	Active channel and flood plain are connected in most areas, inundated seasonally			Active channel appears to be disconnected from the flood plain, with infrequent or no inundation			Little or no connection between flood plain and stream channel and no inundation				
Streambanks low with few or no bank failures	Streambanks may be low or appear to be steepening Top of point bars are below active flood plain			Steep banks, bank failures evident or imminent Point bars located adjacent to steep banks			Steep streambanks and failures prominent Point bars, if present, located adjacent to steep banks				

Criteria 1. Channel stability											
Rating	10	9	8	7	6	5	4	3	2	1	0
	If channel is aggrading (appears to be filling in and is relatively wide and shallow), score this element based on the descriptions in the lower section of the matrix										
	Minimal lateral migration and bank erosion					Moderate lateral migration and bank erosion			Severe lateral channel migration, and bank erosion		
	A few shallow places in reach, due to sediment deposits					Deposition of sediments causing channel to be very shallow in places			Deposition of sediments causing channel to be very shallow in reach		
	Minimal bar formation (less than 3)					3–4 bars in channel			Braided channels (5 or more bars in channel)		

Table 3.8: Criteria for Bank Stability (NRCS, 2009). Natural wood and rock does not mean riprap, gabions, log cribs, or other fabricated revetments. A bank failure refers to a section of stream bank that collapses and falls into the stream, usually because of slope instability

Criteria 2. Bank stability											
Rating	10	9	8	7	6	5	4	3	2	1	0
Banks are stable; protected by roots of natural vegetation, wood, and rock ¹			Banks are moderately stable, protected by roots of natural vegetation, wood, or rock or a combination of materials			Banks are moderately unstable; very little protection of banks by roots of natural wood, vegetation, or rock			Banks are unstable; no bank protection with roots, wood, rock, or vegetation		
No fabricated structures present on bank			Limited number of structures present on bank			Fabricated structures cover more than half of reach or entire bank			Riprap and/or other structures dominate banks		
No excessive erosion or bank failures ²			Evidence of erosion or bank failures, some with reestablishment of vegetation			Excessive bank erosion or active bank failures			Numerous active bank failures		

Criteria 2. Bank stability											
Rating	10	9	8	7	6	5	4	3	2	1	0
No recreational or livestock access			Recreational use and/or grazing do not negatively impact bank condition			Recreational and/or livestock use are contributing to bank instability			Recreational and/or livestock use are contributing to bank instability		

Table 3.9: Criteria for Hydrologic Continuity. Development in the flood plain refers to transportation infrastructure (roads, railways), commercial or residential development, land conversion for agriculture or other uses, and similar activities that alter the timing, concentration, and delivery of precipitation as surface runoff or subsurface drainage. As used here, “natural flow regime” refers to streamflow patterns unaffected by water withdrawals, flood plain development, agricultural or wastewater effluents, and practices that change surface runoff (dikes and levees) or subsurface drainage (tile drainage systems) (NRCS, 2009)

Criteria 3. Hydrologic continuity											
Rating	10	9	8	7	6	5	4	3	2	1	0
Bankfull or higher flows occur according to the flow regime that is characteristic of the site, generally every 1 to 2 years			Bankfull or higher flows occur only once every 3 to 5 years or less often than the local natural flow regime			Bankfull or higher flows occur only once every 6 to 10 years, or less often than the local natural flow regime			Bankfull or higher flows rarely occur		
No dams, dikes, or development in the flood plain, or water control structures are present and natural flow regime prevails			Developments in the flood plain, stream water withdrawals, flow augmentation, or water control structures may be present, but do not significantly alter the natural flow regime			Developments in the flood plain, stream water withdrawals, flow augmentation, or water control structures alter the natural flow regime			Stream water withdrawals completely dewater channel; and/or flow augmentation, stormwater, or urban runoff discharges directly into stream and severely alters the natural flow regime		

Table 3.10: Criteria for Riparian Quantity (NRCS, 2009)

Criteria 4. Riparian quantity											
Rating	10	9	8	7	6	5	4	3	2	1	0
Natural plant community extends at least two bankfull widths or more than the entire active flood plain and is generally contiguous throughout property			Natural plant community extends at least one bankfull width or more than 1/2 to 2/3 of active flood plain and is generally contiguous throughout property		Natural plant community extends at least 1/2 of the bankfull width or more than at least 1/2 of active flood plain		Natural plant community extends at least 1/3 of the bankfull width or more than 1/4 of active flood plain			Natural plant community extends less than 1/3 of the bankfull width or less than 1/4 of active flood plain	
			Vegetation gaps do not exceed 10% of the estimated length of the stream on the property		Vegetation gaps do not exceed 30% of the estimated length of the stream on the property		Vegetation gaps exceed 30% of the estimated length of the stream on the property			Vegetation gaps exceed 30% of the estimated length of the stream on the property	

Table 3.11: Criteria for Riparian Quality (NRCS, 2009)

Criteria 5. Riparian quality											
Rating	10	9	8	7	6	5	4	3	2	1	0
Natural and diverse riparian vegetation with composition, density and age structure appropriate for the site			Natural and diverse riparian vegetation with composition, density and age structure appropriate for the site.			Natural vegetation compromised					Little or no natural vegetation
No invasive species or concentrated flows through area			Little or no evidence of concentrated flows through area			Evidence of concentrated flows running through the riparian area					Evidence of concentrated flows running through the riparian area
			Invasive species present in small numbers (20% cover or less)			Invasive species common (>20% <50% cover)					Invasive species widespread (>50% cover)

Table 3.12: Criteria for Canopy Cover (NRCS, 2009)

Criteria 6. Canopy cover											
Rating	10	9	8	7	6	5	4	3	2	1	0
>75% of water surface shaded within the length of the stream in landowner's property			75–50% of water surface shaded within the length of the stream in landowner's property			49–20% of water surface shaded within the length of the stream in landowner's property			<20% of water surface shaded within the length of the stream in landowner's property		

Table 3.13: Criteria for Pool Availability (NCRS, 2009)

Criteria 7. Pool availability											
Rating	10	9	8	7	6	5	4	3	2	1	0
High-gradient stream/river (>2%)											
More than three deep pools separated by boulders or wood, each with greater than 30% of the pool bottom obscured by depth, wood, or other cover	Two to three deep pools, each with greater than 30% of the pool bottom obscured by depth wood or other cover; at least one shallow pool present		Pools present but relatively shallow, with only 10–30% of pool bottoms obscured by depth or wood cover			Pools absent					
For small streams, pool bottoms may not be completely obscured by depth, but pools are deep enough to provide adequate cover for resident fish	For small streams, pool bottoms may not be completely obscured by depth, but pools are deep enough to provide some cover for resident fish		For small streams, pool bottoms may not be completely obscured by depth, but pools are deep enough to provide minimal cover for resident fish								
Shallow pools also present	At least one shallow pool also present		No shallow pools present								
Low-gradient stream/river (<2%)											

Criteria 7. Pool availability											
Rating	10	9	8	7	6	5	4	3	2	1	0
More than two deep pools separated by riffles, each with greater than 30% of the pool bottom obscured by depth, wood, or other cover			One or two deep pools separated by riffles, each with greater than 30% of the pool bottom obscured by depth wood, or other cover			Pools present but shallow (<2 times maximum depth of the upstream riffle)			Pools absent, but some slow water habitat is available		
Shallow pools also present			At least one shallow pool present			Only 10–30% of pool bottoms are obscured due to depth or wood cover			No cover discernible		

Table 3.14: Criteria for Riffle Embeddedness (NCRS, 2009)

Criteria 8. Riffle embeddedness											
Rating	10	9	8	7	6	5	4	3	2	1	0
Gravel or cobble substrates are <10% embedded			Gravel or cobble substrates are 10–20% embedded		Gravel or cobble substrates are 21–30% embedded		Gravel or cobble substrates are 31–40% embedded		Gravel or cobble substrates are >40% embedded		

3.4.1 Geomorphometric equations

The term “geomorphometric” is derived from “geo” (earth), “morpho” (form) and “metry” (measurement) and it is a technical term associated with the analysis of aerial, linear, relief and gradient of a particular landform (Clarke. 1996). Methods and equations to carry out quantitative study of watershed landforms are not new and they have been applied by many authors to characterize watershed complexity (Thornbury, 1969; Troy and Wilson, 2006; Thorndycroft et al., 2008; Thorp, 2010; Robertson, 2012; Sarmah et al., 2012; Pagella and Sinclair, 2014). In this study, the geomorphometric data were derived from established equations described in Table 3.15.

Table 3.15: Geomorphometric equations applied for this study and the respective originators

Parameter	Unit	Equation	Reference
WATER BASIN			
Area (<i>A</i>)	km ²		Horton, 1945
Perimeter (<i>P</i>)	km		Schumm, 1956
Length (<i>Lb</i>)	km		Schumm, 1956
Width (<i>Wb</i>)	km		Schumm, 1956
Radius equivalent area (<i>R</i>)	km	$R = \sqrt{A/\pi}$	Raghunath, 2006
Highest point (<i>Hmax</i>)	m		Schumm, 1956
Lowest point (<i>Hmin</i>)	m		Schumm, 1956
Relief (<i>Bh</i>)	m	$Bh = Hmax - Hmin$	Schumm, 1956
Primary stream, straight (<i>Ls</i>)	km		Anderson et al., 2014
Primary stream, meander (<i>Lm</i>)	km		Anderson et al., 2014
STREAM			
Total number (<i>Nu</i>)	nos.		Horton, 1945
Total length (<i>Lu</i>)	km		Horton, 1945
Mean length (<i>Lm</i>)	km	$Lm = Lu/Nu$	Horton, 1945
Frequency (<i>Fs</i>)		$Fs = Nu/A$	Schumm, 1956
Drainage density (<i>Dd</i>)		$Dd = Lu/A$	Schumm, 1956
Drainage intensity (<i>Id</i>)		$Id = Fs*Dd$	Bello et al., 2014

Parameter	Unit	Equation	Reference
RATIO			
Compactness (Cc)		$Cc = 0.2821(P/A^2)$	Horton, 1945
Bifurcation (Rb), stream order 2		$Rb = Nu/Nu+1$	Strahler, 1957
Bifurcation (Rb), stream order 3		$Rb = Nu/Nu+1$	Strahler, 1957
Relief		$Rh = Bh/Lb$	Schumm, 1956
Circularity (Rc)		$Rc = 4\pi(A/P^2)$	Miller, 1953
Length width (Rlw)		$Rlw = Lb/Wb$	Singh, 1992
Texture (Rt)		$Rt = Nu/P$	Horton, 1945
Elongation (Re)		$Re = 2R/Lb$	Schumm, 1956
Meandering (Rm)		$Rm = Lm/Ls$	Anderson et al., 2014
Basin width to outlet width		$Ro = Wb/Wo$	Al-Saud, 2009
OTHERS			
Ruggedness number (Rn)		$Rn = (Bh*Dd)/1000$	Strahler, 1964
Factor, form (Ff)		$Rf = A/Lb^2$	Schumm, 1956
Factor, shape (Sf)		$Sf = Lb^2/A$	Horton, 1945
Constant channel maintenance (C)		$C = 1/Dd$	Suresh et al., 2004

3.4.2 Geoinformatics data processing

Topography, watershed, river, stream delineation and digitization were processed using QGIS® on digital elevation model (DEM) data downloaded from US Geological Survey's EROS Data Center, namely Shuttle Radar Terrain Mapper (SRTM) data projected on WGS 1984 (Figure 3.2). Some calculations of geomorphometrics were obtained from the GRASS GIS®, GDAL/OGR® and SAGA® geo-algorithm function. The GRASS plugin's "extract slope" function in QGIS® was utilized to render a Digital Elevation Model (DEM) from SRTM data to reveal areas with $>25^\circ$ slope (marked in red). Ground truthing field surveys were also conducted in the watersheds, rivers and streams to verify data provided by the SAGA® geo-algorithm function and only flowing perennial hydrological features were classified and accounted for in this study. Ephemeral and intermittent hydrological features were disregarded.

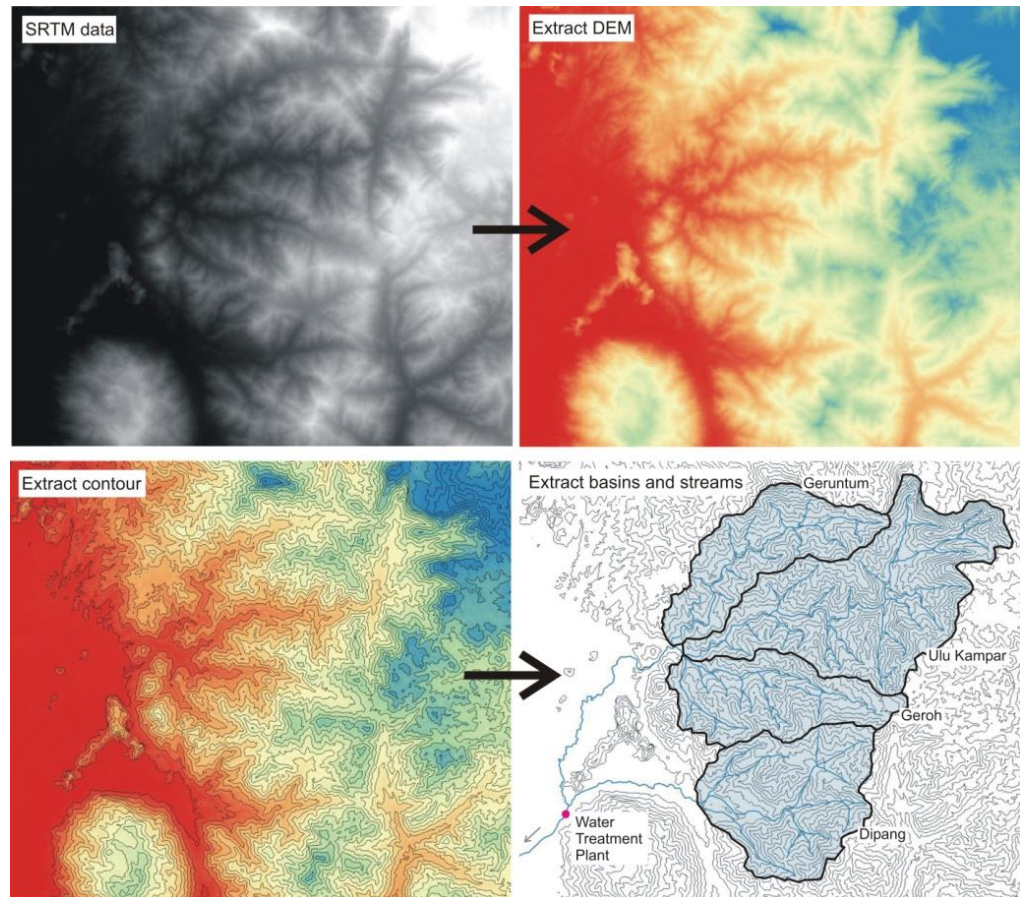


Figure 3.2: QGIS® was utilized to process SRTM’s Digital Elevation Model (DEM). Contour, watershed, river and stream compositions were extracted with GRASS GIS®, GDAL/OGR® and SAGA® geo-algorithm functions. The processing revealed four tributary watersheds in upriver of Kampar River, namely 1) Geruntum River, 2) Ulu Kampar River, 3) Geroh River, and 4) Dipang River

3.5 Meteorological forecast

This study regarded the occurrence of ENSO peak period during the data collection duration of 2015-2016 as a shock test to reflect the resilience of the assessed watersheds’ ES qualities. The Oceanic Niño Index (ONI) is one of the prominent measurables adopted globally to monitor and predict ENSO peak periods (Barnston et al., 1997; Kousky and Higgins, 2007; McGregor et al.,

2013; Prasetyo and Nabilah, 2017; Wang et al., 2017). It is inferred from the sea surface temperature in the central Pacific Ocean known as Niño 3.4, which is a region which spans from longitude 120° to 170° W. The temperature divergence when averaged over a 3-month period is concluded as a particular value of ONI.

A strong positive trend of ONI characterizes an ENSO peak period (NOAA, 2015). Based on ONI analysis from 1970s to 2015, many studies have hypothesized that another ENSO peak period may arrive during the 2015-2016 timeframe (Rembold et al., 2015; Jiménez-Muñoz et al., 2016; Varotsos et al., 2016). When an uptrend of ONI was detected in late 2015, the author started to monitor the surface water volumetric discharge of the studied tributaries (i.e. Geruntum, Ulu Kampar, Geroh and Dipang) on a weekly basis. Eventually, the lowest discharge occurred during the 26-29 March 2016 period (driest days) and an one-off *in-situ* surface water volumetric discharge (Q) measurement exercise was carried out in the outlet points of four tributaries.

3.6 Surface water discharge

The surface water volumetric discharge (Q) was measured by the velocity-area method (Brodie et al., 2007) at the respective primary outlet points, namely Geruntum (4° 27' 20.088" N, 101° 13' 1.884" E), Ulu Kampar (4° 27' 4.392" N,

101° 13' 20.2074" E), Geroh (4° 27' 0.6114" N, 101° 13' 21.4674" E) and Dipang (4° 22' 38.6394" N, 101° 13' 42.528" E).

The cross section area (a) of the primary outlet was estimated by using a steel tape to measure stream width and a few depth dimensions. The time (in seconds) which a half-filled floating plastic bottle took to travel a distance of 10m in the tributary was recorded. Multiple records were taken to ensure an average time was obtained and the flow velocity (m/s) could be calculated. Following Brodie et al. (2007), the surface water volumetric discharge (Q) was calculated by multiplying the tributary's cross section area (m²) with its flow velocity (m/s) and coefficient or correction factor. This was to ensure that the water flow speed of surface which travels faster than the bottom due to riverbed resistance was corrected and taken into account. According to EPA (2016), the correction factor is 0.8 for substrate with rocks and pebbles.

3.7 Economic valuation

The market price method (MPM) is an established approach used to evaluate watershed ES (Rohani, 2013; Barton et al., 2015). The MPM applies prevailing prices for ES that are already commercially traded and reflect the "willingness to pay" by buyers. According to PWB (2013), 88% of produced water is consumed by the domestic sector in Perak state. This study considered the prevailing water tariff as the values of "willingness to pay". A conservative

standpoint was taken and the cheapest tariff code 11 (Table 3.16) was adopted as the market price, with the assumption that that most consumers are from the domestic sector.

Table 3.16: Standard tariff of water in Perak state (PWB, 2016). “RM” denotes Ringgit, the currency of Malaysia

User type	Tariff Code	Rate
Domestic / Government	11	0-10m ³ = RM0.30/m ³
		11-20m ³ = RM0.70/m ³
		>20m ³ = RM1.03/m ³
Business / Industry	21	0-10m ³ = RM1.20/m ³
		11-20m ³ = RM1.40/m ³
		>20m ³ = RM1.61/m ³

3.8 Study site

The scope of this study is limited to the Kampar River and tributary watersheds located in the upriver region of Kampar River. A key intake point (4° 22' 18.228" N, 101° 9' 45.576" E) which supports a water treatment plant (WTP) with a designed production capacity of 36.37 million litres per day (MLD) (PWB, 2013) is located in Kampar River (Figure 3.3). This was to ensure that the data and estimates generated by this study were relevant to the WTP and consequently the local population.

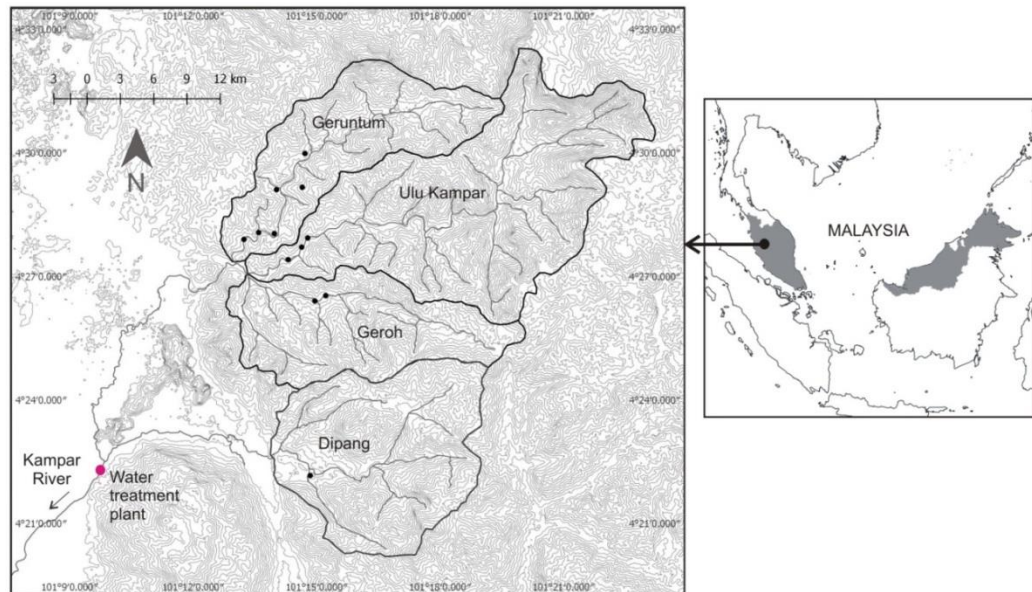


Figure 3.3: The study site consisted of tributaries namely Geruntum, Ulu Kampar, Geroh and Dipang that feed into Kamper River’s water treatment plant. The watersheds were mainly inhabited by the Semai and Temiar indigenous communities and the black dots denote their village settlements

Situated within the western foothill region of the Titiwangsa Mountain Range, the small watersheds support Geruntum, Ulu Kampar, Geroh and Dipang tributaries (Figure 3.3). Collectively the watersheds cover an area of 256.3 km² and have an altitude range of between 100 m to 2000 m above sea level. Together, they provide potable water to a population of 93,084 (DOS, 2010) that reside within the 699.8km² region (MNRE 2011). The region’s population distributions are centred around Gopeng, Jeram, Kamper, Kopisan, Kota Baharu, Kuala Dipang, Lawan Kuda, Malim Nawar, Mambang Diawan, Sungai Siput and Tronoh Mines. The region experiences mesothermic microclimate with a mean annual precipitation of 3,142 mm, high relative

humidity of approximately 82.1% and daily temperature that ranges from 24°C to 32°C (MNRE, 2011).

3.9 Field sampling plan

The MyRII protocol was applied to four individualistic ecohydrological zones along the Kampar River to test its robustness, namely 1) zone A, a natural forested area, 2) zone B, semi-disturbed rural area, 3) zone C, heavily disturbed human settlement area, and 4) zone D, a heavily disturbed perennial wetland area which was disjointed from Kampar River (Figure 3.4) (Table 3.17). Zone B's sampling transects were deliberately designated around a water treatment plant's intake for treatment and supply to the surrounding population. Zone D which was a heavily disturbed lentic region was also intentionally assessed for exploratory testing. This was necessary for counterchecking if the MyRII protocol was able to distinguish negative or unusual inputs that depart from the usual riverine ecosystem.

Each zone consisted of four sampling transects of 25 m length of 800 m apart. The biological, chemical and physical metrics of the MyRII protocol were investigated along the sampling transects in sequence on a monthly basis from October 2015 to March 2017 (18 months) to detect the regular and possible sporadic variances. Biological sampling and physical assessment was carried out along the 25 m transect. Two water samples were taken at the start and end in each 25 m transect for assessing their for physico-chemistry metrics.

Assessment methods for the *a priori* metrics pertaining to biological, chemical and physical elements followed methods highlighted earlier.

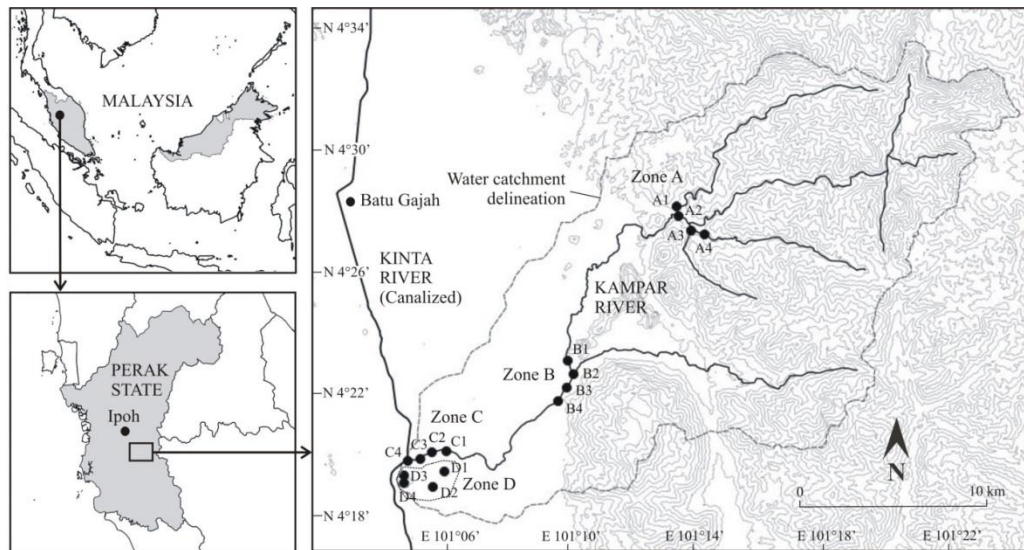


Figure 3.4: The study zones and locations of sampling transect along the Kampar River. Zone A represents a natural forested area while zone B and C represent a semi-disturbed rural area and heavily disturbed human settlement area, respectively. Zone D is a heavily disturbed perennial wetland area that is disjoined from the Kampar River

Table 3.17: Zone description and GPS coordinates of sampling points

Zone description	Sampling point	GPS coordinates (latitude, longitude)
A - Lotic system located at 164 m above sea level with stable riparian areas protected by natural vegetation. A mix of riffles, shallow and deep pools is present.	A1	4° 27' 33.84" N, 101° 12' 57.96" E
	A2	4° 27' 17.64" N, 101° 13' 1.92" E
	A3	4° 26' 51.72" N, 101° 13' 23.88" E
	A4	4° 26' 43.80" N, 101° 13' 47.28" E
B - Lotic system located at 36 m above sea level with channel incising, aggrading and some recovery over riparian areas. No pool or riffle was observed in the slow flowing waters	B1	4° 22' 53.76" N, 101° 9' 38.52" E
	B2	4° 22' 28.56" N, 101° 9' 50.04" E
	B3	4° 22' 4.44" N, 101° 9' 37.44" E
	B4	4° 21' 39.96" N, 101° 9' 20.88" E
C - Lotic system located at 26 m above sea level with riparian clearings and steep banks. Sediment deposition, sandy and muddy substrates have caused the river to be shallow in certain parts.	C1	4° 20' 9.24" N, 101° 5' 57.48" E
	C2	4° 20' 5.28" N, 101° 5' 31.92" E
	C3	4° 19' 54.48" N, 101° 5' 11.04" E
	C4	4° 19' 51.24" N, 101° 4' 47.64" E
D - Lentic system located at 25 m above sea level with isolated ditches, ponds, wetland and lakes. The region is heavily disturbed by anthropogenic activities.	D1	4° 19' 31.44" N, 101° 5' 55.32" E
	D2	4° 19' 5.16" N, 101° 5' 34.44" E
	D3	4° 19' 24.60" N, 101° 5' 3.84" E
	D4	4° 19' 11.28" N, 101° 4' 40.8" E

3.10 Statistical analysis

3.10.1. Variance

The obvious and subtle variances of each metric and index dataset were crucial for research analysis as they were expected to detect anomalies and non-compliances of four eco-hydrological zones studied throughout the 18 months period. All descriptive statistical analyses, namely measures of central tendency and variability including the range, quartiles and standard deviation (SD), were computed, summarized and plotted using functions provided by software IBM SPSS version 20. The values were reported in mean \pm SD. To further ascertain the significance of difference between the central tendencies of datasets, the one-way ANOVA test function of the software was applied. Correlation coefficients (*p*-value) of ≤ 0.05 were considered to be statistically significant, unless otherwise specified. Additionally, the software was also applied to compute the 75%, 50% and 25% percentile thresholds for establishing the “good”, “average” and “poor” rating, respectively, for MyRII.

3.10.2. Correlation

Continuous variables of the metrics and indices had to be explicitly correlated in order to analyse the strength, direction and pattern of relationships. The relationships were explored and analysed using Pearson correlation (*r*) function, coefficient of determination (R^2) and scatter plots generated by

software IBM SPSS version 20. Correlation coefficients (p -value) of ≤ 0.05 were considered to be statistically significant, unless otherwise specified, and the extent of correlation between two variables was considered strong when the r and R^2 value exceeds 0.7.

3.10.3. Cluster analysis

A part of the research was to ascertain whether the metrics and indices are capable of distinguishing and grouping each eco-hydrological zone clearly according to their biological, chemical and physical characteristics. To analyse the BCP multi-dimensional swarm of datasets in a manner that is projected onto an apparent ordination and clustering pattern for visual inspection, the software IBM SPSS version 20 was applied to compute cluster hierarchical analysis and plotting using the Ward's and Neighbour-Joining group linkage method.

The Canonical Correspondences Analysis (CCA) was not adopted after a careful review because the method is typically applied to ordinate two groups of dataset (Matthew et al., 1994; Paliy and Shankar, 2016). Since more than two datasets were examined in this study (i.e. biological, chemical and physical datasets), the Principal Component Analysis (PCA) was applied as it was deemed more suitable for (Krzanowski, 1987; Jolliffe and Cadima, 2016; Lever et al., 2017). Prior to executing PCA computation, the values were normalized by the mathematic expression of $(x-\text{mean})/\text{stdev}$. The Kaiser-Meyer-Olkin test of sampling adequacy and the Bartlett's test of sphericity was also calculated to

ensure the strength of the relationships among variables was valid for PCA application. Subsequently, PCA was computed with Kaiser normalization and Varimax rotation for dataset dimension-reduction. The resultant Eigenvalues were applied to produce the loading biplot for indicating the strength of correlations and similarity directions of the individual metrics and zones.

3.11 Reference site and rating normalization

A credible rating system requires a benchmark of what a healthy river should look like. However, a standard approach for identifying a benchmark condition does not exist. In some regions, anthropogenic disturbance is so pervasive that locating any waterbody that could be considered minimally disturbed or close to historical benchmark condition is virtually impossible. Yet, identification of least-disturbed, or best-attainable condition, within a given region or study area should be possible regardless of land use (Angermeier and Karr, 1994). Regardless of whether the benchmarks, or reference sites, are based on minimally or least disturbed sites, their inclusion into the MyRII development process is critical to ensure uniformity of ratings.

In developing a rating system, many researchers have highlighted challenges associated in determining historic, or reference condition, for rating normalization into a common scale (Karr, 1981; Schofield and Davies, 1996; Wang et al., 2014; Valero et al., 2015). Normalization is a process to transform metric values (irrespective of measurement unit) into a dimensionless value,

scale or rating to depict the “distance from the best performer” (OECD, 2008). In the case of developing a composite index such as the MyRII, the “best performer” is a most natural reference site as advocated by Angermeier and Karr (1994). Unfortunately, Van Liefferinge et al. (2010) found evidence that many studies and assessment systems did not explicitly describe how the reference conditions and normalization processes were defined. This is indeed surprising because it shows that many existing assessment systems have inherent weakness from the time they were first conceived and the results are somewhat questionable. This raises a red flag. Therefore, since this research is supposed to set the foundation in Malaysia, it is obligated to be as transparent as possible on how the reference site and rating normalization were derived.

As it is, Malaysia already has a rating system for the chemical component which is normalized between 0 (poorest) to 100 (excellent), namely the Water Quality Index (WQI) that is practiced by the Department of Environment. This study has adhered to the conventional WQI assessment system and when normalizing the data for chemical metrics. However, for biological and physical components, the 0 (poorest) to 100 (excellent) normalized ratings were not available in Malaysia. Hence, collecting the necessary pilot data from an identified reference site to deduce the appropriate benchmark and ratings became a critical endeavour of this study.

The reference site is taken as “the best of what’s left” or “minimally impaired” where most variances are caused by natural elements and very little

variances are caused by human activities (Karr, 1981). In this study, zone A of Kampar River watershed was tentatively selected as the reference site and the rating classification was deduced from statistical method established by Barbour & Karr (1996) (Figure 3.5).

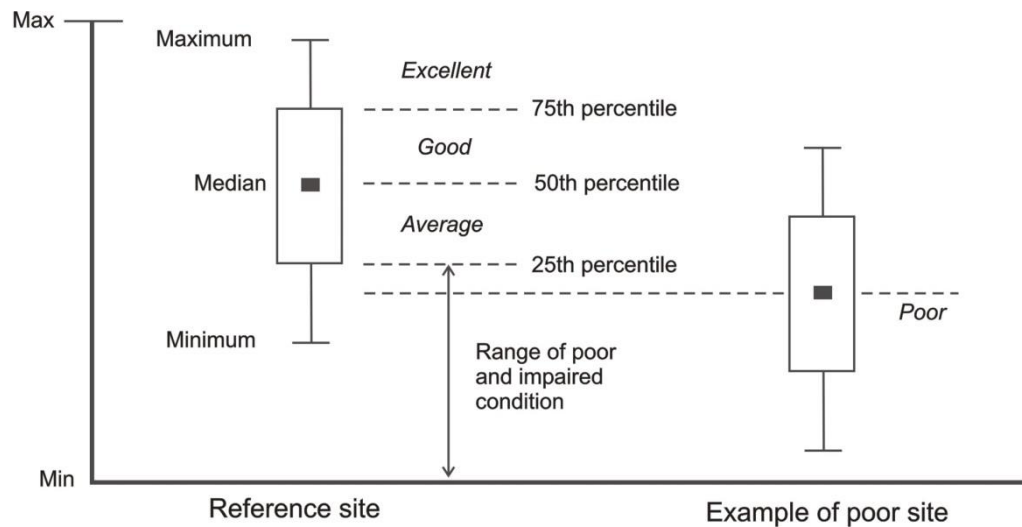


Figure 3.5: MyRII data collected from the reference site is used to estimate the central tendency, or median. Once the median is known, or 50th percentile (interquartile range) is established, the MyRII can then be normalized and the thresholds can be classified. Any MyRII result that falls between the 50th to 75th percentile is classified as “good” and a result that is above 75th percentile is classified as “excellent”. A MyRII result that falls between 25th to 50th percentile is classified as “average” and any result below 25th percentile is classified as “poor” (Barbour and Karr, 1996)

3.12 IQI, WQI and RPQI weighting

For every biologist who favours more weightage to be allocated to IQI to prevent biodiversity loss, there would be a water supply engineer who would regard WQI as being more important because clean raw water means less operational cost is needed for treatment. For government agencies and the local authorities that are responsible of drainage stability, the officers would most certainly value RPQI higher to ensure riparian zones and banks are given proper attention. Moreover, when the sub-indices are humanized, each has its critical niche and merits. For example, the IQI is related to fish as a food source to the local communities while the WQI monitors the quality of drinking water. Along similar lines, RPQI has a role to play in safeguarding the society from flood disasters.

In the development of composite indices, there are two approaches of weighting, namely 1) unequal weighting, and 2) equal weighting (Belhadj, 2012). Unequal weighting, sometimes referred to as “differential weighting”, is applied when there is adequate body of knowledge and data to understand the priorities and trade-offs between metrics. The unequal weightings are usually derived from expert or stakeholder consensus and theoretical formulation. On the other hand, the equal weighting is usually adopted when a subject is relatively new and suffers from data deficiency (Cherchye et al., 2007; OECD, 2008; Decancq and Lugo, 2013). In some instances, composite indices are formulated with a mix of both unequal and equal weighting. As an example,

the well-known WWF Living Planet Index (LPI) is calculated from the time-series of either population abundance or a proxy of abundance. It uses unequal weighting for metrics with large data sets and components with adequate taxonomic references globally. For those without proper taxonomic information and when only small datasets are available, the metrics are given equal weighting.

This is a pilot study into uncharted discipline in Malaysia. Although it cannot be denied that the use of weightage to streamline prioritization is important, at the time of this study, there are far too many questions unanswered, too many contexts and possible variables that are unexplored. The use of multi-disciplinary index for riverine ecosystem assessment is still at its infancy in Malaysia and empirical data that can explicitly clarify the relationships of biological, chemical and physical elements in a comprehensive manner is not available. Therefore, as highlighted earlier, a tilt towards equal weighting makes more sense and stands to reduce tension among decision-makers, users and stakeholder from various fields, academic institutions and government agencies. In principle, an ecosystem of high quality is one that is intricately balanced. No one aspect should be overwhelming others. Hence, in this pilot development, the MyRII is calculated as;

$$\text{MyRII} = 0.333 \cdot \text{IQI} + 0.333 \cdot \text{WQI} + 0.333 \cdot \text{RPQI}$$

Note that when the three equal weightings are added together, the ideal score may be rounded up to equal to 100.

CHAPTER 4

RESULTS

In this section, the raw data results are first reported in the sequence of biological, chemical and physical metrics. Since the literature review process revealed that there is a major gap in the ichthyology and bio-indicator disciplines in Malaysia, a substantial part of this section is allocated to enumerating the biological data collected. Subsequently, the corresponding IQI, WQI and RPQI data is presented and consolidated to attain the composite MyRII result which is the key focus of this study. Finally, the geomorphological and economic data is presented as the supporting baselines.

4.1 Fish-based biological data

A total of 2,439 individuals were encountered in the four zones, representing 57 species, 44 genera and 23 families (Table 4.1). Zone D registered the highest number of species (35), followed by zone B (30), zone A (23) and zone C (14). Although zone A recorded a lower species diversity, the sampling transects registered the highest percentage of native species (99.7%), followed by zone B (65.9%) and zone C (33.3%). With a relative abundance of 23.4%, *Neolissochilus soroides* was the most dominant species in zone A. One way ANOVA test showed mean differences between the zones (Table 4.2) were

statistically significant for species ($F = 30.07$, $p = 0.000$), family ($F = 22.74$, $p = 0.000$), relative abundance of native species ($F = 42.78$, $p = 0.000$), Shannon index ($F = 17.59$, $p = 0.000$) and Pielou index ($F = 24.66$, $p = 0.000$).

The monthly bar charts clearly indicated that most fish-based metrics decreased progressively from zone A to zone C (Figure 4.1 and Figure 4.2). However, in zone D, it was notable that the fish-metric trends could not be conclusively correlated with other studied zones. This was expected as zone D was a lentic zone.

Table 4.1: List of fish species encountered in each zone. “*” denotes introduced species

Family / Species	Zone			
	A	B	C	D
NOTOPTERIDAE				
<i>Notopterus notopterus</i>		2		
CYPRINIDAE				
<i>Barbodes cf. rhombeus</i>	65	14		2
<i>Barbonymus gonionotus*</i>		38	7	20
<i>Barbonymus schwanefeldii</i>		5		
<i>Crossocheilus obscurus</i>	18			
<i>Cyclocheilichthys apogon</i>	8	11		
<i>Cyprinus carpio*</i>		6	3	11
<i>Danio albolineatus</i>	37			
<i>Hampala macrolepidota</i>	9	5		
<i>Hypophthalmichthys nobilis*</i>		1		2
<i>Labeo rohita*</i>			1	4
<i>Labiobarbus leptocheilus</i>	4	10		2
<i>Leptobarbus hoevenii</i>	1	2		1
<i>Leptobarbus rubripinna*</i>		5	3	24

Family / Species	Zone			
	A	B	C	D
<i>Mystacoleucus obtusirostris</i>	33	11		41
<i>Neolissochilus soroides</i>	143			
<i>Osteochilus vittatus</i>	7	10		
<i>Poropuntius normani</i>	6			
<i>Puntigrus partipentazona</i>		15		6
<i>Rasbora vulgaris</i>	63	11		21
<i>Toxabramis houdemeri</i> *				94
BALITORIDAE				
<i>Balitoropsis zollingeri</i>	12			
<i>Homalopteroides smithi</i>	35			
LORICARIIDAE				
<i>Pterygoplichthys disjunctivus</i> *			22	8
SISORIDAE				
<i>Glyptothorax schmidti</i>	51			
SILURIDAE				

Family / Species	Zone			
	A	B	C	D
<i>Silurichthys schneideri</i>	10			
CLARIIDAE				
<i>Clarias aff. batrachus</i>	18	2		
<i>Clarias gariepinus</i> *	2	14	13	23
<i>Clarias leiacanthus</i>	10			
<i>Clarias nieuhofii</i>	2			
PANGASIIDAE				
<i>Pangasianodon hypophthalmus</i> *		8	6	3
BAGRIDAE				
<i>Hemibagrus capitulum</i>		39	28	
<i>Mystus singaringan</i>		14	6	2
APLOCHEILIDAE				
<i>Aplocheilus armatus</i>		8		7
POECILIIDAE				

Family / Species	Zone			
	A	B	C	D
<i>Poecilia reticulata</i> *		10		
SYNBRANCHIDAE				
<i>Monopterus javanensis</i>		2	2	1
MASTACEMBELIDAE				
<i>Mastacembelus favus</i>	8			
AMBASSIDAE				
<i>Parambassis siamensis</i>				49
PRISTOLEPIDIDAE				
<i>Pristolepis fasciata</i>		1		2
CICHLIDAE				
<i>Cichla monoculus</i> *				2
<i>Mayaheros urophthalmus</i> *				341
<i>Oreochromis aureus</i> *		9	19	561

Family / Species	Zone			
	A	B	C	D
<i>Oreochromis niloticus</i> *				3
ELEOTRIDIDAE				
<i>Oxyeleotris marmorata</i>		1		1
ANABANTIDAE				
<i>Anabas testudineus</i>		3	1	10
HELOSTOMATIDAE				
<i>Helostoma temminckii</i>				18
OSPHRONEMIDAE				
<i>Betta pugnax</i>	36			
<i>Trichopodus pectoralis</i> *			2	43
<i>Trichopodus trichopterus</i>				24
<i>Trichopsis vittata</i>		5		6
CHANNIDAE				
<i>Channa gachua</i>	33			

Family / Species	Zone			
	A	B	C	D
<i>Channa lucius</i>				55
<i>Channa micropeltes</i>				2
<i>Channa striata</i>		7	1	7
Total individuals =	611	270	114	1444
Total species =	23	30	14	35
Total family =	8	15	10	15
Native species (%) =	99.7	65.9	33.3	20.7
Shannon index (H') =	1.13	1.31	0.93	0.94
Pielou index (J') =	0.83	0.88	0.81	0.60

Table 4.2: Summary of fish-based metrics averages (n=18, mean \pm SD). “*” denotes native species

Variables / Metrics	Zone A	Zone B	Zone C	Zone D
Individuals	34.00 \pm 15.54	15.00 \pm 5.34	6.33 \pm 2.59	81.50 \pm 29.54
Species	9.78 \pm 2.94	5.33 \pm 1.33	3.61 \pm 1.19	8.39 \pm 2.66
Family	6.17 \pm 1.65	3.44 \pm 1.15	2.89 \pm 0.96	5.33 \pm 1.61
Relative abundance*	99.91 \pm 0.38	66.99 \pm 27.51	37.14 \pm 32.37	17.31 \pm 19.56
Shannon	0.85 \pm 0.19	0.63 \pm 0.12	0.46 \pm 0.14	0.63 \pm 0.18
Pielou	0.88 \pm 0.07	0.87 \pm 0.05	0.90 \pm 0.07	0.69 \pm 0.12

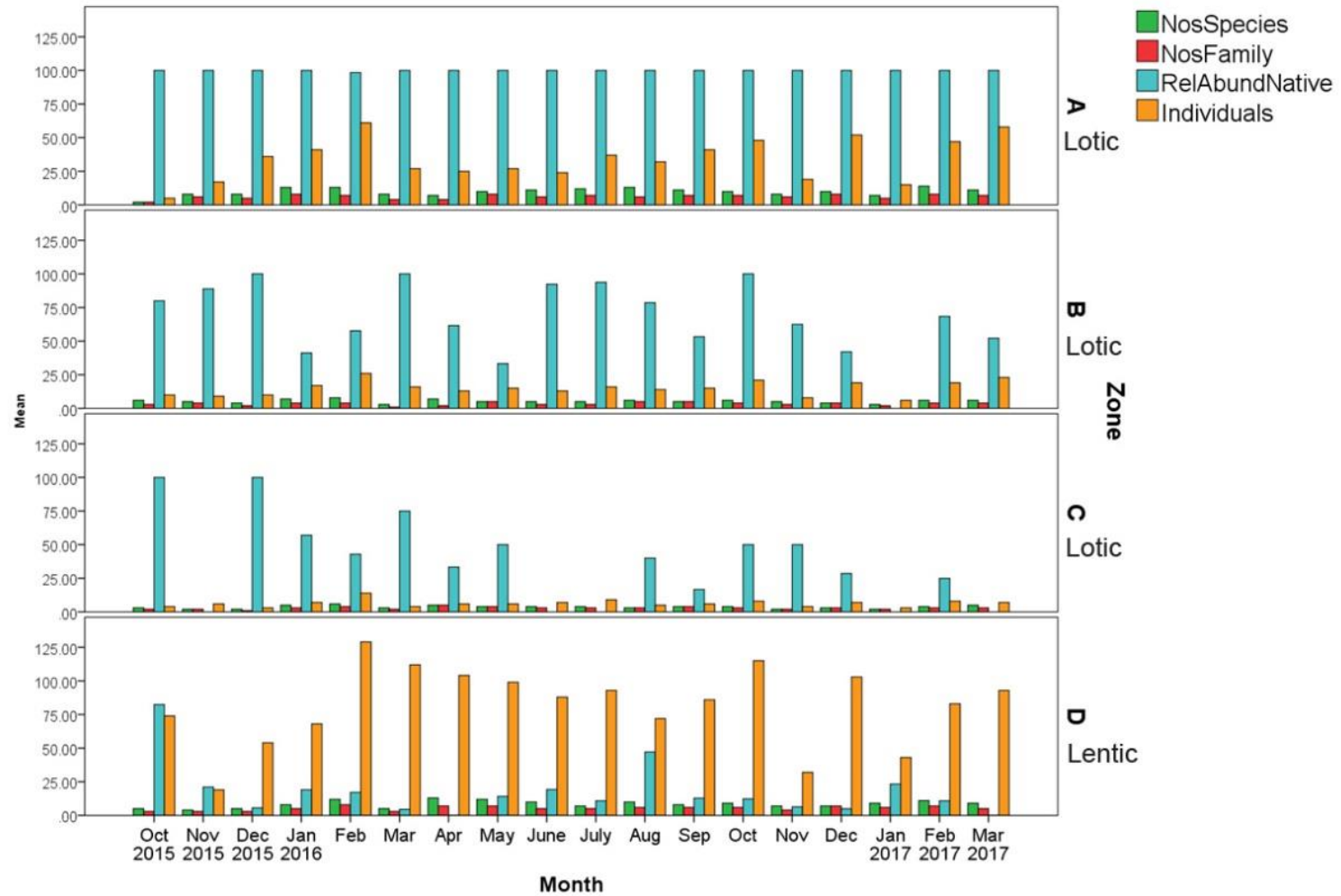


Figure 4.1: Monthly bar chart profiles for comparing fish-based metrics between zones throughout the study period

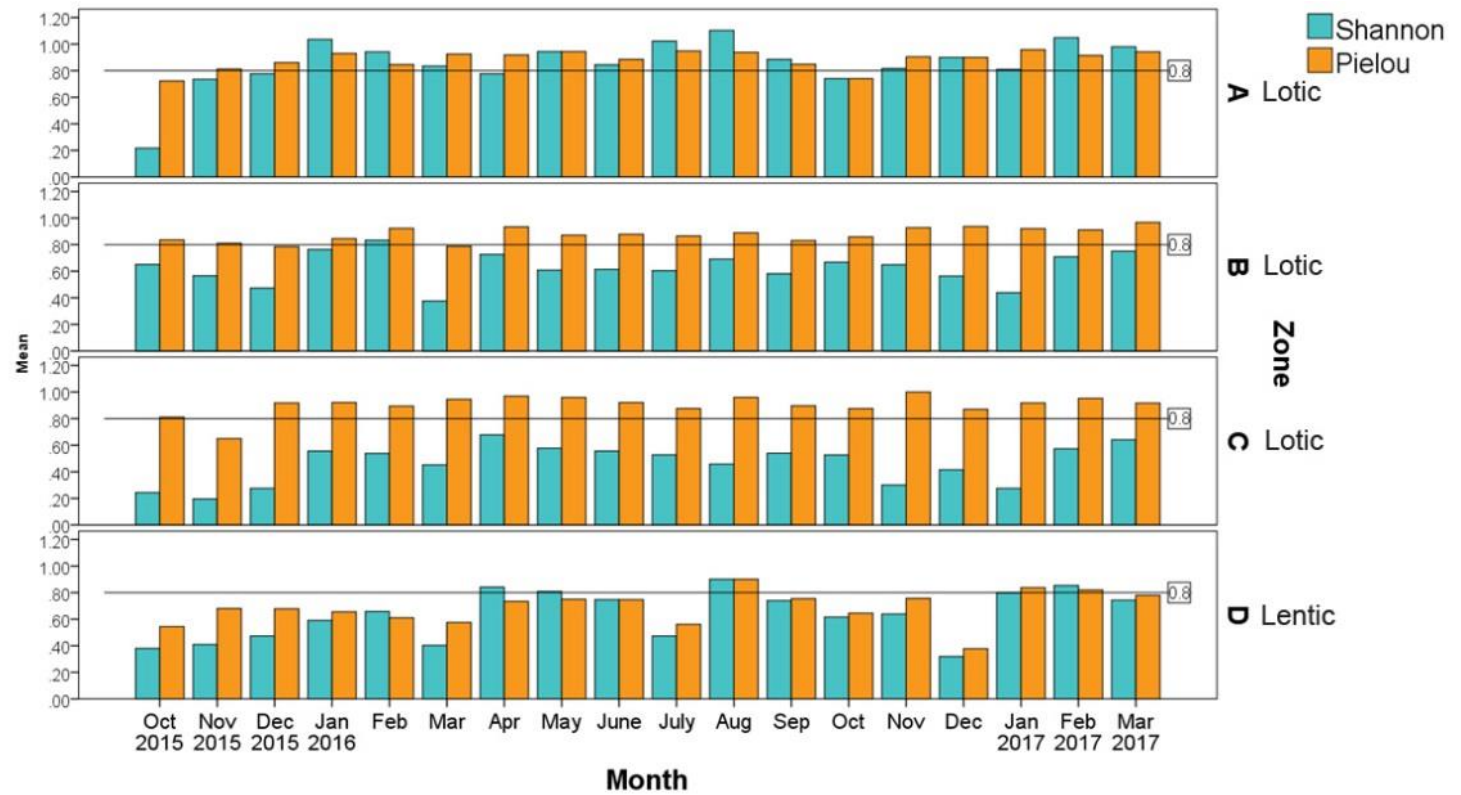


Figure 4.2: Monthly bar chart profiles for comparing Shannon and Pielou indices between zones throughout the study period

4.1.1 Fish taxonomic account

All species encountered in the studied zones were crosschecked with Catalog of Fishes (Eschmeyer et al., 2017) for the latest valid binomial nomenclatures. The genera and species arrangement is in alphabetical order and family systematic ranking follows Nelson et al. (2016). Species that are currently affected by taxonomic uncertainty or could not be identified with confidence were recorded with open nomenclature terms "aff." and "cf." following Lucas (1986) and Bengtson (1988) in taxonomic statements. The most prominent features of the species were focused in identification description. Supplementary commentaries were also provided to describe habitats where the species may be typically encountered and the precautions when identifying some particular species.

Family NOTOPTERIDAE

Notopterus notopterus (Pallas 1769)

Common name: Bronze Featherback

Local name: Belida

Native range: Southern India, Myanmar, Thailand, Sumatra and Java and Malay Peninsula.

Etymology: *Notopterus*: Greek, noton = back + Greek, *pteron* = wing, fin

Description: Body knife-like compressiform, finely scaled body, large membranous opercular flap, terminal mouth, concave head profile, small dorsal fin, caudal fin pointed and continuation from anal fin.

Comments: Inhabits turbid still deep ponds, wetlands and slow flowing canals. Rarely found in the main rivers.

Family CYPRINIDAE

Barbodes cf. rhombeus (Kottelat 2000)

Common name: Spotted Barb

Local name: Tebal sisik

Native range: Mekong Basin, Chao Phraya Basin, Maeklong Basins and peninsular Kra Isthmus of Thailand.

Etymology: *Barbodes*: Latin, barbus = barbel + Greek, oides = similar; *rhombeus*: Latin, rhombeus = rhombus, equilateral geometry.

Description: Body compressiform with scales, terminal mouth, dorsal-fin spine finely serrated, caudal fin forked and prominent blotch at dorsal fin anterior base.

Comments: Inhabits clear or turbid fast, slow and stagnant waters. Observed to feed on some plants, aquatic arthropods and macroinvertebrates. This species is associated with the "catch-all" *Puntius* complex and work is still in progress to

clarify its identity. Some members of the complex have been reassigned to new genera *Dawkinsia*, *Haludaria* and *Pethia* (Pethiyagoda et al., 2012) and *Barbodes* (Kottelat, 2013). Currently, members of *Barbodes* are typically told apart by apomorphic markings on the body. Specimens found in Perak have been frequently cited as *B. binotatus* (Hashim et al., 2012; Ikhwanuddin et al., 2017) but this study hesitates to adopt the same as there are pending taxonomic issues that are well explicated in Roberts (1989: 60-61). *B. binotatus* was described from a holotype of Javan origin and the species is likely to be restricted to Java, Bali, Lombok and Sumatra (Kottelat, 2000). Out of 41 species listed in the *Barbodes* genus which are mostly found in the Philippines, Borneo and Indonesia, *B. rhombeus* occurring in Kra Isthmus of Thailand (Kottelat 2013) may be the closest congener to specimens found in Perak. Farinordin et al. (2017) also highlighted recently that they found two morphological forms of scale below the lateral line in "*B. binotatus*" encountered in tributaries of Kenyir Lake, Terengganu. This opens up the possibility of specimens found in Perak could be *B. rhombeus* or an undescribed species. Until the uncertainty is resolved, we are citing this species as *B. cf. rhombeus* to highlight the possibilities.

Barbonymus gonionotus (Bleeker 1849)

Common name: Silver Barb

Local name: Lampam jawa

Native range: Java.

Etymology: *Barbonymus*: Latin, barbus = barbel + Greek, *anónumos* = anonymous; *gonionotus*: Greek, gōnía = angle + Greek, noton = back

Description: Body strongly compressiform with dorsal profile arched, head small, mouth terminal, caudal fin forked with light orange anal and pelvic fin.

Comments: Not native to peninsula Malaysia. The species was first introduced for aquaculture in Sungai Terengganu and Sungai Perak (Chong et al., 2010). Currently it is widespread throughout Southeast Asia.

Barbonymus schwanefeldii (Bleeker 1854)

Common name: Tinfoil Barb

Local name: Lampam sungai

Native range: Throughout Sundaic and mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Barbonymus*: Latin, barbus = barbel + Greek, *anónumos* = anonymous; *schwanefeldii*: in honour of H. W. Schwanefeld.

Description: Scaled body, strongly compressiform with dorsal profile arched, head small, mouth terminal, caudal fin forked with submarginal stripe on orange/red caudal lobes.

Comments: Inhabits slow water lakes and rivers. The scientific name is often misspelled as *B. schwanenfeldii* (with an extra “n”) in many reports.

Danio albolineata (Blyth 1860)

Common name: Pearl Danio

Local name: (none)

Native range: Myanmar, Laos, Thailand throughout Malay Peninsula to Sumatra.

Etymology: *Danio*: Bengalese, dhani = small; *albolineata*: Latin, albus = white + lineatus = lined.

Description: Caudal fin forked, terminal mouth, incomplete lateral line, two pairs of barbels, maxillary barbels extending beyond pectoral base, rostral barbels extending beyond eye, iridescent blue and orange colouration in life.

Comments: Found in small flowing clear streams (width < 2m) in oil palm plantation along the hillsides.

Crossocheilus obscurus Tan & Kottelat 2009

Common name: Siamese Algae Eater

Local name: Selimang

Native range: Sumatra and Malay Peninsula.

Etymology: *Crossocheilus*: Greek, krossós = fringe + Greek, cheilos = lip; *obscurus*: Latin, obscurus = obscure, unclear, indistinct.

Description: Scaled body, mouth inferior, caudal fin forked, mid-lateral stripe from operculum to caudal fin. *C. obscurus* can be distinguished from the

closest congener *C. oblongus* by displaying faded or unclear mid-lateral stripe in mature individuals (vs. sharp mid-lateral stripe).

Comments: Typically found foraging among pebbles and rocks in hillside clear fast flowing streams and rapids.

Cyclocheilichthys apogon (Valenciennes 1842)

Common name: Beardless Barb

Local name: Cemperas

Native range: Myanmar, Thailand, Malay Peninsula to Indonesia

Etymology: *Cyclocheilichthys*: Greek, kyklos = round + Greek, cheilos = lip + Greek, ichtys = fish; *apogon*: Greek, a = without + Greek, pogon = chin, beard

Description: Fine ridges and folds across top and sides of head, small black spot on scale bases form longitudinal rows along body, mouth terminal, no barbel, caudal fin forked and caudal peduncle ocellated.

Comments: Usually found shoaling in slow moving or stagnant water in ex-tin mining lakes, canals, ditches and swamps.

Cyprinus carpio Linnaeus 1758

Common name: Common Carp

Local name: Kap

Native range: Basins of Black, Caspian and Aral seas in Europe

Etymology: *Cyprinus*: Latin, cyprinus = carp; *carpio*: latinized form of carp which was used by the Romans and Celts.

Description: Scaled overall dark greenish fusiform body, two pairs of barbels, caudal fin forked, terminal mouth and typically with enlarged rounded abdomen.

Comments: Not native to peninsula Malaysia. Care must be taken during identification process because it is a polytypic species having several variant forms to adapt to artificial breeding or environmental influences. Wildtype inhabits turbid well vegetated large rivers and lakes.

Esomus metallicus Ahl 1924

Common name: Striped Flying Barb

Local name: Seluang janggut

Native range: Salween, Mae Klong, Chao Phraya and Mekong basins in Indochina.

Etymology: *Esomus*: Latin, e = out of + Greek, sôma = body, presumably referring to long maxillary barbels; *metallicus*: Latin, metallum = metal, presumably referring to its reflective scales.

Description: An obvious lateral band beginning from behind the eye and extending to the base of the caudal fin, caudal fin forked, lateral line does not extend to the anal fin (in some cases it does not even reach ventral fin base), terminal mouth and extra-long maxillary barbels extending past pelvic base.

Comments: This species is regarded as non native to peninsula Malaysia by Lim and Tan (2002). It can be found shoaling in large numbers in ex-tin mining lakes and still water swamps in zone C.

Hampala macrolepidota Kuhl & van Hasselt 1823

Common name: Jungle Perch

Local name: Sebarau

Native range: Throughout Sundaic and mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Hampala*: Javanese, hampala is the vernacular name for the genus; *macrolepidota*: Greek, makrós = long + Greek, lepdotos = scaled

Description: Scaled fusiform body, mouth terminal, one pair of barbels, caudal fin forked, an obvious black bar between the dorsal and pelvic fins and submarginal stripe on orange/red caudal lobes.

Comments: Observed to swim in groups in well-oxygenated, clear rapids and torrent rivers. It is prized as food and sport fish by the locals.

Hypophthalmichthys nobilis (Richardson 1845)

Common name: Bighead Carp

Local name: Kap kepala besar

Native range: China.

Etymology: *Hypophthalmichthys*: Greek, hypo = under + Greek, ophthalmos = eye + Greek, ichthys = fish; nobilis: Latin, *nobilis* = noble, or celebrated.

Description: Large scaled body with small scattered black spots, mouth terminal slanting upwards, lower jaw extends slightly over upper jaw, without barbel, caudal fin forked and numerous keels extending from pelvic base to anus.

Comments: Not native to peninsula Malaysia. It is a popular food fish that is extensively farmed. Feral population typically inhabits large and deep lakes.

Labeo rohita (Hamilton 1822)

Common name: Rohu

Local name: Kap india

Native range: Pakistan, Nepal, India, Bangladesh, Sri Lanka and Myanmar.

Etymology: *Labeo*: Latin, labeo = with large lips; rohita: Sanskrit, *rohita* = blood or reddish carp.

Description: Slightly reddish/brownish fins, scaled body, caudal fin forked, blunt snout, lips papillose and terminal mouth with maxillary barbels concealed in lateral groove.

Comments: Not native to peninsula Malaysia. Extensively bred by the local aquaculture farms and escapee population inhabits large pond and deep lakes with semi-aquatic vegetation.

Labiobarbus leptocheilus (Valenciennes 1842)

Common name: (none)

Local name: Kawan

Native range: Indochina, Malay Peninsula, Sumatra, Borneo and Java.

Etymology: *Labiobarbus*: Latin, labium = lip + Latin, barbus = barbel; *leptocheilus*: Greek, lepto = fine or thin + Greek, cheilos = lip, edge or margin.

Description: Body with noticeable longitudinal stripes formed by small black mark on each scale, mouth terminal, caudal fin forked with long dorsal fin.

Comments: A pelagic fish that inhabits clear flowing waterways and feeding on organic detritus, benthic algae, phytoplankton, periphyton, small crustaceans and aquatic insect larvae.

Leptobarbus hoevenii (Bleeker 1851)

Common name: Sultan Fish

Local name: Jelawat

Native range: Thailand, Malay Peninsula, Borneo, Sumatra and Java.

Etymology: *Leptobarbus*: Greek, leptós = slender + Latin, barbus = barbel; *hoevenii*: in honour of Jan van der Hoeven.

Description: Scaled plain coloured fusiform body, a black blotch behind opercle, caudal fin forked, mouth terminal, two pairs of barbels, lateral line ending below middle of caudal base and head straight to slightly concave profile.

Comments: A pelagic fish that inhabits clear running waters and intolerant to low dissolved oxygen level. It feeds on plant-based detritus, zooplankton and small macroinvertebrates. This species is often misidentified as *L. rubripinna* and the details of difference are described in Tan and Kottelat (2009). Specimens found in Kampar region are most probably escapees from the aquaculture farms.

Leptobarbus rubripinna (Fowler 1937)

Common name: Red-finned Cigar Shark

Local name: Jelawat siam

Native range: Mekong and Chao Phraya basins.

Etymology: *Leptobarbus*: Greek, leptós = slender + Latin, barbus = barbel; *rubripinna*: Latin, rubra = red + pinna = fin.

Description: *L. rubripinna* can be mainly distinguished from congener *L. hoevenii* with anal and caudal fin lobes rounded and reddish (vs. pointed and dark grey).

Comments: Not native to peninsula Malaysia and typically misidentified as *L. hoevenii*. Commonly bred in aquaculture industry as replacement to *L. hoevenii* as a high value food fish (i.e. *L. hoevenii* is becoming rare due to overfishing). Feral population may be found in rivers, lakes and it has a better tolerance to low dissolved oxygen level in waters than *L. hoevenii*.

Mystacoleucus obtusirostris (Valenciennes 1842)

Common name: (none)

Local name: Sia

Native range: Throughout Sundaic and mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Singapore, Borneo and Indonesia.

Etymology: *Mystacoleucus*: Greek, mystax = whiskered + Greek, iusculus = slightly, or somewhat; *obtusirostris*: Latin, obtusus = blunt + Latin, rostrum = snout or beak.

Description: Most scales with black base, mouth terminal, dorsal-fin with black anterior and distal margins, and caudal fin forked with black distal margin. It has an obscure procumbent predorsal spine pointing towards the snout.

Comments: Inhabits fast rocky streams and well oxygenated swamps. It may be referred to as *M. marginatus* in many reports before it was revised by Kottelat (2013).

Neolissochilus soroides (Duncker 1904)

Common name: Copper Mahseer

Local name: Tengas

Native range: Thailand, Cambodia and Malay Peninsula.

Etymology: *Neolissochilus*: Greek, neos = new + Greek, lissos = smooth + Greek, cheilos = lip; *soroides*: Soro = Javanese name for *Tor soro* + Greek, ides = descendant of, i.e. "like soro"

Description: Scaled bodied, caudal fin deeply forked, cheek with tubercles, mouth terminal and dorsal fin spine not serrated with lateral-line scales 20–24, usually 22, and predorsal scales 8–10. Due to trophic polymorphism *N. soroides* has three mouth types, namely normal, truncated and lobed.

Comments: Only found in well oxygenated and intact forested flowing streams and rivers with sandy and rocky bottoms. This species is often misidentified as *N. hendersoni* which only has lateral-line scales 18-22, usually 20, and predorsal scales 6–8. Moreover *N. hendersoni* has so far only been recorded in northern Malay Peninsula, namely in the regions of Penang, Kedah, Langkawi and Kelantan (Khaironizam et al., 2015). It is also often misidentified as

sympatric species *Poropuntius smedleyi* which has lateral-line scales 27–28 and slightly longer caudal fin lobes.

Osteochilus vittatus (Valenciennes 1842)

Common name: Bonylip Barb

Local name: Terbul

Native range: Throughout Sundaic southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Singapore, Borneo and Indonesia.

Etymology: *Osteochilus*: Greek, osteon = bone + Greek, cheilos = lip; *vittatus*: Latin, vitta = ribbon, band or stripe.

Description: Scaled bodied with some orange/red scale bases, caudal fin deeply fork, mouth terminal, lateral side of upper lip thick with many folds and long dorsal fin.

Comments: Found in turbid streams, rivers and wetlands, and has tolerance to low dissolved oxygen level in waters. Bony but prized as food fish by the locals.



Figure 4.3: Visual data for species, 1) *Notopterus notopterus*; 2) *Barbodes* cf. *rhombeus*; 3) *Barbonymus gonionotus*; 4) *Barbonymus schwanefeldii*; 5) *Crossocheilus obscurus*; 6) *Cyclocheilichthys apogon*; 7) *Cyprinus carpio*; 8) *Danio albolineata*



Figure 4.4: Visual data for species, 9) *Esomus metallicus*; 10) *Hampala macrolepidota*; 11) *Toxabramis cf. houdemeri*; 12) *Hypophthalmichthys nobilis*; 13) *Labeo rohita*; 14) *Labiobarbus leptocheilus*; 15) *Leptobarbus hoevenii*; 16) *Leptobarbus rubripinna*



Figure 4.5: Visual data for species, 17) *Mystacoleucus obtusirostris*; 18) *Neolissochilus soroides*; 19) *Osteochilus vittatus*; 20) *Poropuntius smedleyi*; 21) *Puntigrus partipentazona*; 22) *Rasbora vulgaris*; 23) *Homalopteroides smithi*; 24) *Balitoropsis zollingeri*

Poropuntius smedleyi (de Beaufort 1933)

Common name: (none)

Local name: Tengas daun

Native range: So far the species is only reported in Malay Peninsula (type locality: Johor).

Etymology: *Poropuntius*: Greek, poros = porous + Greek, punctum = pointed; *smedleyi*: in honour of Norman Smedley.

Description: Scaled bodied, caudal fin deeply forked and mouth terminal. Appears similar to *N. soroides* but with slightly longer caudal fin and dorsal fin spine serrated. This species can also be distinguished by lateral-line scales 27–28 compared to *N. soroides* with lateral-line scales 20–24.

Comments: Inhabits well oxygenated and intact forested flowing streams and rivers with sandy and rocky bottoms. This species is often misidentified as a species from the *Neolissochilus* genus.

Puntigrus partipentazona (Fowler 1934)

Common name: Tiger Barb

Local name: Pelampung jaring

Native range: Mekong, Mae Khlong and Chao Phraya basins in Thailand and Malay Peninsula.

Etymology: *Puntigrus*: Greek, punctum = pointed + Latin, tigris = tiger; *partipentazona*: Latin, partire = apart, divide up + Greek, penta = five + Latin, zōna = band or belt.

Description: Scaled bodied, caudal fin deeply forked and mouth terminal. Broad black bars on body with one across the eye, and red/orange pelvic, dorsal and caudal fins.

Comments: Found in still water or very slow flowing water in the weedy marginal zones of ponds, lakes and wetland.

Rasbora vulgaris Duncker 1904

Common name: Malayan Rasbora

Local name: Seluang

Native range: Endemic to Malay Peninsula (Lumbantobing 2014).

Etymology: *Rasbora*: Indian = fish; *vulgaris*: Latin = common.

Description: Scaled elongated bodied, mouth terminal with a symphseal knob that fits into a depression in the maxilla, gape not larger than eye diameter, barbels absent, and caudal fin deeply forked with caudal peduncle ocellated with a metallic dark green spot. Lateral pigmentation features follow Kottelat (2005) and Lumbantobing (2014) under the Lateristriata subgroup.

Comments: Inhabits hillside streams, rivers and also lowland wetlands with sandy-gravel substrate. It is highly adaptable to fast, slow and still waters. This species is sometimes misidentified as its closest congener *R. paviana*.

Toxabramis cf. houdemeri Pellegrin 1932

Common name: Silver blade-minnow

Local name: Pimpin

Native range: Southern China, Hainan Island and northern Vietnam (Chen et al., 1987).

Etymology: *Toxabramis*: Greek, toxotes = archer + abramis = referring to original placement in Abramidinae family; *houdemeri*: in honor of Fernand Édouard Houdemer who collected the type in a market in Hanoi, Vietnam.

Description: Scaled slender body, laterally compressed, keel extending from anal fin base to between the pectoral-fin base, serrated dorsal spine, mouth slightly superior, barbels absent, and caudal fin deeply forked.

Comments: Not native to peninsula Malaysia. Large feral groups can be found in wetlands heavily disturbed by aquaculture activities. Speculated to be introduced together with aquaculture carps population from China. Observed sold in the fresh market as food species and as live feeder fish in the aquarium industry.

Family BALITORIDAE

Homalopteroides smithi (Hora 1932)

Common name: (none)

Local name: Susoh batu

Native range: Mekong, Mae Khlong and Chao Phraya basins in Thailand and Malay Peninsula.

Etymology: *Homalopteroides*: Greek, homalos = flat + Greek, pteron = wing + Latin, oides = likeness; *smithi*: in honour of Hugh M. Smith.

Description: Depressiform, caudal fin lunate, inferior mouth with pectoral fin extending beyond pelvic fin origin.

Comments: Small individuals are widespread but never abundant among smooth rocks and pebbles in fast flowing shallow hillside streams and rivers. Observed to feed on aquatic macroinvertebrates present in organic detritus trapped among the rocks.

Balitoropsis zollingeri (Bleeker 1853)

Common name: Black Lizard Loach

Local name: Puting beliung

Native range: Laos, Vietnam, Cambodia, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Balitoropsis*: Balitora = a genus of fish + Greek, opsis = appearance, resemblance; *zollingeri*: in honour of Heinrich Zollinger.

Description: Depressiform, caudal fin lunate, inferior mouth with pectoral fin not reaching the origin of the pelvic fin.

Comments: Previously grouped under the *Homaloptera* genus and it is often found sympatrically with *Homalopteroides smithi* thus misidentification is possible.

Family SERRASALMIDAE

Piaractus brachypomus (Cuvier 1818)

Common name: Red-bellied Pacu

Local name: Pacu

Native range: Amazon and Orinoco basins in South America.

Etymology: *Piaractus*: Greek, piar = fat, greasy + Greek, arktos = to bear; *brachypomus*: Greek, brachy = short + Greek, pōma = lid, operculum.

Description: Strongly compressiform, body finely scaled, mouth terminal, two rows of teeth on upper and lower jaw, small adipose fin, caudal fin truncated with red/orange belly, pectoral, pelvic and anal fin.

Comments: Not native to peninsula Malaysia and it is bred in aquaculture farms as food species. Feral population often found in low dissolved oxygen

and turbid waters in slow flowing rivers and wetlands. Often sympatric with other introduced species.

Family LORICARIIDAE

Pterygoplichthys disjunctivus (Weber 1991)

Common name: Vermiculated Sailfin Catfish

Local name: Bandaraya

Native range: Madeira basin in Bolivia and Brazil.

Etymology: *Pterygoplichthys*: Greek, pteryx = wing, fin + Greek, hoplon = weapon + Greek, ichthys = fish; *disjunctivus*: Latin, disjunctivus = disjoin, separated.

Description: Strongly despressiform, vermiculated pattern on ventral surface, mouth inferior, armored skin, caudal fin lunate and large dorsal fin.

Comments: Not native to peninsula Malaysia and introduced by the aquarium hobbyist industry. It is widespread in slow flowing rivers and wetlands with low oxygenated and turbid waters. It also has the capability of thriving in mesohaline conditions.

Family SISORIDAE

Glyptothorax schmidti (Volz 1904)

Common name: (none)

Local name: Depu

Native range: Sumatra and Malay Peninsula.

Etymology: *Glyptothorax*: Greek, glyptes = carver + Greek, thorax = chest; *schmidti*: patronym could not be identified, probably in honour of ichthyologist Petr Yulevich Schmidt or biologist Johannes Schmidt.

Description: Depressiform, scaleless, caudal fin forked, barbels four pairs, uniformly dark body with prominent pale mid-dorsal and midlateral stripes, and thoracic adhesive apparatus present on ventral side. It can be further distinguished from other Sundaic congeners by referring to Ng and Kottelat (2016).

Comments: Ubiquitous and inhabits the benthic zone of well oxygenated torrential stream and river. The thoracic adhesive apparatus is adapted to adhere to rock surface to prevent the fish from being swept off by strong currents. It is often sympatric with *Balitoropsis zollingeri* and *Homalopteroides smithi*.

Family SILURIDAE

Silurichthys schneideri Volz 1904

Common name: (none)

Local name: Gemang darat

Native range: South-eastern Thailand, northern Malay Peninsula and northern Sumatra.

Etymology: *Silurichthys*: Greek, silouros = catfish + Greek, odoús = tooth + Greek, ichthys = fish; *schneideri*: in honour Gustav Schneider.

Description: Without scales, exceptionally small dorsal fin, caudal fin rounded, mouth terminal and two long barbels. The species propel itself with wavelike flexure of long anal fin, normally termed as “ribbon fin”.

Comments: Found in slow flowing microhabitats with submerged decaying tree stumps or other organic debris.

Family CLARIIDAE

Clarias aff. *batrachus* (Linnaeus 1758)

Common name: Walking Catfish

Local name: Keli kayu

Native range: Restricted to Sundaic region

Etymology: *Clarias*: Greek, chlaros = lively; *batrachus*: Greek, batrachos = frog-like, perhaps referring to its amphibious ability

Description: Mouth, scaleless dark body with numerous minute white spots, four pairs of barbels with thick fleshy bases, caudal fin rounded, dorsal fin extending to caudal peduncle and supraoccipital process more or less triangular.

Comments: Nocturnal and active by night. The species inhabits still swamps, canals and ditches with soft substrate of organic decaying material and soil sediment. Rarely found in the main rivers. The taxonomic identity of this species remains unclear and the authorities hypothesized that there may be four valid species of Javanese, Indian, Indochinese or Sundaland origins. Currently, the authorities have classified specimens from the Malay Peninsula and Borneo to be *C. aff. batrachus* "Sundaland" until the uncertainty is resolved (Ng and Kottelat, 2008; Lee and Sulaiman, 2015).

Clarias gariepinus (Burchell 1822)

Common name: African Catfish

Local name: Keli afrika

Native range: Africa and Middle East.

Etymology: *Clarias*: Greek, chlaros = lively; *gariepinus*: in honour of its type locality Gariep River (now known as Orange River) in South Africa.

Description: Scaleless body usually with irregular dark blotches on light grey background, white ventral surface, mouth terminal, caudal fin rounded, dorsal fin extending to caudal peduncle and supraoccipital process pointed.

Comments: Not native to peninsula Malaysia but widespread due to its tolerance to heavily polluted waters. It is extensively bred by the local aquaculture industry as food species. Feral population inhabits rivers and wetlands with soft muddy substrate.

Clarias leiacanthus Bleeker 1851

Common name: Forest Walking Catfish

Local name: Keli mata kati

Native range: Throughout Sundaic and mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Singapore, Borneo and Indonesia.

Etymology: *Clarias*: Greek, chlaros = lively; *leiacanthus*: Greek, leios = smooth + Greek, akanthus = spine, thorn.

Description: Scaleless dark brown body marked with vertical rows of yellowish spots, mouth terminal, four pairs of barbels, caudal fin rounded and dorsal fin extending to caudal peduncle.

Comments: Individuals are commonly found in forested or semi-disturbed freshwater or peat swamps and slow streams. It is often sympatric with *C. aff. batrachus* and *C. nieuhoftii*.

Clarias nieuhofii Valenciennes 1840

Common name: Slender Walking Catfish

Local name: Keli limbat

Native range: Throughout Sundaic and mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Singapore, Borneo, Philippines and Indonesia.

Etymology: *Clarias*: Greek, chlaros = lively; *nieuhofii*: in honour of Johan Nieuhof.

Description: Appearance resembles *C. leiacanthus* but possesses elongated eel-like body.

Comments: *C. nigricans* described in eastern Borneo (Ng, 2003), *C. pseudonieuhofii* described in western Borneo (Sudarto et al., 2004) and *C. gracilentus* described in Vietnam (Ng et al., 2011) were reported to be superficially resembled *C. nieuhofii*. Currently these anguilliform species are grouped under the "*C. nieuhofii*" taxonomic complex.



Figure 4.6: Visual data for species, 25) *Piaractus brachypomus*; 26) *Pterygoplichthys disjunctivus*; 27) *Glyptothorax schmidti*; 28) *Silurichthys schneideri*; 29) *Clarias aff. batrachus*; 30) *Clarias gariepinus*; 31) *Clarias leiacanthus*; 32) *Clarias nieuhoftii*

Family PANGASIIDAE

Pangasianodon hypophthalmus (Sauvage 1878)

Common name: Iridescent Shark, Sutchi Catfish

Local name: Patin

Native range: Mekong, Chao Phraya and Mae Klong basins.

Etymology: *Pangasianodon*: Assamese, pangas = name of *Pimelodus pangasius* in India + Greek, an = without + Greek, odon = tooth; *hypophthalmus*: Greek, hypo = below + Greek, ophthalmus = eyes.

Description: Scaleless body, mouth terminal, caudal fin forked, anal fin extending to caudal peduncle.

Comments: Not native to peninsula Malaysia but widespread in rivers due to escapees from the aquaculture industry. Due to its potamodromous nature, the species can be found in low oxygenated and turbid down or upriver but never in shallow fast waters. Attempt to cross breed non-native *P. hypophthalmus* and native *Pangasius nasutus* has successfully produced a hybrid for the aquaculture industry (Hassan et al., 2011), thus species identification of *P. hypophthalmus* may be inconsistent due to hybrids that may exist in the wild.

Family BAGRIDAE

Hemibagrus capitulum (Popta 1904)

Common name: (none)

Local name: Baung

Native range: Southern Thailand, Sumatra, Malay Peninsula and Borneo.

Etymology: *Hemibagrus*: Greek, hemi = partial, half + Portuguese, bagrus = catfish; *capitulum*: Latin, capit = head + Latin, ulum = small.

Description: Scaleless body, depressed head, mouth terminal, four pairs of barbels, caudal fin deeply forked with upper lobe of caudal fin filamentous, and with adipose fin.

Comments: Usually found in downriver where water is lowly oxygenated and turbid. It is also valued as a food fish and bred by the aquaculture industry. Often misidentified as *H. nemurus* or *H. fortis* in many references and literature until Ng and Kottelat (2013) clarified their taxonomical status and localities; *H. nemurus* only occurs in Java Island.

Mystus singaringan (Bleeker 1846)

Common name: (none)

Local name: Baung tikus

Native range: Throughout Sundaic mainland Southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indo-Malay archipelago.

Etymology: *Mystus*: Greek, *mystax* = whiskered; *singaringan*: Indonesian, *singaringan* = vernacular name for this species.

Description: Scaleless light yellow body, depressed head, mouth subterminal, caudal fin deeply forked, extended adipose fin, four pairs of barbels with maxillary barbels reaching beyond anal fin.

Comments: Usually inhabits slow and turbid down rivers and wetlands with soft muddy substrate.

Family APLOCHEILIDAE

Aplocheilus armatus (van Hasselt 1823)

Common name: Blue Panchax

Local name: Kepala timah, Mata lalat

Native range: Pakistan, Nepal, Sri Lanka, India, Bangladesh, throughout Sundaic southeast Asia and Indo-Malay archipelago.

Etymology: *Aplocheilus*: Greek, *aploe* = simple + Greek, *cheilos* = lip; *armatus*: Latin, *armatum* = armed, armoured.

Description: Scaled body, mouth terminal, caudal fin rounded and a white spot on top of head.

Comments: Inhabits still freshwater and hypersaline waters of shallow vegetated canals, paddy fields, water pockets and ditches. It is a larvivorous fish with a reputation as biological control for mosquito larva.

Family POECILIIDAE

Poecilia reticulata Peters 1859

Common name: Guppy

Local name: Gapi

Native range: Northern South America, coastal drainages Guyana, Suriname, of Venezuela, Trinidad, Tobago and the Brazilian states of Amapá and Pará.

Etymology: *Poecilia*: Greek, poikilos = variegated, embroidered; *reticulata*: Latin, reticulum = fine mesh, grid.

Description: Top of head scaled, caudal fin rounded and mouth terminal. The species displays sexual dimorphism where male has obvious colour patterns and a slender modified anal fin (gonopodium) while the female is larger and colourless.

Comments: Not native to peninsula Malaysia. It is a larvivorous fish that can tolerate polluted waters in lakes, ponds, canals and ditches.

Family SYNBRANCHIDAE

Monopterus javanensis La Cepède 1800

Common name: Rice Field Eel

Local name: Belut sawah

Native range: Sundaic southeast Asia from Fujian (China) to Indo-Malay archipelago.

Etymology: *Monopterus*: Greek, monos = one + Greek, pteron = fin; *javanensis*: denoting Java Island.

Description: Anguilliform scaleless body, gill openings at ventral, mouth terminal, pectoral and pelvic fin not present, caudal fin pointed and continuation from anal fin.

Comments: Inhabits shallow water with muddy substrate. In previous papers, this species was commonly cited as *M. albus*. However, a study found *M. albus* to be genetically divided into three clades, namely China-Japan, Ryukyu Islands, and Southeast Asian clades (Matsumoto et al., 2010). Until their taxonomic statuses are clarified, Kottelat (2013) proposes that the Southeast Asian population should be cited as *M. javanensis* and the China-Japan species population should be cited as *M. albus*. Species found in Ryukyu Islands in Japan has not been described and named yet; currently it is simply referred to as the “Ryukyuan” population.

Family MASTACEMBELIDAE

Mastacembelus favus Hora 1923

Common name: Tire Track Eel

Local name: Tilan

Native range: Thailand to the Malay Peninsula.

Etymology: *Mastacembelus*: Greek, mastax = mouth + Greek, emballo = to throw in; *favus*: Latin, favus = honeycomb

Description: Anguilliform body, body scales minute, a row of short dorsal spines (33-37), anal spine present, short flexible and fleshy snout, no pelvic fin, body pattern extending to abdomen, caudal fin pointed and continuation from anal fin.

Comments: Inhabits slow unpolluted waters with sandy/rocky substrate. The species is usually misidentified as *M. armatus* in many reports. In some reports, it may be cited as *M. armatus* var. *favus*. However, Roberts (1986) clarified that *M. armatus* has many distinctions from *M. favus*. He also warns that the two species may be sympatric in some Thai localities but not in Malay Peninsula. Kottelat (2013) recognizes *M. armatus* and *M. favus* as two valid species.



Figure 4.7: Visual data for species, 33) *Pangasianodon hypophthalmus*; 34) *Hemibagrus capitulum*; 35) *Mystus singaringan*; 36) *Aplocheilus armatus*; 37) *Poecilia reticulata* (male); 38) *Poecilia reticulata* (female); 39) *Monopterus javanensis*; 40) *Mastacembelus favus*

Family AMBASSIDAE

Parambassis siamensis (Fowler 1937)

Common name: Glassperch

Local name: Seriding

Native range: Mekong, Mae Khlong, Chao Phraya basin in Indochina, Thailand and Malay Peninsula. Population in Singapore and Indonesia are introduced (Roberts, 1994; Ng et al., 1993; Ng and Lim, 1997).

Etymology: *Parambassis*: Greek, para = near + Greek, anabasis = ascending; *siamensis*: denoting Siam, or Thailand.

Description: Body strongly compressiform, mouth terminal, caudal fin forked, eye preorbital bone with serration on ridge and edge, deep notch on dorsal fin, notable black blotch at spinous dorsal fin and entire body appears translucent.

Comments: Inhabits still water or very slow flowing water in the weedy marginal zones of lower rivers, ponds, ditches, canals, lakes and wetland.

Family PRISTOLEPIDIDAE

Pristolepis fasciata (Bleeker 1851)

Common name: Malayan Leaf-fish

Local name: Patung

Native range: Sundaic southeast Asia and Malay-Indo archipelago.

Etymology: *Pristolepis*: Greek, *pristis* = saw + Greek, *lepis* = flake, scale;
fasciata: Latin, *fascia* = band, strip, stripe.

Description: Body strongly compressiform, mouth terminal, caudal fin rounded, lateral line interrupted.

Comments: Inhabits turbid still vegetated ponds, wetlands and slow flowing canals. Rarely found in the main rivers.

Family CICHLIDAE

Cichla monoculus Spix & Agassiz 1831

Common name: Peacock Cichlid

Local name: (none)

Native range: Brazil, French Guiana, Guyana and Suriname.

Etymology: *Cichla*: Greek, *kichle* = wrasse; *monoculus*: Latin, *mono* = one + Latin, *culus* = eye.

Description: Scaled compressiform body, mouth terminal, discontinued lateral line, caudal fin truncated, ocellated on posterior end of hypural plate and three broad bars with some black spots on yellowish body.

Comments: Not native to peninsula Malaysia. It was first introduced by anglers as game fish into mining pools of Batu Gajah and Air Kuning in Perak (DOF, 2007). It is now widespread in lakes and wetlands. The taxonomic diversity and ecological behaviours of cichlid fishes from Middle America and Africa are extensively discussed by Rican et al. (2017).

Mayaheros urophthalmus (Günther 1862)

Common name: Mayan Cichlid

Local name: (none)

Native range: México, Belize, Nicaragua, Honduras and eastern Guatemala.

Etymology: *Mayaheros*: Maya = Mesoamerican Mayan people + Mayan, heros = hero; *urophthalmus*: Greek, oura = tail + Greek, ophthalm = relating to eye.

Description: Compressiform scaled body, mouth terminal, branchiostegal membrane pink/orange, seven (sometimes eight) bars on body and dark blotch on truncated caudal fin base.

Comments: Not native to peninsula Malaysia. An eurytopic species that can tolerate a wide range of environment in lowland freshwater lakes, canals, wetlands and brackish biotopes.

Oreochromis aureus (Steindachner 1864)

Common name: Blue tilapia

Local name: Tilapia

Native range: Northern and Western Africa, and the Middle East.

Etymology: *Oreochromis*: Greek, oreos= mountain + chromis = fish; *aureus*: Latin, aurum = golden.

Description: Compressiform scaled dark body, mouth terminal, caudal fin truncated, metallic blue cheek.

Comments: Not native to peninsula Malaysia and introduced by the aquaculture industry. Feral population inhabits shallow waters in wetland with sandy substrate which the males require to build spawning pits.

Oreochromis niloticus (Linnaeus 1758)

Common name: Nile tilapia

Local name: Tilapia

Native range: Northern and eastern Africa.

Etymology: *Oreochromis*: Greek, oreos= mountain + chromis = fish; *niloticus*: denoting Nile River.

Description: Compressiform scaled dark body, mouth terminal, small vertical stripes throughout depth of truncated caudal fin.

Comments: Not native to peninsula Malaysia and introduced by the aquaculture industry. It is also often misidentified as sympatric species *O. aureus*.

Family ELEOTRIDIDAE

Oxyeleotris marmorata (Bleeker 1852)

Common name: Marble Goby

Local name: Ketutu

Native range: Throughout Sundaic southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Oxyeleotris*: Greek, oxys = sharp + Greek, eleos = bewildered;
marmorata: Latin, marmorō = marble.

Description: Fine scaled body with mottled pattern, mouth terminal, lower jaw projecting, head broad and flattened, caudal fin rounded and with two separate dorsal fins.

Comments: Found in ponds, lakes and swamps. Not usually found in running rivers and fast rapids.

Family ANABANTIDAE

Anabas testudineus (Bloch 1792)

Common name: Climbing perch

Local name: Puyu

Native range: Widespread throughout India, throughout Sundaic southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Anabas*: Greek, anabasis = climbing up; *testudineus*: Latin, testudo = tortoise + Latin, ineus = made from.

Description: Scaled body, mouth terminal, caudal fin rounded, with operculum serrated with spines, dark spot on opercle posterior margin and caudal peduncle. Color in life ranges from green, olive, light brown to dark.

Comments: Occurs in muddy, turbid, stagnant water bodies. It is an obligate air breather with a distinct ability to survive in hypoxic waters or for several days out of water. Several species may be confused under the name *A. testudineus* and awaiting further clarification (Kottelat, 2013).



Figure 4.8: Visual data for species, 41) *Parambassis siamensis*; 42) *Pristolepis fasciata*; 43) *Cichla monoculus*; 44) *Mayaheros urophthalmus*; 45) *Oreochromis aureus*; 46) *Oreochromis niloticus*; 47) *Oxyeleotris marmorata*; 48) *Anabas testudineus*

Family HELOSTOMATIDAE

Helostoma temminckii Cuvier 1829

Common name: Kissing gourami

Local name: Temakang

Native range: Widespread throughout Sundaic southeast Asia namely Cambodia, Vietnam, Thailand, Malay Peninsula, Borneo and Indonesia.

Etymology: *Helostoma*: Greek, helo = nail + Greek, stoma = mouth; *temminckii*: in honour of Coenraad Jacob Temminck.

Description: Scaled body strongly compressed laterally, caudal fin indented and mouth terminal with brown-coloured protrusible thick lips.

Comments: While the variety offered by the fishkeeping hobby industry is typically pinkish, the wildtype is usually dark green. It is associated with moderately turbid and clear water habitats with submerged vegetation.

Family OSPHRONEMIDAE

Betta pugnax (Cantor 1849)

Common name: Penang Betta

Local name: Sepilai batu

Native range: Malay Peninsula and Singapore.

Etymology: *Betta*: Malay, betah = persistent, or resolute; *pugnax*: Latin, pugnax = combative.

Description: Head rhombic when viewed dorsally, greenish to bluish iridescent spots on the scales and operculum, mouth terminal and caudal fin broadly lanceolate.

Comments: Usually found in peripheries of stagnant water pockets in hillside streams with overhanging riparian vegetation and rocky sandy substrate. Taxonomic and distribution account of *B. pugnax* and other species in the *Betta* genus is discussed and described extensively in Tan and Tan (1996) and Tan and Ng (2005) .

Trichopodus pectoralis Regan 1910

Common name: Snakeskin gourami

Local name: Sepat siam

Native range: Mekong and Chao Phraya basins in Cambodia, Laos, Thailand, Vietnam and Myanmar.

Etymology: *Trichopodus*: Greek, tricho = hair + Greek, podus = leg; *pectoralis*: Latin, pectus = pectoral, breast.

Description: Mottled lateral stripe across body, mouth terminal, caudal fin slightly emarginated, long filamentous pelvic fin ray extending posteriorly to caudal fin.

Comments: Not native to peninsula Malaysia. Capable of breathing atmospheric air and can tolerate turbid and low oxygenated water in stagnant ponds and swamps.

Trichopodus trichopterus (Pallas 1770)

Common name: Three spot gourami

Local name: Sepat ronggeng

Native range: Widespread throughout the Sundaic mainland southeast Asia and Malay Peninsula.

Etymology: *Trichopodus*: Greek, tricho = hair + Greek, podus = leg; *trichopterus*: Greek, tricho = hair + Greek, pterón = wing.

Description: Mouth terminal, two spots on the body, caudal fin slightly emarginated, long filamentous pelvic fin ray with orange spotted anal and caudal fin.

Comments: Found in low oxygenated lowland ponds, lakes and swamps. Not usually found in running rivers and fast rapids. It is often sympatric with other species from the Osphronemidae family.

Trichopsis vittata (Cuvier 1831)

Common name: Croaking Gouramy

Local name: Karim

Native range: Widespread throughout the Sundaic mainland southeast Asia and Indo-Malay archipelago.

Etymology: *Trichopsis*: Greek, tricho = hair + Greek, ópsis = appearance; *vittata*: Latin, vittatus = stripe, band.

Description: Body usually with three lateral stripes, mouth terminal, caudal fin broadly lanceolate and long filamentous pelvic fin ray.

Comments: Commonly found in lowland swamp habitat with dense vegetation.

Family CHANNIDAE

Channa gachua (Hamilton 1822)

Common name: Dwarf Snakehead

Local name: Haruan kedak

Native range: Sundaic mainland southeast Asia and Indo-Malay archipelago.

Etymology: *Channa*: Latin, channe = referring to a form of sea perch; *gachua*: Bengali, gachua = vernacular name for this species.

Description: Scaled body, mouth terminal, red/orange margin on long dorsal, anal and rounded caudal fin.

Comments: Usually found in slow moving waters in hillside streams with overhanging riparian vegetation and rocky sandy substrate. Conte-Grand et al. (2017) reported that species commonly cited as *Channa gachua* in many

papers may be erroneous. This species is involved in a complex of two widespread phylogenetic lineages. They propose that the true *C. gachua* belongs to the western lineage that covers Bangladesh, India, Nepal, Sri Lanka and Myanmar (Rakhine region). They also suggest that specimens should be cited as *C. limbata* if they are encountered in eastern lineage which covers Myanmar towards Vietnam, southern China, Thailand, peninsular Malaysia and Indonesia. Until further detailed studies emerge to conclusively validate the eastern lineage, this paper continues to adopt *Channa gachua*.

Channa lucius (Cuvier 1831)

Common name: Forest Snakehead

Local name: Bujuk

Native range: Widespread throughout Tenasserim mountain range in Myanmar east to the Mekong and south to the Indo-Malay archipelago.

Etymology: *Channa*: Latin, channe = referring to a form of sea perch; *lucius*: Latin, lucius = light.

Description: Scaled body, mouth terminal, caudal fin rounded, a series of black blotches on body and oblique bars on abdomen.

Comments: Commonly found in lowland swamp habitat with dense vegetation and submerged large woody debris and snag.



Figure 4.9: Visual data for species, 49) *Helostoma temminckii*; 50) *Betta pugnax*; 51) *Trichopodus pectoralis*; 52) *Trichopodus trichopterus*; 53) *Trichopsis vittata*; 54) *Channa gachua*; 55) *Channa lucius*; 56) *Channa micropeltes*

Channa micropeltes (Cuvier 1831)

Common name: Giant Snakehead

Local name: Toman

Native range: Widespread throughout the Sundaic mainland southeast Asia and Indo-Malay archipelago.

Etymology: *Channa*: Latin, channe = referring to a form of sea perch; *micropeltes*: Greek, mikros = small + Greek, pelte = shield.

Description: Scaled body, mouth terminal, caudal fin rounded, blue, green, purple or pink patterns along with black irregular lateral stripes on body (juveniles have two clear stripes) and prominent canine teeth.

Comments: Occurs in deep pond, lakes and wetlands.

Channa striata (Bloch 1793)

Common name: Striped Snakehead

Local name: Haruan

Native range: Pakistan, Peninsula India, Sundaic mainland southeast Asia and Indo-Malay archipelago.

Etymology: *Channa*: Latin, channe = referring to a form of sea perch; *striata*: Latin, striatus = striped.

Description: Scaled body, mouth terminal, caudal fin rounded, faint chevron bars on body with white ventral surface.



Figure 4.10: Visual data for species, *Channa striata*

4.1.2 Species occurrence in zones

A total of 16 introduced species were recorded in the zones. Zone A recorded the highest percentage of native species occurrence (99.7%) followed by zone B (65.9%) and zone C (33.3%). As expected, species from Cyprinidae (21 species) were numerically most abundant in Kampar River catchment, followed by Clariidae (four species), Osphronemidae (four species) and Channidae (four species). The rank abundance, diversity and sympatric occurrences of native and introduced species in each zone are highlighted in Figure 4.11 and 4.12 respectively.

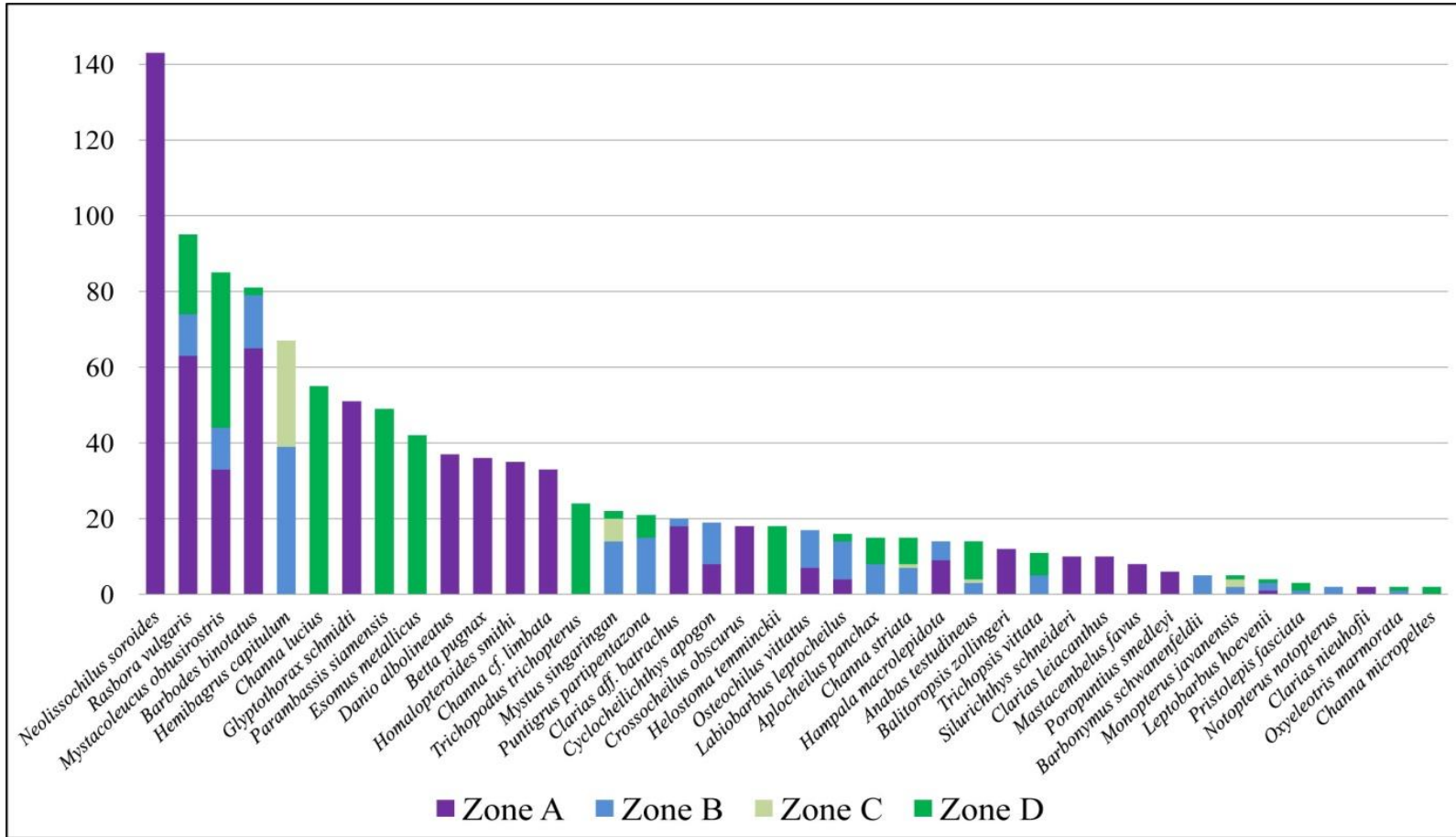


Figure 4.11: Rank abundance, diversity and sympatric occurrences in native species population among studied zones

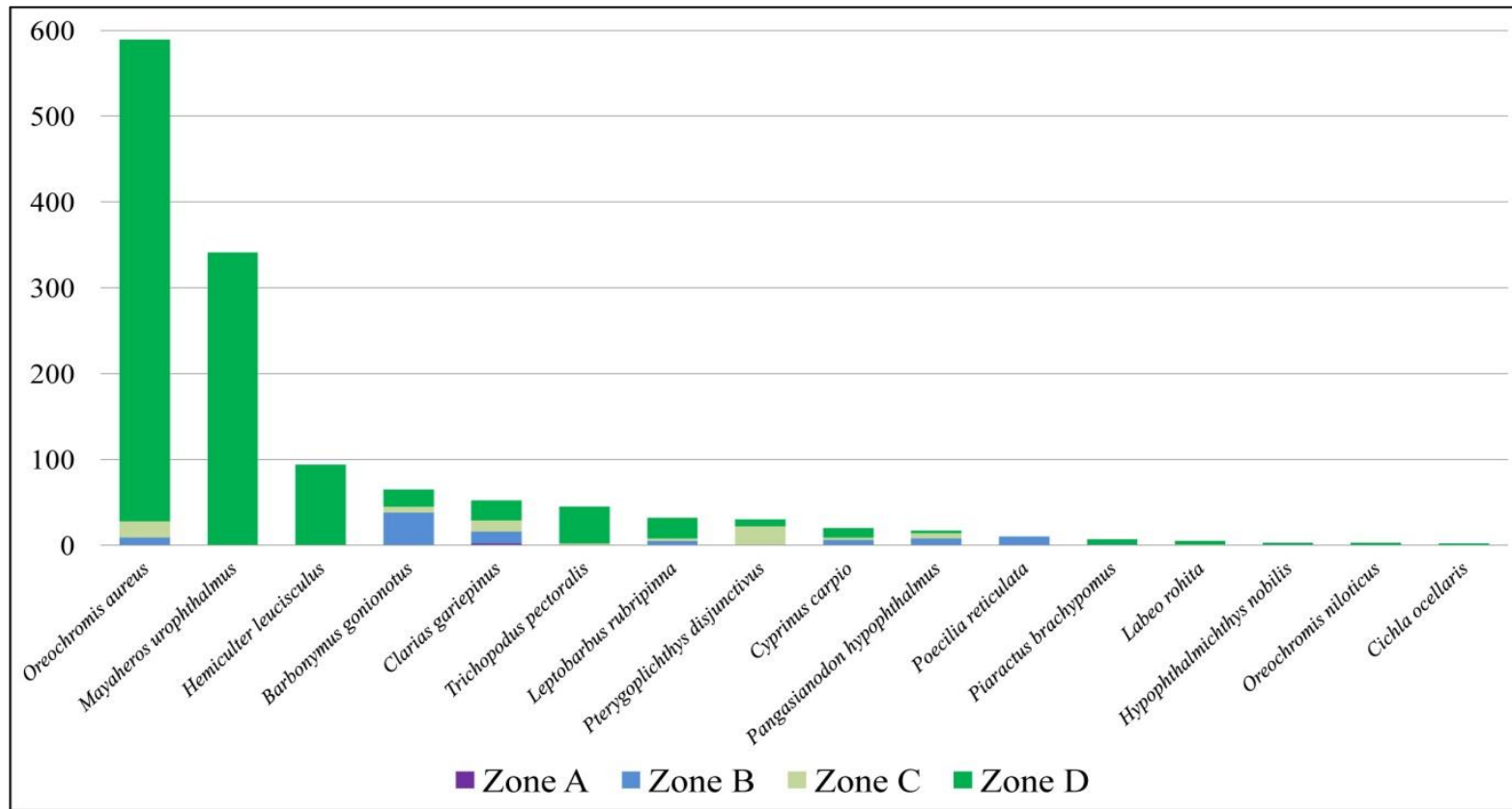


Figure 4.12: Rank abundance, diversity and sympatric occurrences in introduced species population among studied zones

4.2 Water chemistry data

A total of 144 water samples were extracted from the four zones for testing, and the mean values of studied physico-chemistry parameters are presented in Table 4.3. As forecasted, there was a pronounced dry weather in March 2016 (Figure 4.13). In May 2016, a slightly higher precipitation was recorded but the condition was short-lived and the dry weather persisted until October 2016 (Figure 4.14). Although August 2016 recorded the lowest precipitation, river level trend data did not show a continuous low level. There were intermittent increases and decreases of river level and flow velocity variations between May 2016 and November 2016. In the context of water constituent concentration, such a condition may not have enabled abnormal pollutant build-up and nutrient concentration to occur in adjoining sampling points at zones A, B and C.

Table 4.3: Summary of water chemistry values (n = 36, mean ± SD) in compliance to class IIA-IIB standard. Results that breached the limits of class IIA-IIB are in italics

Parameters	Zone A	Zone B	Zone C	Zone D	Class IIA-IIB limit
DO (mg/L)	8.97±0.86	7.62±0.61	6.80±0.59	6.01±2.10	5.0-7.0
BOD5 (mg/L)	<i>7.03±2.65</i>	<i>6.86±2.46</i>	<i>7.25±3.02</i>	<i>5.39±2.26</i>	< 3.0
COD (mg/L)	21.36±6.80	19.50±3.60	21.17±0.19	18.80±3.40	< 25.0
AN (mg/L)	0.0250±0.0243	0.0353±0.0305	0.0608±0.0483	0.1542±0.2090	< 0.3
TSS (mg/L)	<i>43.36±129.39</i>	<i>29.19±32.66</i>	<i>43.22±29.14</i>	<i>23.03±12.17</i>	< 50.0
pH	7.09±0.31	6.94±0.31	7.06±0.32	7.26±0.39	6.0-9.0
Temperature (°C)	24.03±0.80	26.69±0.92	29.00±1.52	32.93±1.29	Normal + 2°C
Turbidity (FAU)	<i>68.35±206.23</i>	<i>44.14±44.29</i>	<i>57.42±37.65</i>	<i>30.67±15.94</i>	< 50.0
FE (mg/L)	0.2386±0.4233	0.4714±0.4787	0.5944±0.3666	0.3856±0.2826	< 1.0
Nitrite (mg/L)	0.0053±0.0029	0.0051±0.0033	0.0164±0.0097	0.0166±0.0236	< 0.4
Nitrate (mg/L)	6.54±3.09	4.47±1.94	5.12±2.38	<i>7.01±2.49</i>	< 7.0
Phosphate (mg/L)	0.7081±0.9339	0.2061±0.1074	0.2294±0.0961	1.23±1.01	n/a
Sulphate (mg/L)	5.14±6.65	1.69±1.77	2.19±1.78	1.31±1.70	< 250.0
Salinity (%)	0	0	0	0	0.5-1.0
WQI	87.60±5.06	87.29±3.18	84.36±3.88	83.02±5.59	76.5-92.7

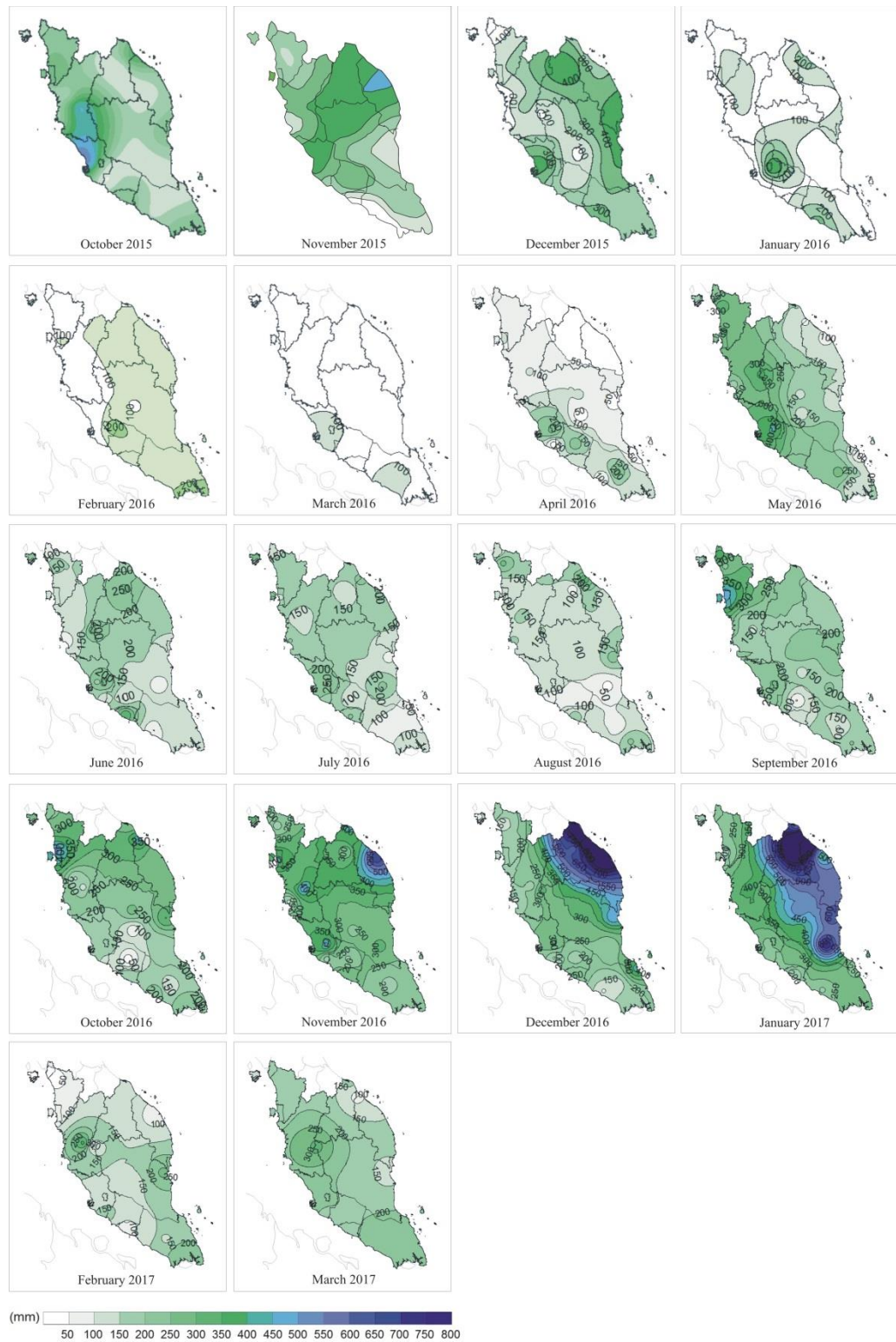


Figure 4.13: Regional precipitation pattern in peninsular Malaysia during the study duration. March 2016 was notably the driest month (Meteorological Department of Malaysia, 2017)

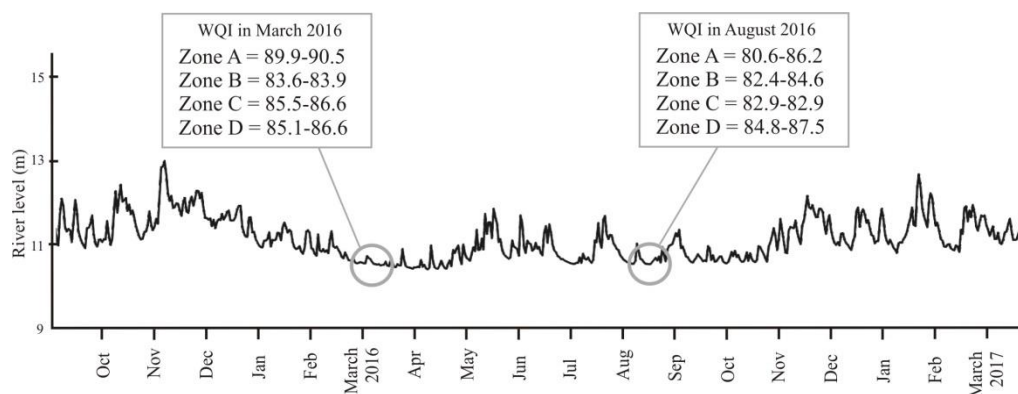


Figure 4.14: Monthly time series hydrography of Kampar in Zone C

A one-way ANOVA test showed that WQI differences between zone A (87.60 ± 5.06), zone B (87.29 ± 3.18), zone C (84.36 ± 3.88) and zone D (83.02 ± 4.88) were statistically significant ($F = 8.81$, $p = 0.000$). It was apparent that water quality deteriorated progressively from upriver to downriver, i.e. the WQI mean values decreased gradually from zones A to D. This lends support to the study's proposition that each zone was an individual ecohydrological unit which should be sampled and examined separately. From the satellite images shown on Google Earth®, zone B appeared to be a rural agricultural region while zones C and D were heavily disturbed anthropogenic regions.

As mentioned earlier, Kampar district hosts a population of 92,850 with a density of 138 persons per km². Such WQI deterioration corresponded with the levels of anthropogenic presence and disturbance where untreated organic and inorganic wastes may be discharged and accumulated in the lower parts of the river. Organic and inorganic pollutants extract DO in the water for their

decomposition processes, and since the DO parameter is the largest constituent (22%) of the WQI mathematical equation, any reduction of DO will lower the result of WQI. DO in zone D (6.01 ± 2.10 mg/L) where aquaculture, agriculture and livestock farming activities were most intense, was markedly lower than zones A (8.97 ± 0.86 mg/L), B (7.62 ± 0.61 mg/L) and C (6.80 ± 0.59 mg/L). Moreover, zones with forested surroundings may have benefitted from the effect of tree shading. Such condition lowered environmental temperature and induced more DO in the water. Given that the highest temperature was registered in zone D (32.93 ± 1.29 °C) as compared to zone A (24.03 ± 0.80 °C), B (26.69 ± 0.92 °C) and C (29.00 ± 1.52 °C), the WQI results were consequently lower in zone D.

In April 2016, there was an unusual drop in WQI for zones A (70.7–71.6), B (77.9–81.7) and C (71.8–78.8). It must be stressed that the drops could not be construed as a response to low precipitation because, incidentally, there was an atypical storm in zones A, B and C during the monthly water sampling process on 24 April 2016. While other WQI parameters fell within the acceptable ranges, high levels of sedimentation occurred and the TSS recorded were abnormally high in zones A (524 and 602 mg/L), B (125 and 130 mg/L) and C (135 and 136 mg/L); thus, the resultant WQI was lower than average levels. This illustrates how an alluvial river could become typically polluted by heavy sedimentation during intense precipitation in the tropical Malaysia climate. This study did not regard data incurred as an outlier because it was a natural occurrence. The values were included into the scatter plot graphs and

linear regression calculation to reflect the reality. Such evidence suggests that intense precipitation can also have negative impact on water quality.

All variables did not show an apparent pattern of clustering or correlation, with the exception of WQI and DO variables which showed a weak clustering pattern among the zones (Figure 4.15). However, linear regression values (R^2) calculated between precipitation and key parameters of WQI did not show a strong correlation. A residual maximum likelihood (REML) linear mixed model regression was further performed to examine the fixed and random effects. The results showed no significant effect of precipitation on DO ($F = 1.77$, $p = 0.187$), COD ($F = 2.62$, $p = 0.108$), BOD5 ($F = 0.971$, $p = 0.326$), AN ($F = 1.93$, $p = 0.167$), TSS ($F = 1.45$, $p = 0.231$) and pH ($F = 1.07$, $p = 0.303$).

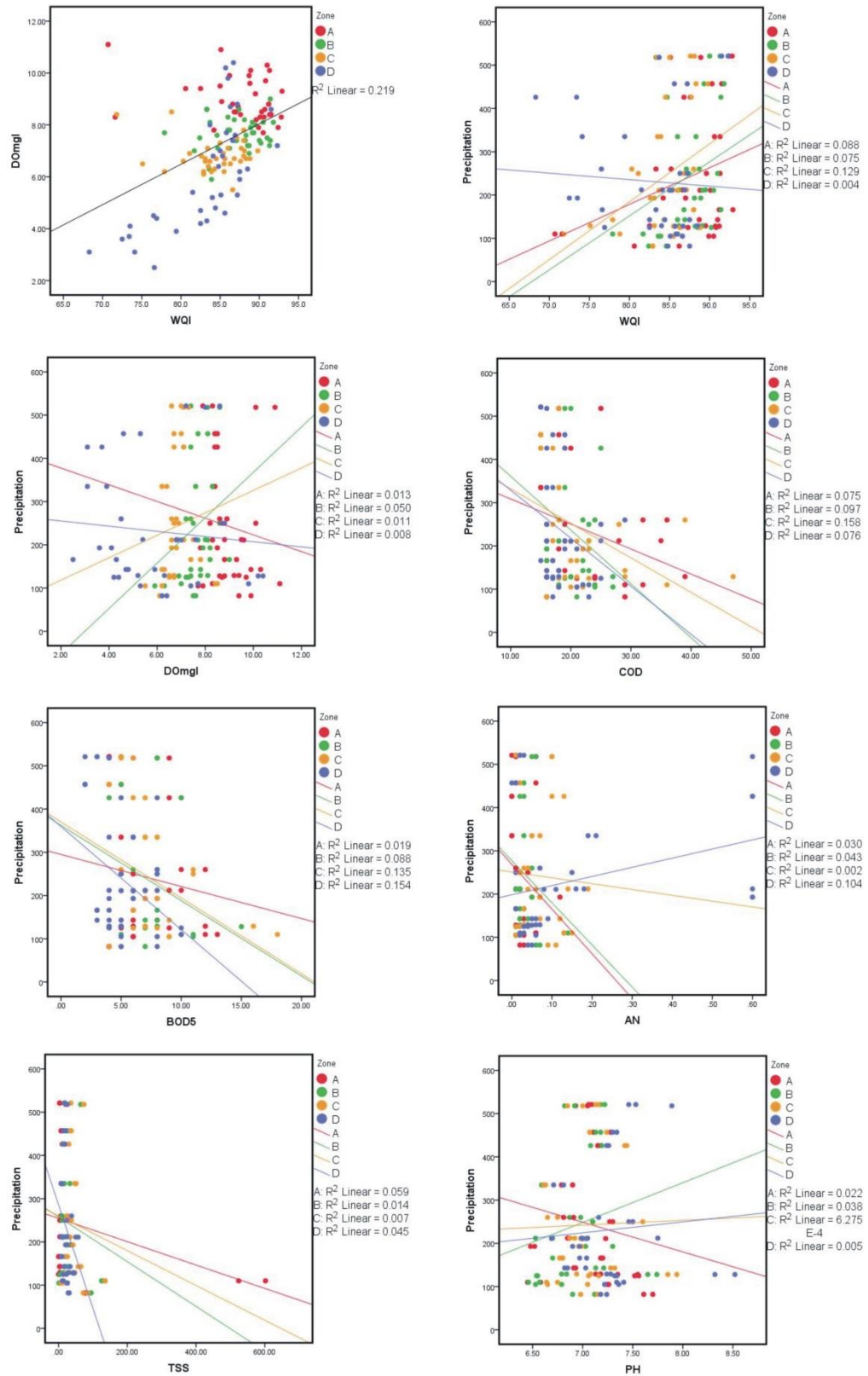


Figure 4.15: Scatter plots to visualise R² linearity and data clustering patterns among studied zones

Notable negative correlations were observed for COD, BOD₅ and TSS for all zones, i.e. when precipitation decreased, there was an increase in these parameters. WQI results during the low precipitation period of February–May and July–September 2016 remained high and complied to class IIA-IIB standard. Based on these results as well as the trend and plots, it could be inferred that low precipitation did not negatively impact the WQI levels of zones A, B and C at the time of this study. Despite experiencing a reduced dilution factor in Kampar River during the strong El Niño event, WQI results of all zones were still within the specification of the favourable class IIA-IIB. In the case of zone D which was an isolated EHU, precipitation levels did not appear to correspond to the variability of WQI at all.

4.3 River physical data

The individual metric of RPQI was typically rated highest in zone A and the lowest in zone C (Figure 4.16), namely channel stability (n = 18, zone A = 10.00 ± 0.00 , B = 7.11 ± 1.02 , C = 6.83 ± 0.86 , D = 7.11 ± 1.02), bank stability (zone A = 10.00 ± 0.00 , B = 8.00 ± 0.00 , C = 8.00 ± 0.00 , D = 7.55 ± 2.00), hydrologic continuity (zone A = 10.00 ± 0.00 , B = 6.61 ± 1.14 , C = 5.61 ± 1.09 ; D = 0.00 ± 0.00), riparian quantity (zone A = 10.00 ± 0.00 , B = 5.89 ± 1.32 , C = 2.61 ± 0.61 , D = 5.5 ± 2.57), riparian quality (zone A = 10.00 ± 0.00 , B = 5.77 ± 1.76 , C = 1.38 ± 0.61 , D = 4.67 ± 2.27), canopy cover (zone A = 8.44 ± 2.47 , B = 1.94 ± 1.83 , C = 0.00 ± 0.00 , D = 4.33 ± 3.49), pool availability (zone A = 9.89 ± 0.47 , B = 1.72 ± 1.44 , C = 0.38 ± 1.24 , D = 8.94

± 0.23) and riffle embeddedness (zone A = 10.00 ± 0.00 , B = 2.38 ± 0.77 , C = 1.16 ± 0.86 , D = 0.67 ± 0.76). The RPQI metrics of each transect in each zone showed minor variance during the 18 months study period (Figure 4.17). The RPQI results implied that precipitation shocks from monsoonal and tropical storms have little effect on the river's physical attributes.

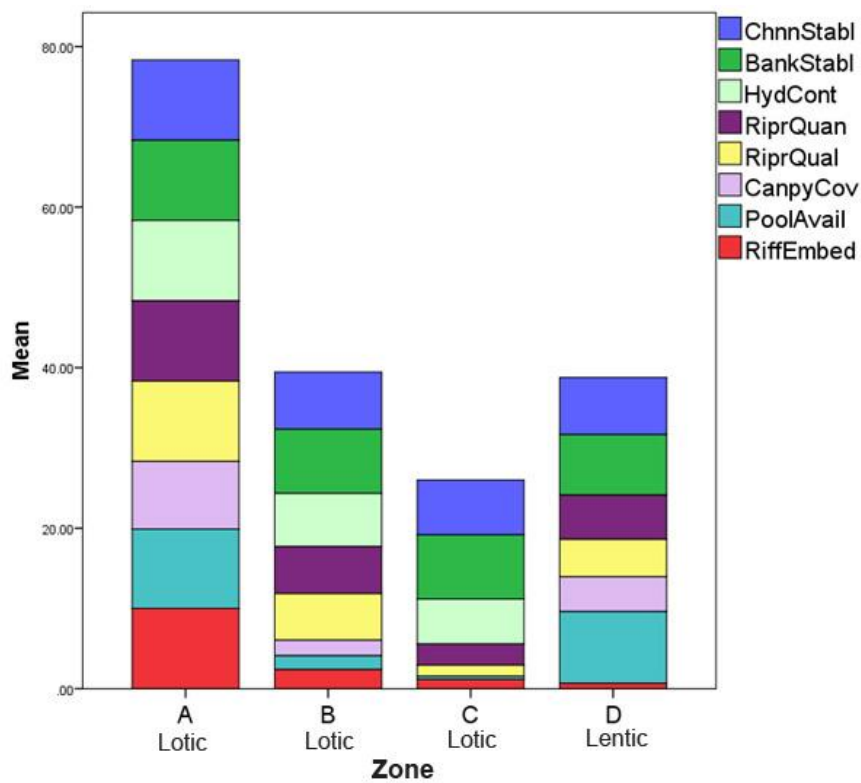


Figure 4.16: Stacked bar chart showing proportion of RPQI criteria rating results in each zone

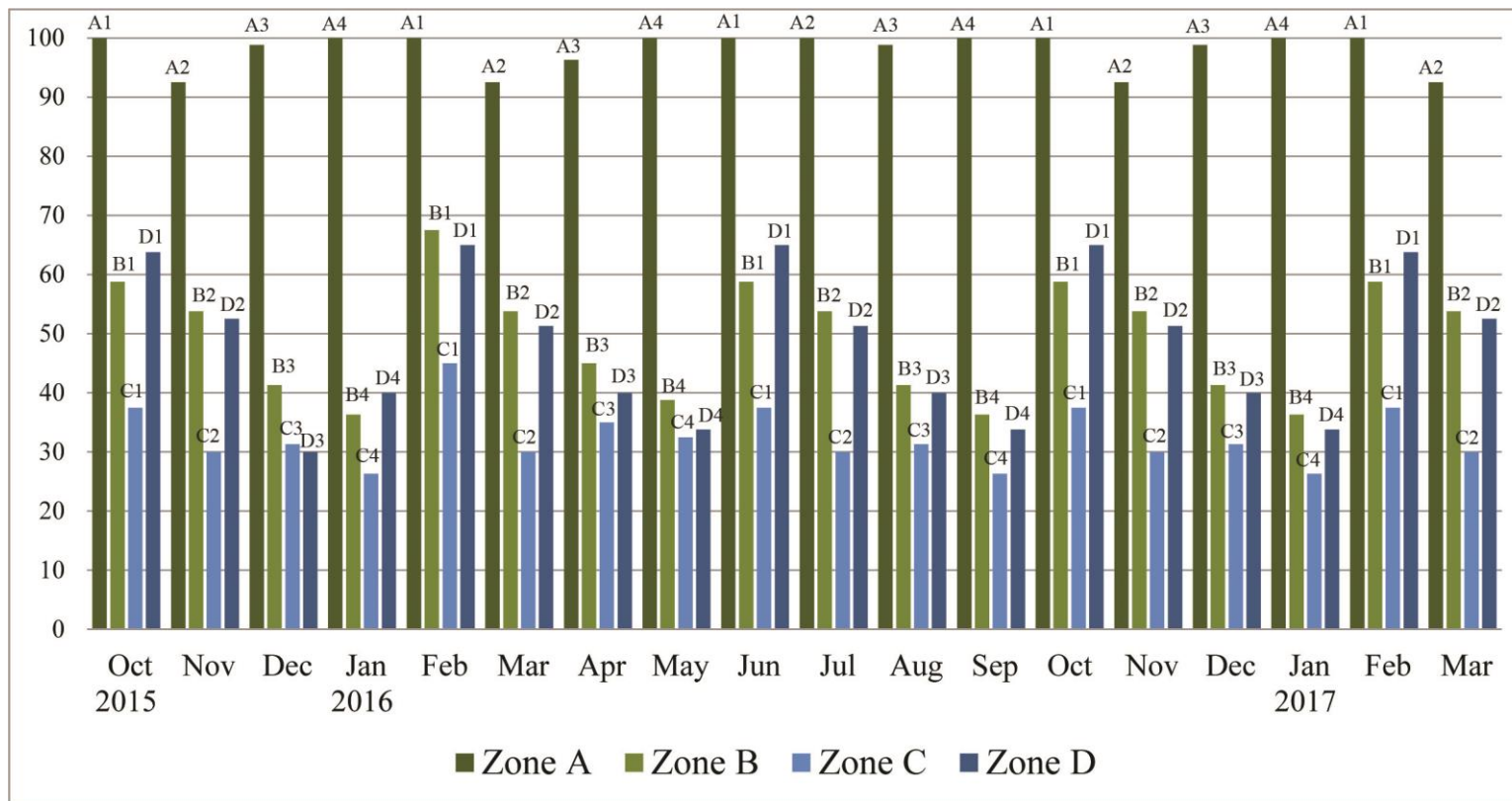


Figure 4.17: Monthly bar chart profiles for comparing RPQI values between zones and individual sampling transect throughout the study period

Zone A recorded the highest RPQI values (97.92 ± 3.12) as it was largely free from artificial modification while transects in zone B (49.35 ± 9.76) and C (32.51 ± 4.93) comprised of degraded physical properties of various degrees. Zone D (48.49 ± 12.41) also did not register favourable RPQI values as the region was clearly heavily disturbed by agriculture and aquaculture economic activities. One way ANOVA test showed mean differences between the zones were statistically significant for RPQI rating ($F = 203.59, p < 0.001$). The results showed that the proposed RPQI protocol was successful in reflecting various magnitudes of physical impairment in each ecohydrological zone along Kampar River. When the RPQI data of zone D was omitted for calculating the overall integrity from upriver to downriver (i.e. zone A, B and C), the results showed that the 35km Kampar River had a RPQI mean of 59.93 ($n = 54, SD = 28.72$). The visual data of each zone's physical characteristics is presented in Figure 4.18.



Figure 4.18: Physical characteristics of the assessed zones

4.4 IQI, WQI and RPQI data

Zone A was explicitly selected as the reference site and as expected, the highest scores was attained in zone A (IQI = 83.62 ± 9.41 ; WQI = 88.01 ± 4.80 ; RPQI = 97.92 ± 3.12), followed by zone B (IQI = 51.23 ± 9.66 ; WQI = 87.16 ± 2.77 ; RPQI = 49.35 ± 9.76) and zone C (IQI = 35.25 ± 9.54 ; WQI = 83.75 ± 4.54 ; RPQI = 32.51 ± 4.93) (Figure 4.19).

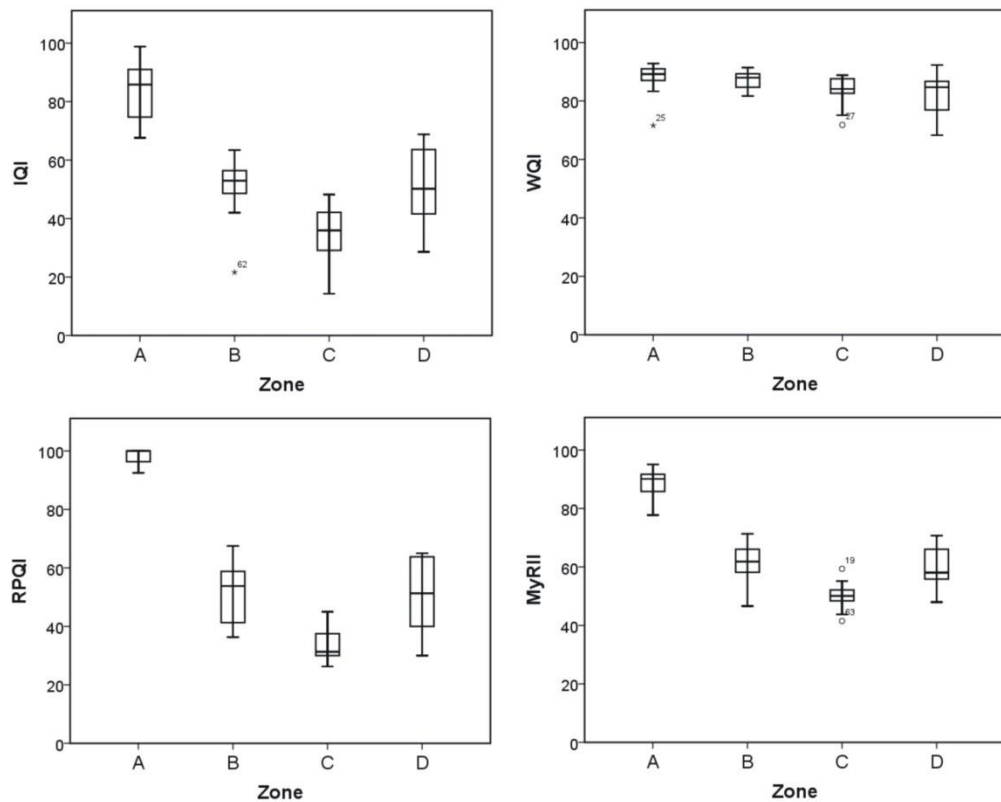


Figure 4.19: Stem plots for comparing IQI, WQI, RPQI and MyRII among the assessed zones. Zone A has the highest ratings since it was the most intact ecohydrological zone (i.e. reference site) while zone C scored the lowest ratings because it was a heavily disturbed segment of the Kampar River

As a disjointed ecohydrological zone from the Kampar River, zone D (IQI = 50.33 ± 12.69 ; WQI = 82.68 ± 6.19 ; RPQI = 48.49 ± 12.41) attained higher scores when compared to zone C. A one way ANOVA showed that the mean differences in scores were statistically significant between the zones for IQI ($F = 69.536$, $p < 0.001$), WQI ($F = 5.358$, $p = 0.002$), RPQI ($F = 203.597$, $p < 0.001$) therefore supporting the earlier supposition that that each ecohydrological zone was distinct and has to be assessed separately.

4.5 MyRII ratings

The core function of the MyRII was to detect and rate different levels of river impairment. This was achieved when the highest MyRII was attained by zone A (88.95 ± 4.29), followed by zone B (61.95 ± 5.90) and zone C (50.00 ± 4.29) respectively. The data revealed a clear trend in MyRII mean values decreasing progressively from upriver to downriver. Zone D (59.9 ± 6.39) did not appear to be influenced by such trend. One way ANOVA calculation showed the mean differences were statistically significant between the zones for MyRII ($F = 177.584$, $p < 0.001$) and suggested that the MyRII ratings were successful in characterizing each zone according their levels of anthropogenic disturbances. While the scatter plots between MyRII, IQI and RPQI variables showed strong linear regression values (R^2), notably, the linear regression values were weak when they were plotted against the WQI variable (Figure 4.20).

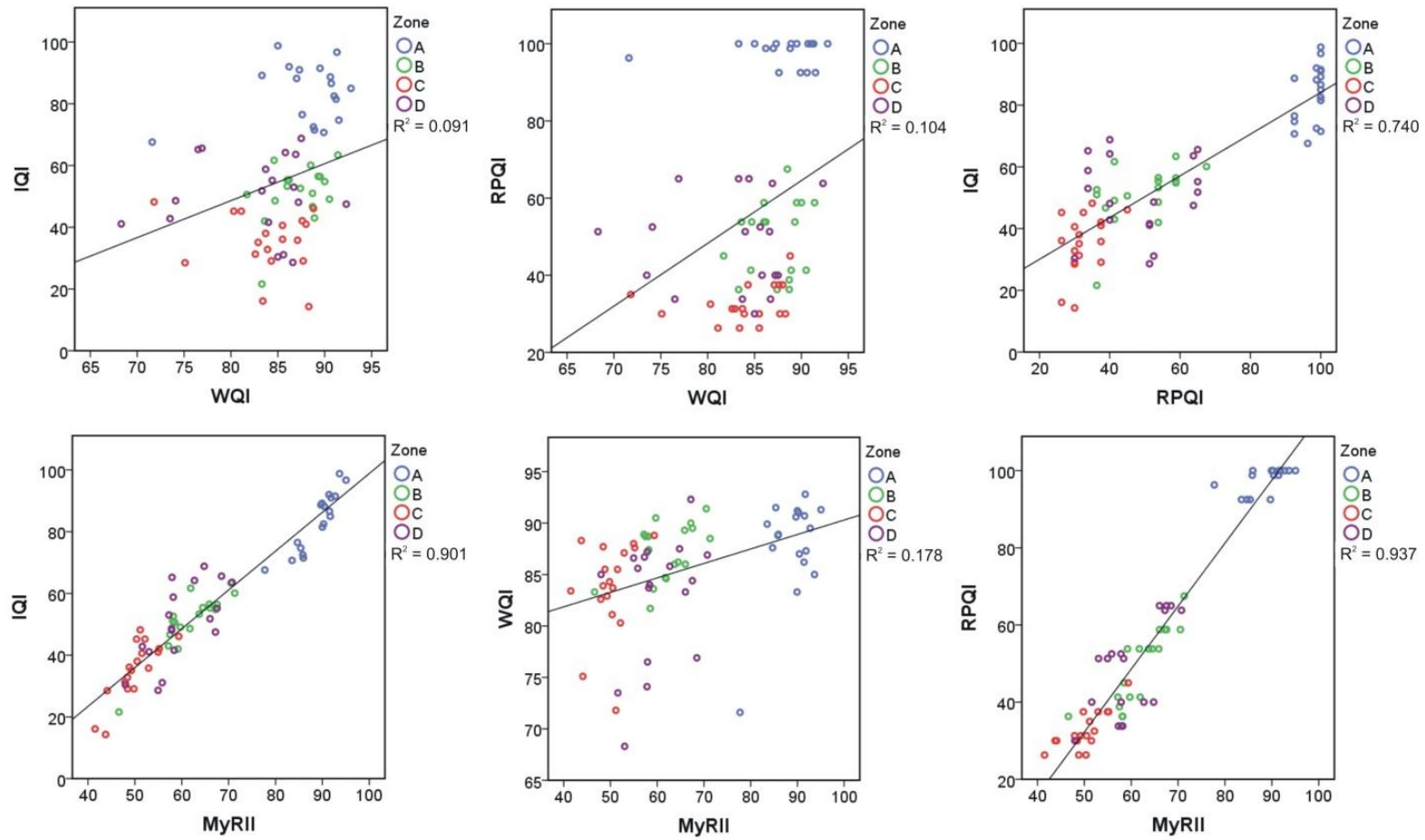


Figure 4.20: Scatter plots show a noticeable clustering pattern among the zones and linear regression (R^2) values suggested that WQI has weak correlation with other indices in all zones assessed. This reinforces the notion that water chemistry assessment alone is not robust enough for determining the level of river integrity

WQI appeared to be erratic when correlated with IQI and RPQI. To investigate further, Pearson correlation (r) was performed amongst the metrics and the majority of the WQI's water physico-chemistry metrics, namely COD, BOD₅, AN, TSS and pH were found to show weak correlation with other metrics of IQI and RPQI (Table 4.4 and Table 4.5) - with the exception of DO. The DO metric showed significant correlation with the native species abundance ($r = 0.547$), hydrologic continuity ($r = 0.641$) and riffle embeddedness ($r = 0.628$) metrics. In contrast, data showed that all IQI and RPQI metrics have a strong correlation with each other (Table 4.6). The evidence suggested that most of the water physico-chemistry metrics currently adopted by the authorities to deduce the WQI may not be empirically robust to reflect river integrity. This finding lends support to the proposition that river integrity assessment should also include biological and physical metrics as a balance and to compensate for the limitations of water chemistry-based metrics.

Table 4.4: Pearson correlation (*r*) between WQI and IQI metrics. Only the relationship between dissolved oxygen (DO) and percentage of native species (NS) shows a strong correlation

	DO	BOD5	COD	AN	TSS	pH	NosSpecies	NosFamily	NativeSpecies	Shannon
DO	1	.012	-.042	-.376**	.052	.127	.234*	.216	.574**	.432**
BOD5	.012	1	.784**	-.064	.233*	-.148	-.020	.058	-.013	.089
COD	-.042	.784**	1	-.062	.230	-.230	.045	.076	-.035	.113
AN	-.376**	-.064	-.062	1	.047	.083	.023	.089	-.387**	-.087
TSS	.052	.233*	.230	.047	1	-.201	-.099	-.135	.010	.006
pH	.127	-.148	-.230	.083	-.201	1	.119	.167	-.138	.007
NosSpecies	.234*	-.020	.045	.023	-.099	.119	1	.891**	.196	.867**
NosFamily	.216	.058	.076	.089	-.135	.167	.891**	1	.123	.764**
NativeSpecies	.574**	-.013	-.035	-.387**	.010	-.138	.196	.123	1	.337**
Shannon	.432**	.089	.113	-.087	.006	.007	.867**	.764**	.337**	1

Significant correlation between WQI and IQI metrics are in italics

**Significant at $p < 0.01$

*Significant at $p < 0.05$

Table 4.5. Pearson correlation (*r*) between WQI and RPQI metrics. Significant correlation between WQI and RPQI metrics are in italics

	DO	BOD5	COD	AN	TSS	pH	ChnnSt abl	Bank Stabl	HydC ont	RiprQ uan	RiprQ ual	Canpy Cov	PoolA vail	RiffEm bed
DO	1	.012	-.042	-.376**	.052	.127	.388**	.247*	<i>.641**</i>	<i>.380**</i>	<i>.439**</i>	.291*	.148	<i>.628**</i>
BOD5	.012	1	<i>.784**</i>	-.064	<i>.233*</i>	-.148	-.101	.063	.126	-.105	-.130	-.114	-.207	.008
COD	-.042	<i>.784**</i>	1	-.062	.230	-.230	-.059	.008	.055	-.065	-.085	-.012	-.114	-.013
AN	-.376**	-.064	-.062	1	.047	.083	-.276*	-.223	-.435**	-.245*	-.250*	-.149	.130	-.295*
TSS	.052	<i>.233*</i>	.230	.047	1	-.201	-.027	.006	.084	-.030	-.024	-.026	-.077	.058
pH	.127	-.148	-.230	.083	-.201	1	-.123	-.190	-.271*	-.119	-.148	.003	.189	-.103
ChnnStabl	<i>.388**</i>	-.101	-.059	-.276*	-.027	-.123	1	<i>.698**</i>	<i>.640**</i>	<i>.870**</i>	<i>.833**</i>	<i>.819**</i>	<i>.580**</i>	<i>.850**</i>
BankStabl	<i>.247*</i>	.063	.008	-.223	.006	-.190	<i>.698**</i>	1	<i>.568**</i>	<i>.623**</i>	<i>.587**</i>	<i>.542**</i>	<i>.338**</i>	<i>.683**</i>
HydCont	<i>.641**</i>	.126	.055	-.435**	.084	-.271*	<i>.640**</i>	<i>.568**</i>	1	<i>.499**</i>	<i>.538**</i>	<i>.300*</i>	-.045	<i>.792**</i>
RiprQuan	<i>.380**</i>	-.105	-.065	-.245*	-.030	-.119	<i>.870**</i>	<i>.623**</i>	<i>.499**</i>	1	<i>.970**</i>	<i>.900**</i>	<i>.660**</i>	<i>.777**</i>
RiprQual	<i>.439**</i>	-.130	-.085	-.250*	-.024	-.148	<i>.833**</i>	<i>.587**</i>	<i>.538**</i>	<i>.970**</i>	1	<i>.833**</i>	<i>.649**</i>	<i>.803**</i>
CanpyCov	.291*	-.114	-.012	-.149	-.026	.003	<i>.819**</i>	<i>.542**</i>	<i>.300*</i>	<i>.900**</i>	<i>.833**</i>	1	<i>.729**</i>	<i>.665**</i>
PoolAvail	.148	-.207	-.114	.130	-.077	.189	<i>.580**</i>	<i>.338**</i>	-.045	<i>.660**</i>	<i>.649**</i>	<i>.729**</i>	1	<i>.550**</i>
RiffEmbed	<i>.628**</i>	.008	-.013	-.295*	.058	-.103	<i>.850**</i>	<i>.683**</i>	<i>.792**</i>	<i>.777**</i>	<i>.803**</i>	<i>.665**</i>	<i>.550**</i>	1

**Significant at $p < 0.01$

*Significant at $p < 0.05$

Table 4.6: Pearson correlation (r) between IQI and RPQI metrics. Significant correlation between IQI and RPQI metrics are in italics

	ChnnStabl	BankStabl	HydCont	RiprQuan	RiprQual	CanpyCov	PoolAvail	RiffEmbed	NosSpecies	NosFamily	NativeSpecies	Shannon
ChnnStabl	1	.698**	.640**	.870**	.833**	.819**	.580**	.850**	.476**	.401**	.631**	.491**
BankStabl	.698**	1	.568**	.623**	.587**	.542**	.338**	.683**	.314**	.309**	.513**	.339**
HydCont	.640**	.568**	1	.499**	.538**	.300*	-.045	.792**	.070	.053	.788**	.328**
RiprQuan	.870**	.623**	.499**	1	.970**	.900**	.660**	.777**	.582**	.501**	.640**	.575**
RiprQual	.833**	.587**	.538**	.970**	1	.833**	.649**	.803**	.606**	.516**	.674**	.613**
CanpyCov	.819**	.542**	.300*	.900**	.833**	1	.729**	.665**	.624**	.550**	.457**	.512**
PoolAvail	.580**	.338**	-.045	.660**	.649**	.729**	1	.550**	.767**	.714**	.170	.556**
RiffEmbed	.850**	.683**	.792**	.777**	.803**	.665**	.550**	1	.505**	.472**	.729**	.587**
NosSpecies	.476**	.314**	.070	.582**	.606**	.624**	.767**	.505**	1	.891**	.196	.867**
NosFamily	.401**	.309**	.053	.501**	.516**	.550**	.714**	.472**	.891**	1	.123	.764**
NativeSpecies	.631**	.513**	.788**	.640**	.674**	.457**	.170	.729**	.196	.123	1	.337**
Shannon	.491**	.339**	.328**	.575**	.613**	.512**	.556**	.587**	.867**	.764**	.337**	1

**Significant at $p < 0.01$

*Significant at $p < 0.05$

The principal component analysis (PCA) was carried out and Eigen values indicated that the first two factors explained 59.35% and 11.58% the variance, respectively (Figure 4.21). Collectively, the factors contribute to 70.93% of the total variance of all variables considered in the analysis. The Kaiser-Meyer-Olkin measure of sampling adequacy indicated that the strength of the relationships among variables was high (KMO = .833), and Bartlett's test of sphericity was significant ($\chi^2(171) = 1534.79, p < 0.001$). Hence the PCA loading plot indicated IQI and RPQI metrics were strongly correlated with each other (Figure 4.22). However, with the exception of DO, all other WQI metrics showed weak relationship with IQI and RPQI metrics.

In cluster hierarchical analysis and plotting, the Ward's and Neighbour-Joining linkages demonstrates that the MyRII protocol and its metrics are able to distinguish the reference site (zone A) clearly while in zone B and C, there are some overlaps i.e. some sampling points in zone B were similar to zone C's characteristics during the 18 months' trial (Figure 4.23, Figure 4.24).

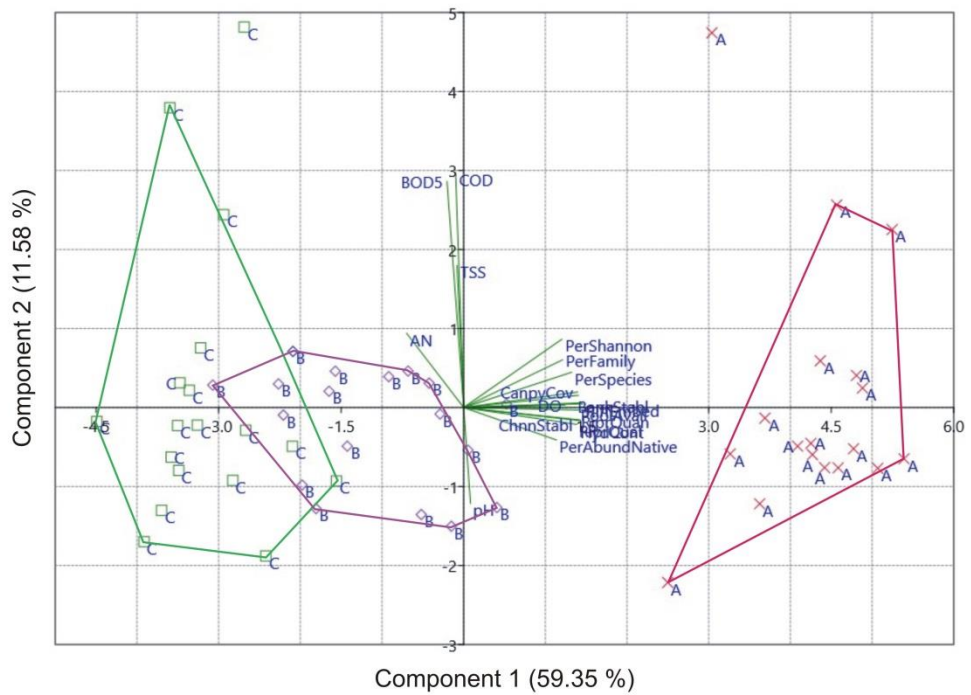


Figure 4.21. The principal component analysis (PCA) loading plot, variable directions and zone clustering patterns. The variable directions show biological and physical metrics are strongly correlated. Values from zone A (reference site) are clearly distinguished while some values are overlapping between zone B and C.

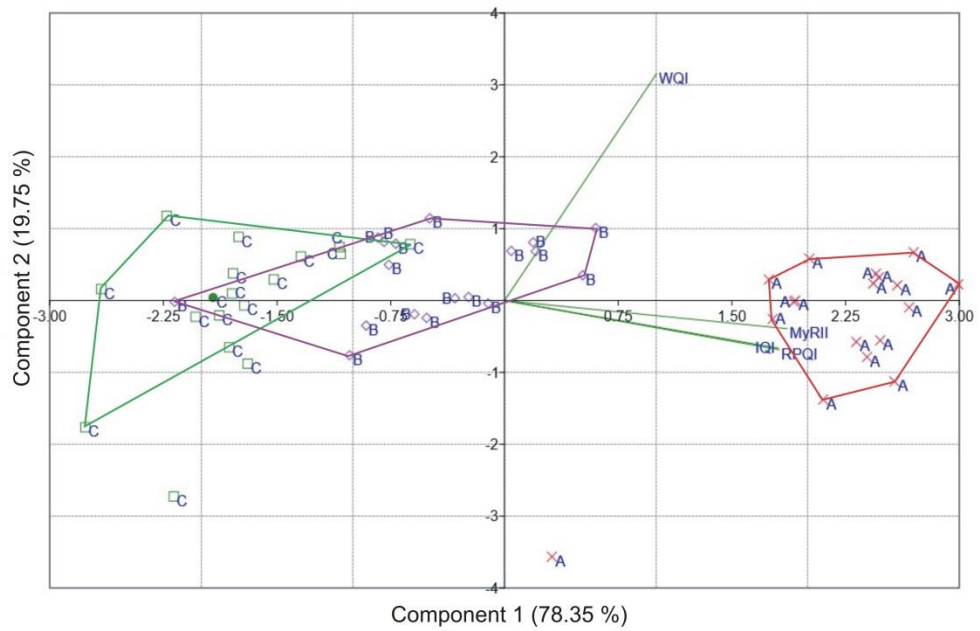


Figure 4.22. The principal component analysis (PCA) loading plot, indices directions and zone clustering patterns. The variable directions show IQI and RPQI metrics are strongly correlated with MyRII. However, there is a departure in WQI's direction. This shows the WQI is not entirely reliable to reflect biological and physical qualities of river integrity.

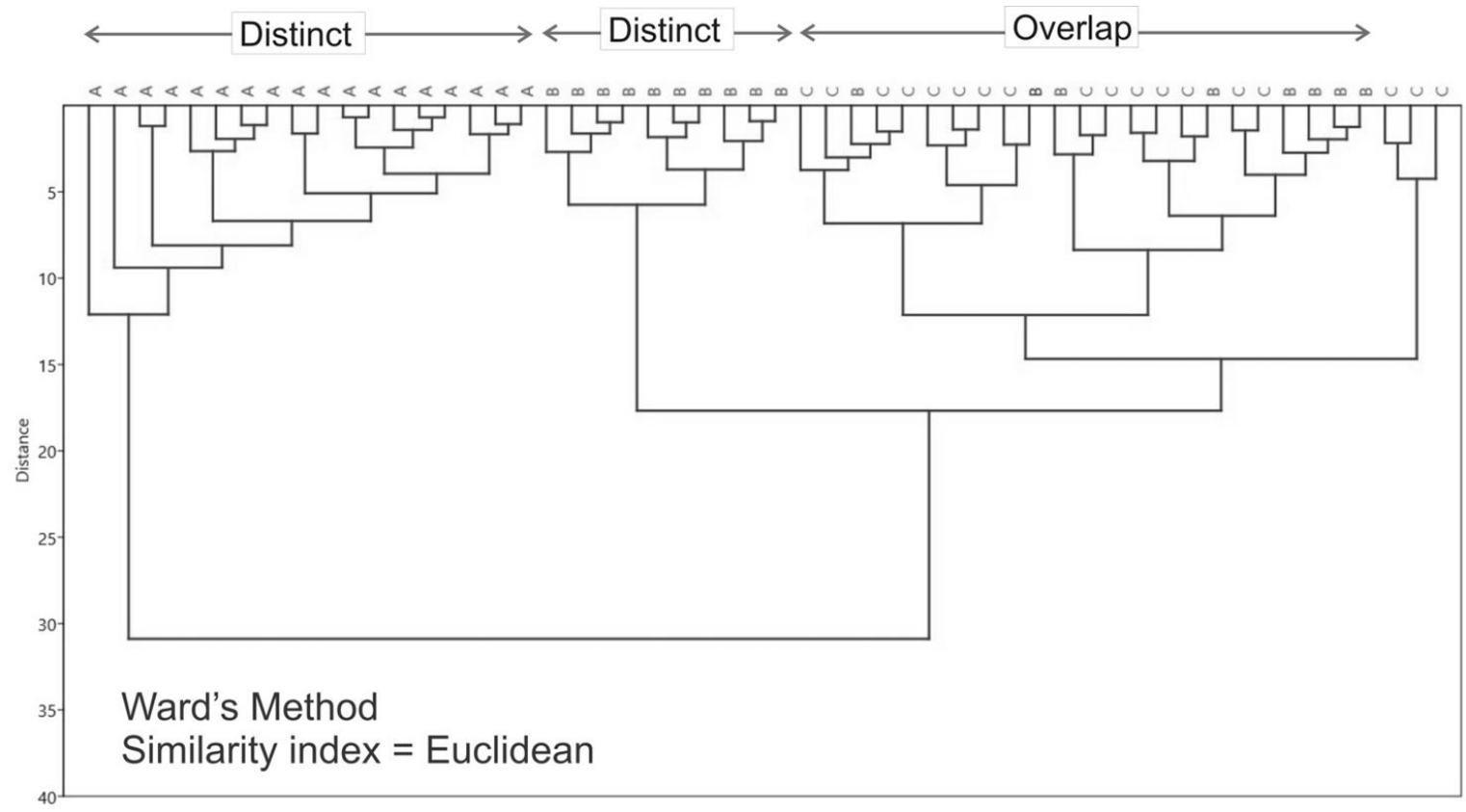


Figure 4.23. Cluster hierarchical plot by Ward's Method

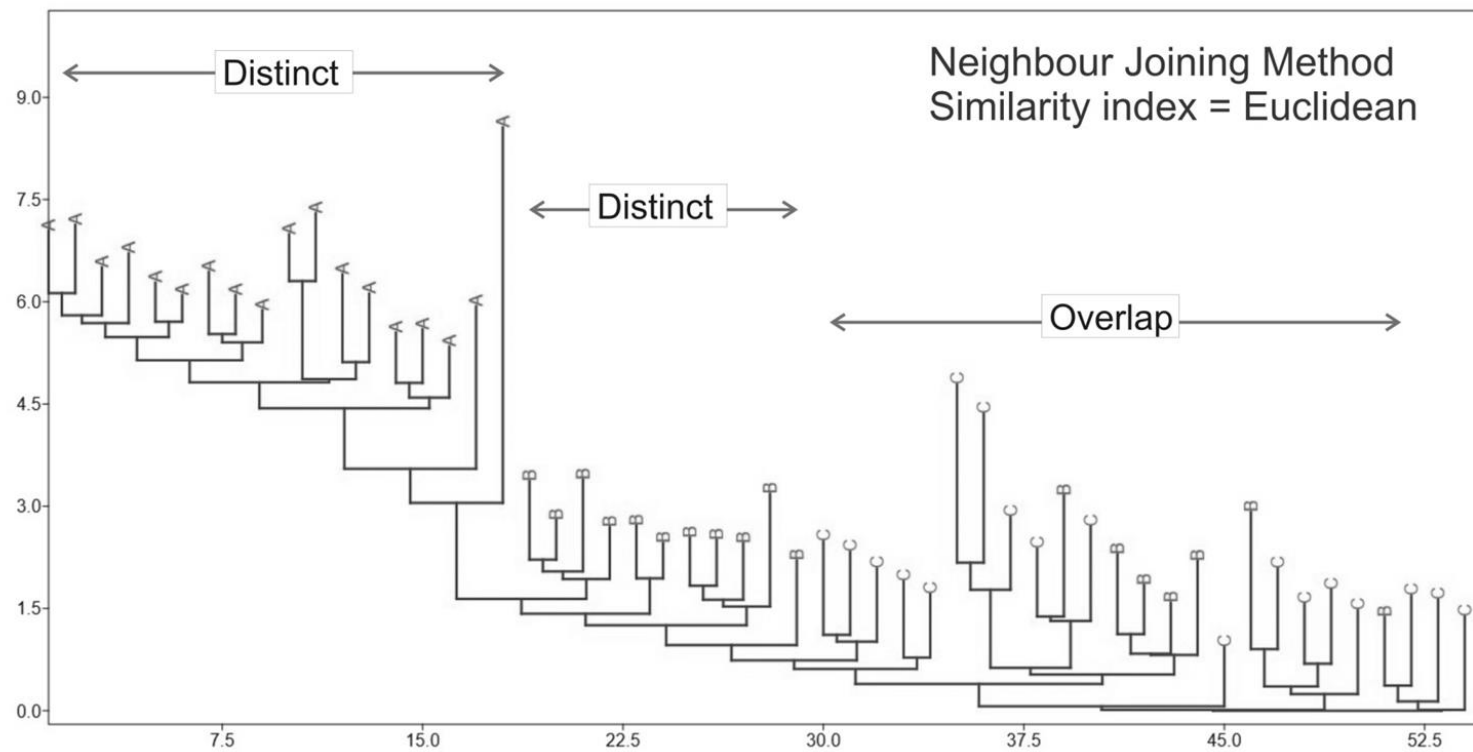


Figure 4.24. Cluster hierarchical plot by Neighbour-Joining Method

4.5.1 Reference site and final MyRII results

As expected, reference site zone A achieved the highest MyRII rating (88.95 ± 4.29) since it was selected as “the best of what’s left” or “minimally impaired” as defined by Karr (1981). However, field observations indicated that it may not be feasible to adopt Karr’s (1981) recommendation strictly when normalizing a reference site's MyRII to rate other sites. In Peninsular Malaysia, the less-disturbed sites are typically found in the foothill regions of the Titiwangsa Mountain Range. A site of higher altitude, although unaffected by anthropogenic disturbances, may not be considered as a practical reference site due to its gradient difference which causes turbulent waters. During the IQI sampling exercise, typically, mostly small and specialized torrent-adapted species were encountered such as *Glyptothorax schmidtii*, *Homalopteroides smithi* and *Balitoropsis zollingeri* (Ng et al., 2018). Such niche species community structure may not be a realistic benchmark for IQI. Species adapted to slow and deep waters need to be accounted for when formulating a wholesome IQI.

As mentioned earlier, zone B was a segment of the Kampar River where raw water is currently being extracted for supply to the surrounding human population. Although the WQI mean value was the highest in zone A (88.01 ± 4.80), the WQI mean value in zone B (87.16 ± 2.77) was also found to be in compliance to the Class IIA-IIB standard. The waters flowed slower in

zone B and various deep and shallow waters fish species were encountered (Ng et al., 2018).

It should be understood that a river assessment index may not gain wide acceptance if its normalized and standardized rating is too high and beyond the reach of most sites. Therefore, under the prevailing circumstances mentioned earlier in this sub-section , it was determined that the MyRII values of zone A and B should be combined for deducing the rating classification of "excellent", "good", "average", "poor" and "impaired" in an empirical manner (Figure 4.25). The approach was also expected to be more wholesome in the context of obtaining realistic IQI values and took into account of zone B's WQI values that are currently acceptable for water supply to the surrounding human population.

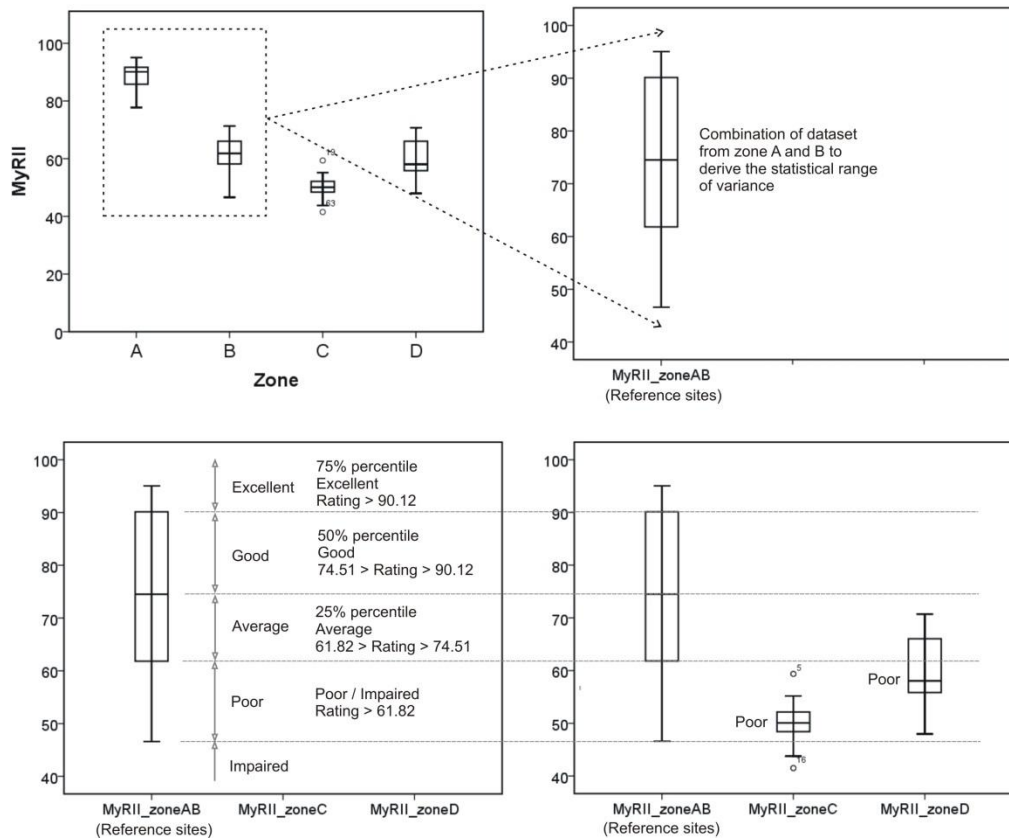


Figure 4.25: Based on MyRII results presented on Figure 4.19, the MyRII data of zones A and B was combined to deduce the classification thresholds for reference site (left). Consequently, the "poor" classification was assigned to zones C and D (right) when benchmarked against the thresholds

The results obtained from zone D (IQI = 50.33 ± 12.69 ; WQI = 82.68 ± 6.19 ; RPQI = 48.49 ± 12.41 ; MyRII = 59.9 ± 6.39) suggested that the wetland performed poorly when assessed with IQI and RPQI metrics, but functioned reasonably well when assessed with WQI metrics. Based on MyRII rating classification, zone D was classified as "poor".

However, it must be noted that the MyRII rating classification established in this study may not be suitable for assessing zone D because it was derived from reference sites zone A and B with hydrological continuity (lotic system). Zone D was mainly a lowland multi-basinal swampland (lentic system) that was disjointed from the nearby Kampar River. Since it lacked constant volumetric turnover and waters were typically stagnant, the water body did not exhibit RPQI metrics such as riffle embeddedness and hydrologic continuity for assessment. Under such conditions, the IQI, WQI and RPQI metrics and dynamics may differ. The necessary rating protocol for lentic systems may be determined by future researches as it is not under the scope of this study.

4.6 Watershed geomorphology data

The four tributary watersheds that consisted of Geruntum, Ulu Kampar, Geroh and Dipang that fed into Kampar River host 115 streams and they have a combined area of 256.3 km². The surface water discharge (Q) measured for each tributary was 160.37 MLD, 346.29 MLD, 139.97 MLD and 233.23 MLD for Geruntum, Ulu Kampar, Geroh and Dipang, respectively. The corresponding geomorphometric results are presented in Table 4.7.

Table 4.7: Geomorphological data for the tributary watersheds

Parameter	Geruntum	Ulu Kampar	Geroh	Dipang	Unit
WATER BASIN					
Type	Dendritic	Dendritic	Dendritic	Dendritic	
Substrate	Rocky	Rocky	Rocky	Rocky	
Area (A)	47.5	99.7	46.4	62.7	km ²
Perimeter (P)	36.4	57.2	35.7	34.1	km
Length (Lb)	14.34	19.68	12.71	9.82	km
Width (Wb)	4.38	7.83	4.88	7.55	km
Radius equivalent area (R)	3.88	5.63	3.84	4.47	km
Highest point ($Hmax$)	1661	2068	1499	1426	m
Lowest point ($Hmin$)	127	133	144	83	m
Relief (Bh)	1534	1935	1355	1343	m
Primary stream, straight (Ls)	12.40	12.75	7.92	7.68	km
Primary stream, meander (Lm)	16.34	17.42	8.80	9.15	km
Primary outlet, width	11.2	16.3	8.5	12.2	m
Primary outlet, cross section area (a)	2.69	6.68	2.25	4.09	m ²
Primary outlet, flow speed (v)	0.69	0.60	0.72	0.66	m/s
Surface water discharge (Q)	1.86	4.01	1.62	2.70	m ³ /s

Parameter	Geruntum	Ulu Kampar	Geroh	Dipang	Unit
Surface water discharge (daily)	160.37	346.29	139.97	233.23	MLD
STREAM					
Order 1	13	25	13	11	nos.
Order 2	12	12	7	4	nos.
Order 3	0	11	4	3	nos.
Total number (Nu)	25	48	24	18	nos.
Total length (Lu)	40.07	77.96	38.71	45.52	km
Mean length (Lm)	1.60	1.62	1.61	2.53	km
Frequency (Fs)	0.53	0.48	0.52	0.29	
Drainage density (Dd)	0.84	0.78	0.83	0.73	
Drainage intensity (Id)	0.44	0.38	0.43	0.21	
RATIO					
Compactness (Cc)	0.0046	0.0016	0.0047	0.0024	
Bifurcation (Rb), stream order 2	1.08	2.08	1.86	2.75	
Bifurcation (Rb), stream order 3	0	0.92	0.57	0.75	
Relief	106.97	98.32	106.61	136.76	
Circularity (Rc)	0.45	0.38	0.46	0.68	
Length width (Rlw)	3.27	2.51	2.60	1.30	
Texture (Rt)	0.69	0.84	0.67	0.53	

Parameter	Geruntum	Ulu Kampar	Geroh	Dipang	Unit
Elongation (Re)	0.54	0.57	0.60	0.91	
Meandering (Rm)	1.32	1.37	1.11	1.19	
Basin width to outlet width	0.39	0.48	0.57	0.62	
OTHERS					
Ruggedness number (Rn)	1.29	1.51	1.13	0.98	
Factor, form (Ff)	0.23	0.26	0.29	0.65	
Factor, shape (Sf)	4.33	3.88	3.48	1.54	
Constant channel maintenance (C)	1.19	1.28	1.20	1.38	

Collectively, the four tributaries supplied 879.86 MLD to the downriver of Kampar River where the water treatment plant was located. As expected, there was a significant positive correlation between surface water discharge (Q) and area (A) ($r = .989$, $p < .05$) and a strong negative correlation between surface water discharge and compactness ($r = -.950$, $p < .05$). Other parameters did not show strong linear relationship with the surface water discharge of the watersheds. The ratio of surface water discharge (Q) and area (A) was 0.039, 0.040, 0.035 and 0.043 for Geruntum, Ulu Kampar, Geroh and Dipang, respectively. As shown on Figure 4.26, the scaling and predictive relationship between surface water discharge (Q) and area (A) may be expressed by a linear regression equation of:

$$Q = 0.05A - 0.5$$

where:

Q = Surface water discharge (m^3/s)

A = Area (km^2)

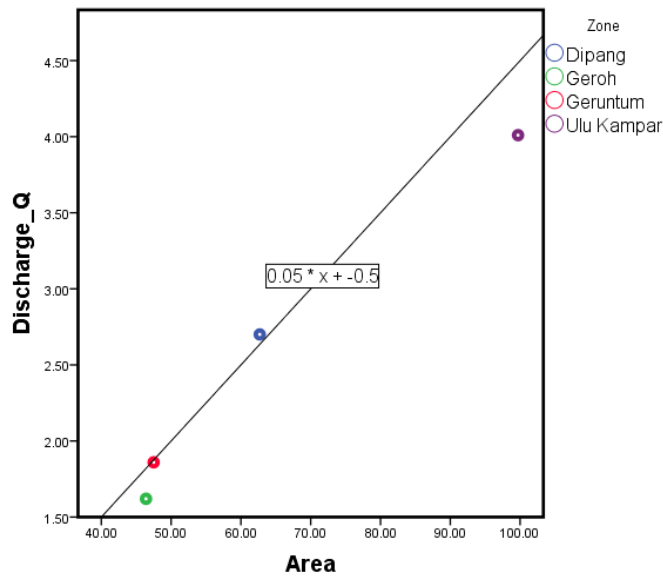


Figure 4.26: Scatter plot diagram showing linear regression equation and correlation between surface water discharge (Q) and area (A). The equation may be referred to for forecasting surface water discharge volume if the watershed area size is known in the surrounding regions along Titiwangsa Mountain Range foothills

A strong drought was observed during the period of March-April 2016. This was an anomaly because historical precipitation data shows that the period of March-April was typically a high precipitation period (Figure 4.27). With the exception of January and November, most months in 2016 experienced lower precipitation when compared with historical data. Although surface water volumetric discharge (Q) threshold was measured to be the lowest during the 26-29 March 2016 period, fortunately, no water shortage was reported in all areas that were linked to the mentioned WTP. It was apparent that the watersheds were capable of sustaining their ES during the “worst-case” scenario presented at the time of this study.

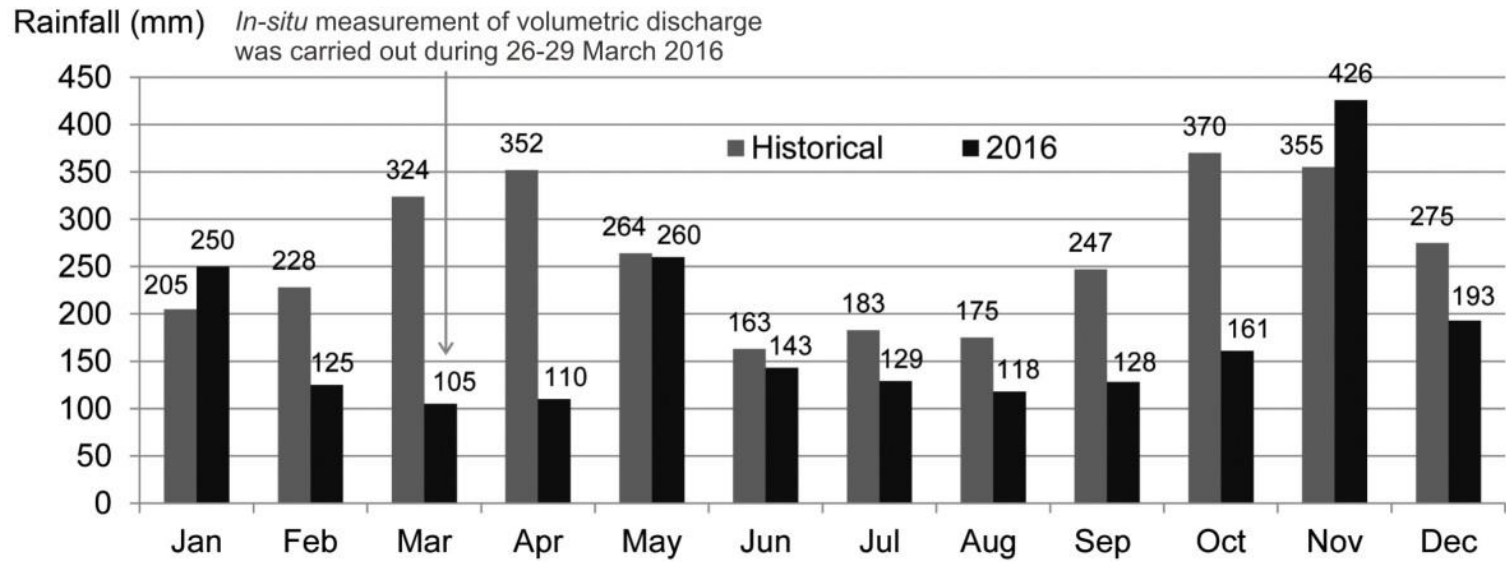


Figure 4.27: Comparison of historical mean monthly precipitation data with the mean monthly precipitation data of 2016

4.7 Ecosystem service economic value

The Water National Services Commission, or Suruhanjaya Perkhidmatan Air Negara (SPAN) stipulates that 225 litre day⁻¹ hydraulic flow rate as the national standard for population equivalent (PE) or unit per capita loading for 24 hours (SPAN 2015). Data from the Department of Statistics (2010) indicates that the population 1991 was 78,701 but it was increased to 93,084 in 2010. During the period of 1991-2000 and 2000-2010, the population growth rate was 3.41% and 17.22% respectively. By multiplying the assumed population of 93,084 with 225 litre day⁻¹, the water demand by the current population was estimated to be 20,943,900 litre day⁻¹ or 20,943.90 m³ day⁻¹ (20.94 MLD).

However, the average supply distribution leakage of non-revenue water (NRW) was reported to be at 30.4% in Perak state (PWB 2013). Therefore, 30,091.80 m³ day⁻¹ (30.09 MLD) would have to be drawn from Kampar River and processed to produce 20.94 MLD. The Kampar WTP was designed for 36.37 MLD production (PWB 2013) and therefore the production reserve margin was 17.26%. With the supposition of another 17.22% population growth in another 10 years' time, the WTP should be upgraded before 2026 to correspondingly meet the water demand.

As mentioned earlier, 88% of treated water is consumed by the domestic sector. Assuming the average tariff of RM 0.70/m³ ("RM" denotes Ringgit, the currency of Malaysia) is applicable to the 93,084 population's

consumption pattern of 20,943.90 m³ day⁻¹ (20.94 MLD), the ecosystem service and economic value of Kampar upriver watersheds is estimated to be RM14,660.73 day⁻¹ or RM5,351,166.45 yr⁻¹ in 2016. With a projected population growth of 17.22% in 2026, the water demand may rise to 24,550.44 m³ day⁻¹ (24.55 MLD). Therefore the watershed ES economic value of the four tributary watersheds may be correspondingly increased to RM17,185.30 day⁻¹ or RM6,272,637.42 yr⁻¹ in 2026. Since the four watersheds have a combined area of 256.3 km² or 25,630 hectares, they were worth RM208.79 ha⁻¹ yr⁻¹ in 2016 and RM244.74 ha⁻¹ yr⁻¹ in 2026 in the context of freshwater retention, regulation and provision.

CHAPTER 5

DISCUSSION

The results were fairly consistent with those from previous works in developed countries and other parts of the world (Lasne et al., 2007; Terra et al., 2010; Prudente et al., 2017). Nonetheless, it is recognized that this study was novel in the context of Malaysia and perhaps the tropical Southeast Asia region. As expected, some anomalies and noteworthy features were encountered in the data collected. These warrant comparison with other studies and discussion under a broader context to inform future studies.

Also, since one of the key objectives of this study was driven by the Malaysian government's call to establish the “... *means and measures* to complement existing policy directions related to water resources” as highlighted earlier, it would be useful to discuss some field observations and MyRII application challenges to inform users, stakeholders and policymakers. This is crucial for driving the next steps beyond this study for ensuring successful implementation of the MyRII protocol in Malaysia.

5.1 Biological metrics

5.1.1 Species niches

There is a need to enquire – why was there an overall higher species count in zones with lower RPQI values as described in Table 4.1? This was demonstrated in zone B (30 species) and D (35 species) that registered higher species counts than zone A (23 species) which attained the highest RPQI values. The species diversity of zone C was expected to be low (14 species) due to severe river physical impairment. Transects in zone A were clearly the most pristine and devoid of anthropogenic pressures and yet the species diversity was less.

It should be reiterated that zone A consisted of a meandering upriver segment with clear and fast flowing waters. Basically, fish species have to “go with the flow” hence only species with strong propulsion ability and specialized morphology would not be swept away. The results in zone A showed that dominant species like *Neolissochilus soroides*, *Barbodes cf. rhombeus* and *Rasbora vulgaris* possessed forked tail and fusiform body profile which are highly efficient in navigating and moving in turbulent waters. Some species such as the *Glyptothorax schmidti* has also developed the highly evolved “thoracic adhesive apparatus” (Figure 5.1) and suction cup shaped pectoral-fins to latch onto rocks.



Figure 5.1: *Glyptothorax schmidti*'s “thoracic adhesive apparatus” (ventral view) is highly adapted to latching on smooth rocks and pebbles typically found in zone A's fast flowing river

Many species are also small enough to forage in hyporheic zone (below substrate surface) where the flow velocity is substantially reduced. Other species with rounded tail and non-specialized morphology such as *Channa gachua* and *Betta pugnax* were encountered in zone A too but these were found in water pockets and velocity refugia that occurred along the riparian areas.

By contrast, zone B and D comprised of broader alluvial plains where the waters were considerably slow. Under such calm and homogenous conditions, more species of various tail and body morphologies were able to thrive, for example *Helostoma temminckii* (truncated tail and lateral compressiform body), *Monopterus javanensis* (pointed tail and anguilliform body) and *Mystus singaringan* (forked tailed and ventral compressiform body). Introduced species also added to the fish diversity in zone B and D. Such introduction is not unique to the study site and it is a common occurrence in all

anthropogenic areas in Southeast Asia (Ng et al., 1993; Peh, 2010). It should be highlighted that while zone D recorded the most species, this should not be misconstrued as a high level of waterbody physical quality was present. In fact, zone D was a heavily disturbed region and only 20.7% of individuals encountered were native species. Most of the species encountered in zone D were introduced species, evidently escapees from the local aquaculture farms. It is argued that zone A has less species compared to zone B and D for reasons mentioned.

5.1.2 Introduced species

Correspondingly, this brings up another question – if overall there were less species in zone A, why has the monthly sampling results yielded a consistently higher species count in zone A (9.78 ± 2.94) as compared to zone B (5.33 ± 1.33)? This may be attributed to fish population density and habitat quality. During the monthly sampling exercises, more individuals were encountered in zone A (34.00 ± 15.54) as compared to zone B (15.00 ± 5.34). This inevitably raised the probability of encountering more species in zone A. There were more individuals in zone A due to higher density of good quality hydraulic-habitats in the absence of anthropogenic pressure, and this is in consistent with the resultant RPQI values. It should be noted that zone D registered the highest level of individuals encountered (81.50 ± 29.54) but this cannot be associated with RPQI values or habitat quality. Many species

encountered in zone D were introduced species and their population may be artificially increased by escapees from the local aquaculture activities.

Such revelation has somewhat exposed a flaw in applying fish-based metrics for validating a river assessment system. Evidently, fish do not merely reflect environmental changes, some introduced species can also become the cause of change (Byers, 2002). Piscivorous cichlids such as *Mayaheros urophthalmus* and *Oreochromis niloticus* were recorded in zone D. Being eurytopic, they can be present in a wide range of aquatic systems, and causing predation-related impacts to the indigenous populations (DOF, 2007). Such aggressive species are regarded as negative indicators to represent impairment caused by anthropogenic disturbances (Harris, 1995). With negative indicator presence, a decrease in native fish species diversity and abundance can be expected.

5.1.3 Species physiology and niche behaviours

The IQI may also be influenced by the local fish species' natural physiology and niche behaviours such as feeding guilds, foraging ranges and reproduction tendency. In zone A, the species encountered were typically small and they have narrow ecological ranges, thus there was a higher probability to encounter them during the sampling exercises. Some species such as the *Homalopteroides smithi* and *Glyptothorax schmidti* were strictly found in torrent river system with rocky substrate. These species have specialized

pectoral and pelvic fins that are shaped like suction cups to latch on rocks. All transects in zone A had rocky substrate and these highly adapted torrent species were easily encountered.

On the other hand, species typically encountered in zone B and C were large species with morphology that were adapted to slow and deep waters. These included the *Hemibagrus capitulum*, *Pangasianodon hypophthalmus* and *Leptobarbus rubripinna* that were also more tolerant to environmental changes and disturbances (Ng et al., 2018). Naturally, they have extensive dispersal ranges. The difficulty in capturing them was reflected by the variation in zone C's IQI. In zone D's transects where the benthic and pelagic strata were stagnant and open, the *prey* catching and *predator avoidance* strategy of each species may have contributed to the variation. Carnivorous predators like *Channa striata* and *Oxyeleotris marmorata* typically hide in dense semi-aquatic vegetation while stalking their prey (Smale, 1992; Turesson and Bronmark, 2007). These species were rarely encountered in the sampling transects. Conversely, there were species that exhibit shoaling behaviour (i.e. swimming in a large group) to confuse predators (Cushing and Harden-Jones, 1968; Pavlov and Kasumyan, 2000) and they were frequently encountered. These included the *Oreochromis aureus*, *Mayaheros urophthalmus* and *Toxabramis* cf. *houdemeri* (Ng et al., 2018). It is apparent that the IQI assessment requires some basic knowledge on ichthyology and behaviour of the native and introduced species for effective interpretation.

5.2 Chemical metrics

5.2.1 Non-compliances of BOD₅ values

The non-conformance of BOD₅ occurred across all zones. By definition, the BOD₅ parameter refers to the amount of oxygen that is consumed at 20 °C in 5 days for microbiological aerobic decomposition (oxidation) of organic material in 1 L of water (Jouanneau et al., 2014). The key purpose of assessing BOD₅ is to determine the amount of natural organic detritus and anthropogenic organic waste in the water sample (Zainudin, 2008). High BOD₅ levels in all zones suggests that the sampling points were consistently receiving a fair amount of organic loading from the natural environment in zone A (e.g. decaying leaves, branches) and anthropogenic environment in zones B, C and D (e.g. sewage, agricultural runoff). Evidently, this tells us that BOD₅ may not be necessarily low in natural environment. Studies show that BOD₅ loadings can be caused by the aerobic decomposition of organic litter expelled into the aquatic system from the natural terrestrial system (Mallin et al., 2006; Elozegi and Pozo, 2016).

It should be noted that although there was non-compliance in BOD₅ results, the overall DO and COD results were within class IIA-IIB standard. In sites where the DO level was naturally high as recorded in all zones, a slightly higher BOD₅ was not expected to pose a problem because the COD results were still within the class IIA-IIB standard. Furthermore, a major contributor

of DO in the waters is by aeration and such intensive air-water exchange process was observed to be consistently present in the many riffles and rapids along the Kampar River.

5.2.2 Non-compliances of Turbidity values

In the case of turbidity, zone C registered a high mean value (57.42 ± 37.65 FAU) and this was expected because the zone was densely populated and typically accumulated high pollutant loadings from upriver. However, the mean value in zone A (68.35 ± 206.23 FAU) also breached the limits of class IIA-IIB (< 50 FAU). Many studies have shown that natural alluvial waterbodies may be naturally turbid due to the high content of dissolved organic carbon (DOC) (Ertel et al., 1986; Meyer and Edwards, 1990; O'Connell et al., 2000; Wallace et al., 2008; Hladyz et al., 2011). In Malaysia, this occurrence was also observed in blackwater systems such as those in Maliau River Basin, Sabah (Harun et al., 2010) and Setiu River Basin, Terengganu (Suratman et al., 2017).

In natural environment, water discharging slowly and percolating through forest litterfall biomass such as decaying leaves, barks and twigs produces tannin-stained tea-coloured water (Meyer, 1990; Parolin and Worbes, 2000). This may also explain the high levels of BOD₅ that were recorded in zones A and B. The amount of carbon leaching depends primarily on the rate of organic litterfall and period of inundation in the water. Such occurrences are

a natural part of the river ecological system (Edwards and Meyer, 1987). Therefore, the turbidity parameter is not always a suitable measurement of water quality to determine whether a particular site is polluted by anthropogenic contaminants. Our data shows water which flows from a natural environment can also display high turbidity.

5.2.3 Non-compliances of NO₃-N and AN values

The NO₃-N parameter in zone D (7.01 ± 2.49 mg/L) was slightly over the class IIA-IIB limit (< 7.0). During the 18 month field data collection process, Zone D was observed to accommodate a wide range of vegetable cultivation plots, fruit orchards, oil palm plantations and livestock farms. As such, it was speculated that the marginally higher concentration was caused by diffused or non-point source pollution from fertiliser runoff.

Further literature review showed that the condition was not unique to zone D as studies elsewhere have frequently linked the presence of NO₃-N to imprudent fertiliser application. For example, Li et al. (2015) demonstrated that excessive nitrogen concentrations were significantly higher in areas where intensive agricultural activities are practiced. Along similar lines, Benckiser et al. (2015), Chen et al. (2018) and Górski et al. (2017) have also encountered such a condition. Since zone D was a limnological region where livestock farming was carried out, we also speculate that animal biowastes were carelessly disposed into the sampling site by the locals. This indicated an

absence of proper management in disposing pollutants and controlling runoffs. Animal urine and dung are regarded as major source of AN loading in pastures and waterbodies around livestock farms (Laubach et al., 2013; Li et al., 2015). This could also have caused the high levels of AN detected in 11 December 2016 and 15 January 2017 when the AN levels rose beyond the acceptable limit of 0.3 mg/L. As mentioned in the Results section, the sporadic anomaly was included in our descriptive statistics and linear regression calculation to reflect the reality of anthropogenic environment where random and unexpected incidents may occur. However, this was not an immediate concern because the water bodies in zone D was not a potable water intake area.

5.2.4 Non-compliances of DO values

DO warrants a special attention as it represents 22% weightage of the overall WQI calculation. Any variation in DO values would affect WQI and the fish population structure reasonably. Although DO was typically lower in zone D, as mentioned earlier, there were exceptions. An abnormally high level of DO was recorded in zone D during the sampling exercise on 24 April 2016 (9.8 mg/L) and 14 September 2016 (10.2 and 10.4 mg/L). A high level of algae growth seemed to be present in the sampling points. Longer periods of sunlight, higher temperatures and decreased water turnover rates (i.e. nutrient concentration) due to the severe El Niño event may have offered a favourable condition for algal bloom. Moreover, in zone D, waters were stagnant, shallow and susceptible to a higher intensity of oxygen dielcycling induced by aquatic

organisms. The corresponding anoxia ($O_2 = 0$ mg/L), hypoxia ($O_2 = 2-3$ mg/L), normoxia ($O_2 = 5-6$ mg/L) and hyperoxia ($O_2 > 9$ mg/L) conditions may develop in cycles throughout 24 h (Lakani et al., 2013). The above-average DO level in April and September 2016 may be caused by algal bloom that produced oxygen supersaturation, or DO at hyperoxia level, as a by-product of photosynthesis in the presence of extended sunlight hours during the El Niño event (Figure 5.2).

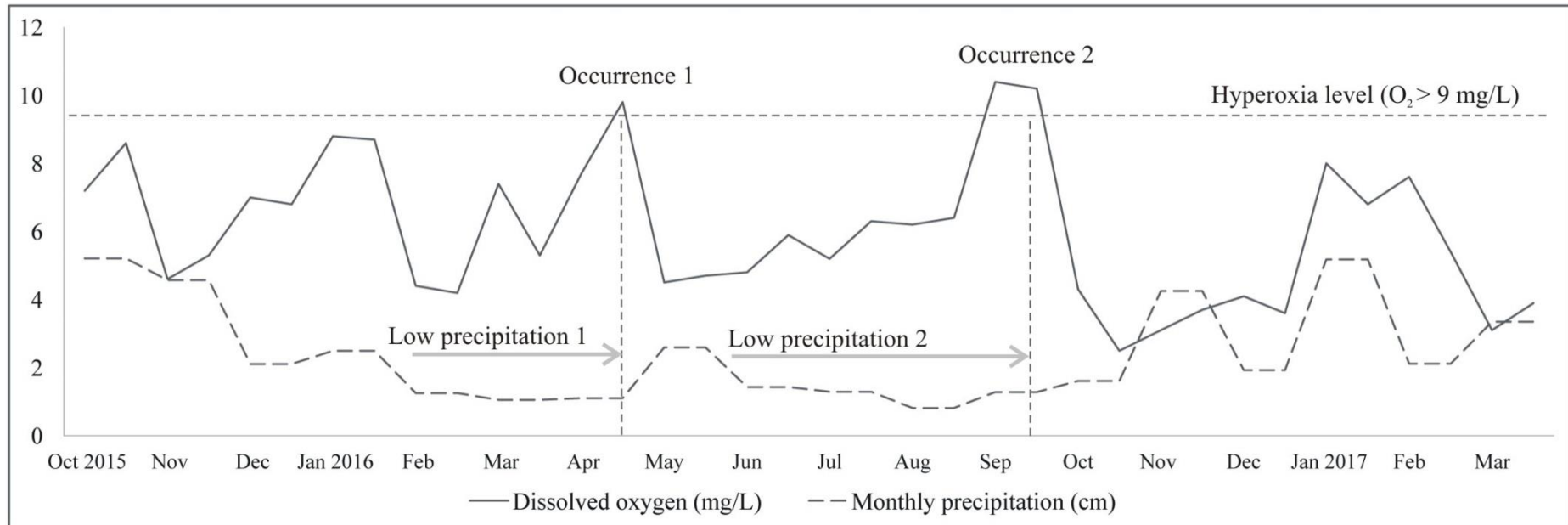


Figure 5.2: Dissolved oxygen values in zone D reached hyperoxia level in April and September 2016. The hyperoxia occurrences were preceded by periods of low precipitation, i.e. extended sunlight period that promotes algal growth

Although water was warmer and expected to hold less oxygen during warm weather, the dense algal bloom produced a surplus of oxygen and this was detected during our sampling exercise (Figure 5.3). Conversely, such incident was not observed in other zones where water was flowing and there was high volumetric turnover. This gives little opportunity for unusual algal growth to occur.



Figure 5.3: Intense algal bloom observed in zone D's sampling point after the prolonged low precipitation period

Comparing with other regions, such observation was also detected by Mosley et al. (2013) when they recorded abnormally high levels of algae in Lower Lakes, South Australia, during the drought period of 2009. They deduced that as a consequence of the lack of flushing (volumetric change), total nitrogen, phosphorus and chlorophyll followed an increasing trend. The lakes were classed as hyper-eutrophic during the dry season and high levels of DO were recorded. This was similar to the conditions

observed in zone D. Correspondingly many other studies have reported similar occurrences during the dry season (Rhodes et al., 1993; Bond et al., 2008; Binding et al., 2011).

5.2.5 Water chemistry and hydrology implications

It is widely recognized that natural perturbations of the river physical qualities may cause biological alteration at the individual sites (White & Pickett, 1985; Death & Winterbourn, 1994; Poole & Berman, 2001; Peckarsky et al., 2014). As such, failure to account for such natural disturbances will confound interpretations of the results produced by a physical assessment system that was validated by biological indicators. This study was conducted in the tropical region and we have an *a priori* reason to deduce that water temperature is not a critical factor.

Numerous species that were found in zone A (mean temperature = 24.03°C) were also found in zone D (mean temperature = 32.93°C), such as *Barbodes* cf. *rhombeus*, *Labiobarbus leptocheilus* and *Rasbora vulgaris*. Despite the water temperature difference, local fish species have the ability to thrive throughout the studied zones and the natural temperature variance has little implication on biological data collected in this study.

From field observation, water temperature variation in the zones was not naturally induced. Unlike localities in temperate countries, our study site in Malaysia

experiences a stable temperature range of 24 to 32°C throughout the year (Ng et al., 2017). Moreover, the studied zones were located in a relatively small area size of 690 km², therefore the zones were expected to experience the same homogenous ambient temperature. Studies have found that rivers in anthropogenic areas tend to be warmer due to the effects of urban heat islands and the removal of riparian vegetation (Brown, 1970; Nelson and Palmer, 2007). It was observed that zone A's transects shaded by riparian forest had recorded the lowest water temperature while zone C and D's transects which was bare and open to direct solar radiation recorded a higher degree of water temperature.

It was observed that a natural disturbance that may affect the fish-based metrics was hydrological variability caused by precipitation shocks. The River Continuum Concept postulates that the riverine system is a continuous gradient of physical network that should be considered in its entirety when attempting to understand the biological dynamics (Vannote et al., 1980). During incidences of heavy storm in the upriver, transects in the downriver where the weather was fine were observed to experience an elevated level of total suspended solids (TSS) in the waters. Studies have shown that high concentration of suspended organic and inorganic particles can negatively affect the fish community (Death, 2010; Jellyman et al., 2013).

Moreover, the river water levels are typically higher due to more intense volumetric flow during stormy weather. Such factor is known as hydromorphology, a term derived from water flow and morphology (Newson et al., 2012). Variation in hydromorphology is known to alter fish movement and distribution across the river

network (Church, 2002; Carlisle et al., 2010). Such proposition was demonstrated during October 2015 when the Shannon index was exceptionally low in zone A. The author argues that the sharp decline was primarily caused by a sudden change in hydromorphology (i.e. elevated volumetric flow) as a storm had occurred a few hours before the sampling exercise. The fish population may have deviated from its usual foraging behaviour and gone into hiding in velocity refugia along the river. A refugium is defined as a location where the adverse effects of disturbance are considerably lower than in the surrounding area (Lancaster and Belyea, 1997). It seems fair to suggest that many fish species may have avoided the temporary hydraulic stress by hiding in hyporheic zone (below substrate surface), under large rocks and sunken snag structures where the flow velocity was substantially reduced. Fish original distribution configuration is usually quickly re-established after a disturbance event and such behaviour is widely reported by previous studies (Church, 2002; Carlisle et al., 2010). It is therefore strongly advised that any biological assessments should not be conducted on any particular day when a storm has occurred or during the monsoon season to minimise undesirable biases.

5.3 Physical metrics

5.3.1 Implication on IQI and WQI

A striking aspect of the results was the wide variation in IQI and RPQI scores, while the WQI scores were reasonably consistent among the sampling transects within the same zone. Notably, the coefficient of variation (CV) of IQI was the lowest in zone A (0.12) and highest in zone C (0.28) (Figure 5.4). This suggests that IQI assessment in zone A was yielding consistent results in any of the four sampling transects throughout the 18 months data collection exercise. However, the IQI values in zone C were highly variable and may be caused by the unstable WQI and RPQI metrics in the sampling transects. Being located downriver, this was not surprising as zone C was expected to accumulate pollutants from upriver and its physical attributes were more susceptible to changes caused by water volumetric fluctuation.

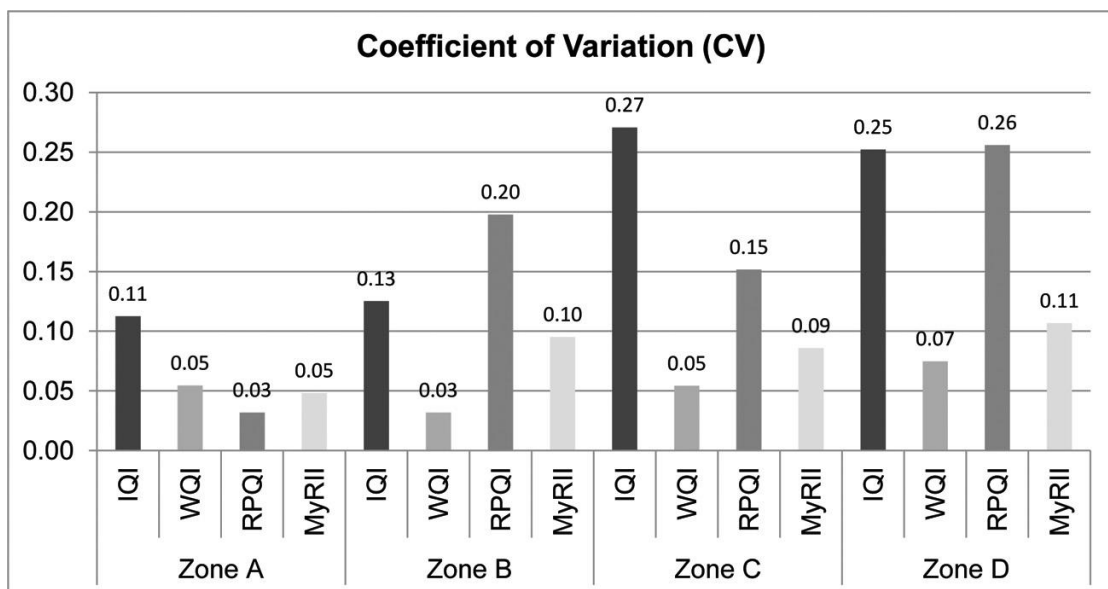


Figure 5.4: Bar chart shows that the coefficient of variation (CV) for most indices was the lowest in zone A. This reflects the unmatched stability and suitability of zone A as a reference site

The river stretch in zone C was observed to be a straight channel and therefore the water flowed faster, especially during stormy weather when the river experiences high volumetric loading from upriver. It also lacked the substrate and riparian complexity to provide velocity refuges for fish. And yet, during fair weather when the water flow was slow and the river was shallow, the fish population had the opportunity to recover. Such natural and anthropogenic disturbances may have caused the ichthyofaunal sampling results to fluctuate extensively and correspondingly causing a high degree of CV in zone C's IQI results. Natural disturbances (e.g. storm) may not have stressed the sampling transects in zone A because the river physical structure was in excellent condition. It was resilient enough to sustain a consistent level of ichthyofaunal composition.

The CV of RPQI was higher in the sampling transects in zone B and C when compared with zone A. This indicated that the sampling transects in zone B and C did not exhibit homogenous physical and hydrological characteristics although each transect were only 800 m apart. The RPQI variation was the highest in zone D because each sampling transect was a lentic unit with distinct physical characteristics. It should be pointed out that despite the variations, the resultant MyRII in each zone was able to reflect the appropriate level of integrity. The key strength of the MyRII was that its multidisciplinary sub-indices were explicitly formulated to counterbalance each other based on equal weighting.

5.4 Water provision ecosystem service value

In lieu of the establishment of geomorphological and ES economic baseline data and the level of linear relationship between area size and volumetric discharge in the studied watersheds, it would be helpful to further discuss some critical issues and questions that also emerged from this study.

Generally, a small watershed's geomorphological complexity and stability is more sensitive and susceptible to any short or long term disturbances, whether natural or anthropogenically induced (Clarke, 1996; Ritter et al., 2002). Any substantial disturbances may affect a watershed ES quality pertaining to retention, regulation and provision of freshwater (Thorp et al., 2010), and in turn influences the watershed's economic value. Hence, what are the economic implications if the watersheds in upland Kampar River are degraded, and what may be the contributing factors that may decrease the watersheds' geomorphological integrity? The discussion also focused on the possible conservation mechanisms that may assist in managing and policy-making to enhance the small watersheds located in the foothills of Malaysia.

5.4.1 Economic comparisons

As highlighted earlier, literature on watershed ES economics is scant in the Southeast Asia. At the time of this study, no case study or review paper could be found for comparison purposes, with the exception of those that originated from developed

countries. Certainly, it is discriminatory to compare monetary values established in this country with those from developed countries as the Malaysian currency Ringgit is much weaker. However, it would be interesting to include monetary values in the discussion to provide some benchmarks for guiding the stakeholders and policymakers.

As a comparison, Hill et al. (2014) estimated that the watersheds' freshwater provision ES in United States were on the average valued at USD245.00 or RM980.00 ha⁻¹ yr⁻¹ (currency exchange USD1.00 = Malaysian RM4.21) while the studied watersheds in Kampar River uplands were worth RM208.79 ha⁻¹ yr⁻¹ in 2016. Smith et al. (2006) reported that USDA compensated farmers at USD50.00 acre⁻¹ yr⁻¹ (1 acre = 0.404686 hectare) for watershed related conservation safeguards. A value of USD163.00 acre⁻¹ yr⁻¹ was estimated by Costanza et al. (2006) for watersheds in New Jersey, US. In Muskoka River and Black River–Lake Simcoe watersheds, Canada, Austin et al. (2012) calculated their freshwater provision ES as between CAD33.20 to CAD236.77 ha⁻¹ yr⁻¹ (currency exchange Canadian CAD1.00 = Malaysian RM3.08). Values given may be taken as the baselines in developed countries although the values in developing countries have yet to emerge. However, with the freshwater provision ES value established by this study on four watersheds located in Perak, the values elsewhere may be inferred from their respective water tariffs.

Perak's water tariff is among the lowest when compared to other states in Malaysia and other cities in Southeast Asia (Figure 5.5). Johor's water tariff appears to be the highest in the country and roughly on par with Cebu and Jakarta city. Their water tariff is 195% higher than Perak's. This provides an indication of their freshwater

provision ES values although the proper studies need to be carried out to ascertain the values more precisely. Singapore's water tariff is the highest in Southeast Asia, roughly 350% higher than Perak's, but this should not be entirely construed as the local watershed's freshwater provision ES value. Singapore is an island state and the freshwater is sourced from a combination of local watershed, imported water, reclaimed water and desalinated water. At the time of this writing, reclaimed water makes up to 40% of Singapore's water demand (PUB, 2017).

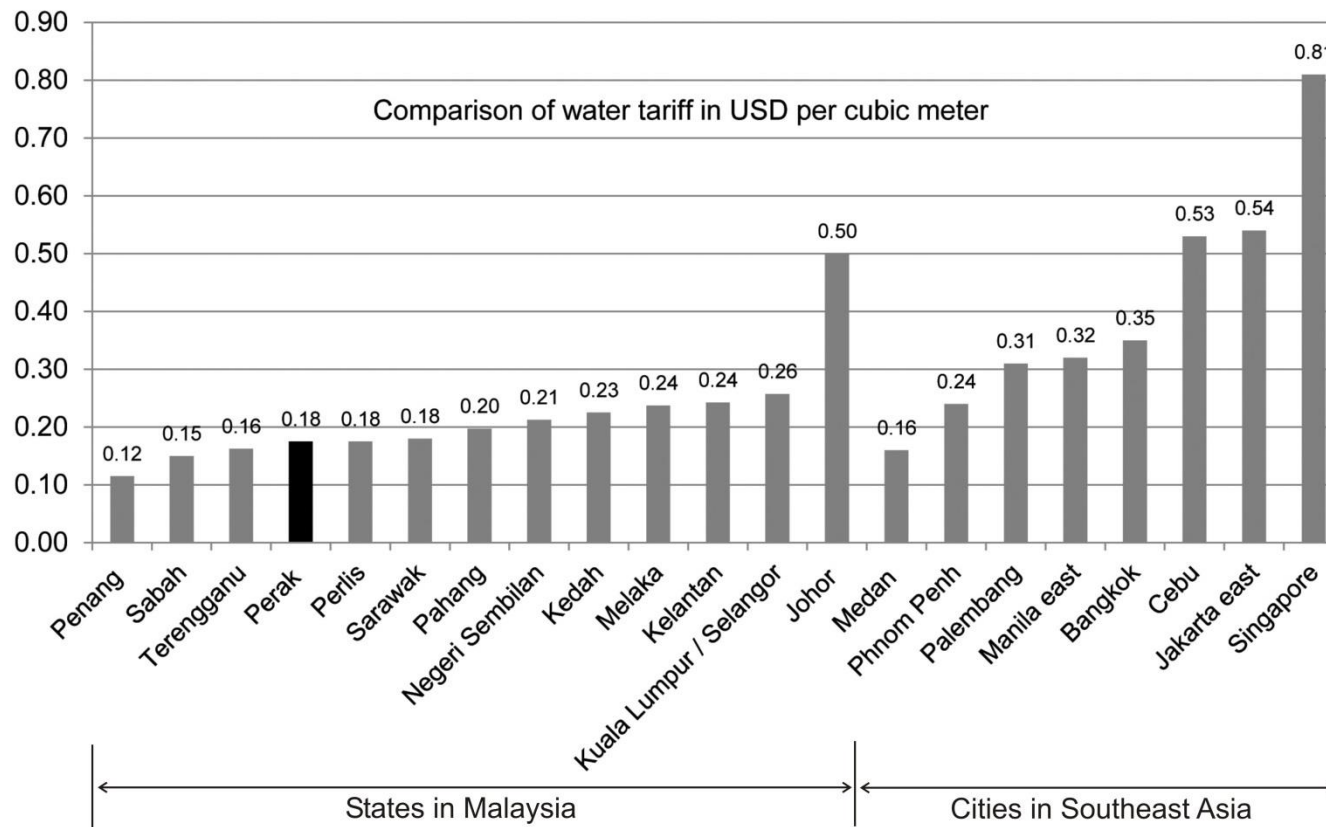


Figure 5.5: Comparison of water tariffs in USD per m³ (USD1= RM4) at domestic category (Band 2) between Malaysian states and other major cities in Southeast Asia at the time of this study. The study site of this research is located in Perak as indicated in black bar

Source: Combined data from McIntosh (2014), SPAN (2017) and PUB (2017)

5.4.2 Watershed integrity

A watershed is beneficial to the society only when it is able to store, regulate and release water gradually to prevent undesirable events such as floods or water shortages (Everard and Quinn, 2015; Distefano and Kelly, 2017). This is especially critical during the ENSO event that triggers extreme dry weather periodically. Flotemersch et al. (2016) define “watershed integrity” as a watershed capacity to support and maintain a full range of ecological processes and functions essential for the sustainability of watershed resources and services provided to society. A watershed’s geomorphological features have definite influence on its hydrological response (Thorndycroft et al., 2008; Thorp et al., 2010) and this implies that ideally a watershed’s geomorphological features have to be as natural as possible, or intact, for the best performance.

However, a report published by the Millennium Ecosystem Assessment (2005) highlighted that about 60% of watershed ES have been degraded and overexploited globally. On the local front, unsustainable hillside economic practices were critical issues (Abdul Rahim, 1998; Ziegler et al., 2006; Chan, 2005). Deforestation (Chimeli et al., 2011; NEPcon, 2016), and water pollution from the agriculture industry (Chan, 2005; Oksel et al., 2009; Khalik et al., 2013) and the manufacturing industry (Kamarudzaman et al., 2011; Sujaul et al., 2013) have also been frequently reported in Malaysia. It is widely recognized that when the watersheds degrade and become polluted, more

resource inputs and costs will be required to supply water (MEA, 2005). For example, the operational cost of water purification processes in the water treatment plants will be increased. Consequently, the water tariff will be increased and it has a financial impact to the society.

Hydrography signature is a plausible indicator for watershed geomorphology because the signature and trend is dictated by the routing of water through a watershed (Patton and Baker, 1976; Ritter et al., 2002). For example, the drainage density (Dd), relief (Bh) and circularity (Rc) geomorphometric variables are often associated with the intensity of volumetric flow rises and falls during stormy weathers (Miller, 1953; Schumm, 1956; Patton and Baker, 1976; Chorley et al., 1984; Singh, 1992). In heavily disturbed watershed, the flow regime during storm events are characterized by sharp spikes and these are termed as “flashiness” (Chorley et al., 1984; Singh, 1992). Such variance is illustrated in Figure 5.6 which shows a comparison of four hydrography signatures, namely Kampar River and Triang River which represent the natural landscapes, and Batu River and Damansara River which represent heavily altered landscapes.

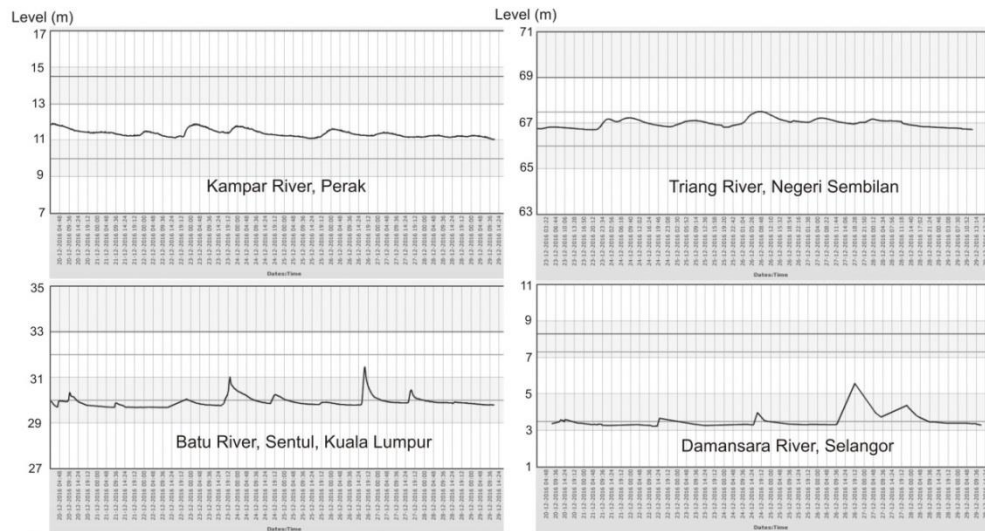


Figure 5.6: Hydrograph plot of rivers during the period 20-29 December 2016 to show the differences between natural and heavily altered watersheds (Department of Irrigation and Drainage, 2017)

One of the key factors for such “flashiness” signature is the lack of geomorphological complexity, such as areas which are homogenized by anthropogenic land-use activities that are unsustainably carried out (Ziegler et al., 2006; The, 2011). In contrast, areas with highly complex landforms tend to retain more precipitation and allow greater rates of infiltration, therefore lowering the possibility of “flashiness” (Rodríguez-Iturbe and Valdés, 1979; Brass, 1990). As mentioned earlier, the hallmark of watershed with high integrity is one that is able to store and regulate the release of freshwater. If the release is too intense during a short period of time, flooding in the downriver may occur and this will have negative economic implications to the society.

5.4.3 Community-based conservation

This study was focused on small tributary watersheds because there has been an increase of successful examples on the decentralizing of responsibilities for watershed management to the community level (Chan, 2005; Balint, 2006; Chang et al., 2009; Vote et al., 2015; Feng et al., 2018; Suhardiman et al., 2018). In tropical regions such as Malaysia where high-intensity precipitation over a short duration is common, landscape-level disturbances affect the hydrography signature more than channel disturbances (Feng et al., 2011; Sargaonkar et al., 2011). Consequently, in smaller watersheds, the volume of surface run-off is more prominent when compared to channel flow (Singh, 1992). Moreover, it is more practical for any conservation framework or policy that involves the communities to focus on small watersheds which the locals live and work in because a smaller area is more manageable for them (Chang et al., 2009). However, to successfully promote small watershed conservation, there is a need to devise a way to support and compensate the communities. Without such harmonization and policy-level safeguards, they may revert to fulfilling their livelihood with the most profitable practices and these usually entail unsustainable land-use practices that disturb the watershed geomorphology.

There is already a rapidly growing literature on many harmonization frameworks globally which indicates the popularity and necessity on integrating and motivating upriver and downriver communities to support

watershed conservation (Chan, 2005; Balint, 2006; Feng et al., 2018). Such eco-compensation schemes are explicitly termed as Payment for Watershed Ecosystem Services (PWES) (Feng et al., 2018). Briefly, the PWES approach usually works on the principle of, 1) developer protects, 2) saboteur rehabilitates, 3) beneficiary compensates, or 4) polluter pays (Engel et al., 2008; Pagiola et al., 2008; Wunder, 2013). So far, there is no official implementation of PWES scheme in Malaysia although the literature shows there was an increase of 42 schemes in 2008 to 69 schemes in 2018 in the developing countries of Africa, Latin America, East and South Asia, and Southeast Asia (Porras et al., 2008; Feng et al., 2018).

Wunder et al. (2015) deduce that government financed PWES schemes were more cost-effective than user-financed PES because of economies of scale and reduced transaction costs. They also highlighted that company and NGO implemented PWES schemes were more successful because they played the intermediary roles for transparency between the government agencies and communities for determining and transferring payments from users to providers (Davenport et al., 2007; Ghazoul, 2007). However, a typical PWES issue is that, not all residents in the watersheds may be equitably compensated. Some residents may be living in the watershed but working elsewhere during the day. There are some who may be too old to actively participate in conservation activities that require field work. In the case of tributary watersheds in upland Kampar River, the residents are mostly Semai and Temair indigenous communities who have no legal land rights in the watershed. The National Land Code 1965 does not recognize ancestral lands

inherited from generation to generation and this includes lands occupied by the indigenous communities (Hamzah, 2013). Understandably, there are some issues that may obstruct PWES scheme implementation in Kampar River upland and elsewhere in Peninsular Malaysia. These are some precautions highlighted and briefly discussed to guide proponents wishing to start planning and producing policies for deploying PWES schemes to safeguard small watersheds in Malaysia.

5.5 MyRII implementation challenges

Moving forward, some overarching issues in the users' perspective may need to be addressed for effective implementation of the MyRII protocol. It was apparent that the WQI metrics were reasonably straightforward to quantify and the discipline of water quality testing is widely practiced in Malaysia. Moreover, protocol users without the necessary water testing apparatus and facilities may send water samples for testing in the many MS ISO/IEC17025 accredited laboratories in the country. Literature and manuals to assist in interpreting WQI metrics and the results are also widely available. Similarly, the RPQI quantification processes are also uncomplicated and it is detailed in the comprehensive SVAP2 manual (NRCS, 2009).

Regrettably, ichthyology is not a common discipline and the subject is markedly riddled with knowledge gaps in Malaysia. Although Cantor (1849)

has started enumerating species diversity in Malaysia for more than 160 years ago, unfortunately, ichthyology is still considered to be in the discovery and exploratory stage (Lim et al., 1993; Lim and Tan, 2002; Ahmad and Khairul-Adha, 2005). The predicament was further compounded by the lack of interest and funding constraints that have left the ichthyology discipline with various unresolved taxonomic problems (Ahmad and Khairul-Adha, 2005; Ng et al., 2017b). Politically, Malaysia comprises of the west (peninsular) and the east (Sabah and Sarawak) which are divided by the South China Sea. Species taxonomy, diversity and biogeography are expected to differ among the regions and the prevailing taxonomic issues may have some impacts on the IQI application. However, recently, the ichthyofaunal diversity and biogeography has been reviewed and updated by in Sabah (Ng et al., 2017c). It is hoped that such work would be emulated in Sarawak and other states in Peninsula Malaysia region.

To support the application of MyRII, a concise guide on fish taxonomy and identification techniques (Ng et al., 2017a) and an annotated fish checklist with pictorial guide for Kampar River (Ng et al., 2018) has also been published to support MyRII deployment locally. In preparation for the future, a checklist has also been published by the author for species found in Perak state (Ng et al., 2019). These peer-reviewed checklists are expected to assist IQI assessors in species identification to a certain degree. At the very least, they would be able to record the appropriate photographs and collect the necessary voucher specimens for verification by ichthyologists. In such cases, ichthyologists from the Fisheries Research Institute (Freshwater Division) (peninsular), Likas

Fisheries Research Center (Sabah) and Fisheries Research Institute (Sarawak) may be consulted. If the MyRII protocol can be widely accepted and applied, the movement may give the fish taxonomy discipline a new practical purpose. Hopefully, this would create more interest for the ichthyology discipline to support the implementation of the proposed MyRII protocol.

5.5.1 Stakeholder feedbacks

The stakeholder of relevance to the proposed MyRII approach is mainly Department of Irrigation and Drainage (DID) which is legislatively entrusted to manage all rivers in Malaysia. It was assumed that as the department is directly linked to river assessment activities therefore the officers have a justified interest in any new approaches proposed. Hence it was essential to engage and obtain feedback from DID to gain a deeper understanding on how they would perceive and exchange further views on the proposed MyRII approach.

On 12th July 2019, the author co-hosted an official dialogue meeting together with Perak State DID Headoffice in Bangunan Sri Perak in Ipoh to gather feedback from the officers involved in river management. The meeting was chaired by Assistant Director Puan Ir. Salfarina Mohd Sharif. It was attended by departmental representatives from the 1) Corporate Office, 2) Hydrology and Water Resources, 3) Urban Drainage and Flood Prevention, 4) Coastal and Agriculture Irrigation, 5) Mechanical and Electrical Engineering

Services, 6) Land Surveying, and 7) Federal Projects Management Office. In total, 11 officers attended the meeting. The meeting started with the author giving a 1.5 hours presentation of the research and findings to the officers with a Powerpoint file. Since all officers did not possess postgraduate proficiency, the author spent more time and effort to elaborate the statistical illustrations and findings in a manner which was easier to comprehend. The Powerpoint file used during the presentation was readapted from the version used during the author's Work Completion Seminar (WCS) and it was enhanced with more illustrations. A dialogue was carried out after the presentation.

The officers expressed appreciation to the author for filling in the research gaps and proposing a wholesome river assessment system for Malaysia. They found the presentation valuable and the Assistant Director mentioned, "... we learned so many things today". Most of them revealed that it was the first time they were exposed to physical and biological metrics for measuring river integrity (currently, they were only familiar with water physico-chemistry assessments). They found RPQI and WQI protocols were straight forward and can be easily applied if the government is to adopt the MyRII protocol. However, some officers felt that fish species identification proficiency required by the IQI protocol would be a challenge. This issue was expected by the author and it was already documented in the thesis under item 5.6. In anticipation to the issue, a comprehensive fish identification guide for Sg Kampar has already been published (Ng et al., 2018). At the time of this writing, the author had also published the fish checklist for Perak (Ng et al., 2019) and Sabah (Ng et al., 2017c), and the author hopes to generate more

state-level checklists in the future to address the issue. These were conveyed to the officers.

Additionally, the author had also sought feedback from professional consultant En. Mohd Azham Yahaya of Europasia Engineering Services Sdn Bhd (www.europasia.com.my), a leading company in Malaysia that provides environment impact assessment. En. Mohd Azham is one of the few professional consultants in Malaysia who is well versed in ichthyology. As mentioned in literature review, there is an acute lack of ichthyologists in Malaysia (Ahmad and Khairul-Adha, 2005) and thankfully En. Mohd Azham had agreed to provide feedback. He is responsible for aquatic species assessment work for the company. Below is the content of his feedback via email (verbatim):

“1. I’ve gone through Casey’s work. The idea is to add fish survey and river physical assessment together with WQI as river monitoring.

2. Perhaps after conducting several surveys from other rivers Casey could develop a river status table that indicates healthiness or sensitivity of the river (based on MyRII rating) which is then could be incorporated into ESA assessment.

3. MyRII maybe could be one of the indicators in payment for ecosystem services.

4. Which government agencies should conduct river physical assessment?”

Four items were highlighted. Item 1 was a general statement while item 2 and 3 were suggestions. To item 4, the author proposed that the Department of Irrigation and Drainage (DID) to be the government agency responsible for conducting the physical assessment (RPQI) as the department is legally responsible to protect and oversee matters pertaining to river, floodplain and riparian areas under the following Acts, 1) Kanun Tanah Negara 1965 aan Perairan (Seksyen 62), 2) Akta Pemuliharaan Tanah 1960, 3) Akta Kerja-kerja Saliran 1954 (1988), 4) Akta Jalan, Saliran dan Bangunan 1974 (1994), and 5) Akta Jalan, Saliran dan Bangunan 1974 (1994).

5.6 Limitations and future researches

This study is not comprehensive but aimed at providing first foundation for river integrity assessment in Malaysia. The validation exercise so far has only been conducted on a small scale level in Kampar River due to the lack of resource thus information herein should be viewed with some caution as outcomes may not be similar in other rivers due to variability in natural and anthropogenic characteristics. The MyRII system needs testing in more rivers to drive further refinement. From data and insights highlighted in the Results and Discussion section, it is clear that the MyRII system has some limitations. For transparency, the limitations and precautions are discussed in the following sections. Additionally, some future investigations are also suggested to

reinforce the MyRII protocol and explore other means of measurement for assessing and monitoring river and watershed ecological integrity.

5.6.1 Fish taxonomy and IQI interpretation

The Kampar River waterbasin region is still in exploration and discovery phase in terms of ichthyology. The species list enumerated in the Results section is preliminary at best and the variety of species is expected to increase as more lateral and longitudinal surveys along the main river and tributaries that feed into Kampar River are carried out in the future. Future studies should include night sampling to unveil nocturnal species for refining the checklist.

Some species taxonomic statuses and valid scientific names are still unsettled and problematic although they were described long ago, such as *Barbodes cf. rhombeus*, *Channa gachua*, *Clarias aff. batrachus* and possibly *Anabas testudineus* that are involved in complexes. However, this does not mean that the taxonomic statuses of other species are stable. Revision shocks in fish taxonomy are common and non-ichthyologists should not be distracted by emerging nomenclature and taxonomic problems. Contentious identification issues take time to be resolved and they are inevitable in the field of taxonomy. Such concerns should be left to trained ichthyologists to monitor as they have a professional duty to validate and update the literature with the most current and valid species scientific names. It should be stressed that there is currently no universal criteria or platform for updating and crosschecking

valid scientific names in a real time manner. Taxonomic nomenclatural consistency for all fish species is an elusive ambition, a fact well understood by ichthyologists. Therefore it is always important to refer to the most current reviews or species descriptions published by the authorities to communicate species identity.

As shown in the results, Pielou index and the quantity of individuals encountered during sampling exercise did not have significant correlation with RPQI values. This implies that fish-based data collected should always be interpreted with a reasonable level of understanding on fish taxonomy, behaviour and ecology. In nature, some fish species may swim in groups (polarized) or individually (non-polarized) (Brown, 2000). Fish also may not be evenly distributed due to prey-predator interactions, food availability, spawning behaviour and other factors (Bramblett and Fausch, 1991). Consequently, finding individuals at regular intervals along the length or depth of the sampling transects cannot be expected (Harris, 1995) and the quantity of individuals captured may also be dependent on fishing gear methods and the variance in hydro-morphology. These factors should be investigated in future researches.

5.6.2 Water chemistry variations

This study represents field data of water quality variances and responses to an unusual dry weather event that may be used to inform policy and decision making on freshwater safety, security and pollution management in the natural and anthropogenic ecosystems. Data and analyses generated may also be used as the benchmarks to monitor or compare with subsequent studies, conducted locally or elsewhere in the Southeast Asia region to examine the impacts of strong El Niño occurrences in the future.

Nonetheless, the magnitude and pattern of water quality variation are typically area specific. Hence, the findings should be viewed with some caution as this may not be the same case with study sites of different terrestrial, aquatic and anthropogenic characteristics. Although this study deduced that the strong El Niño event in 2016 has no significant linearity with WQI and the supplementary water physico-chemistry parameters measured, this may not be the case if Kampar River watershed receives higher concentrations of pollutant from natural and anthropogenic pressures in the future. This investigation so far have only been on a small scale and relatively short term and therefore makes no conclusions about the possible water quality variances and uncertainties that might arise in the subsequent strong El Niño occurrences. More comprehensive studies in other water catchments are recommended in conjunction with future strong El Niño events to expand and deepen the understanding of water quality responses to climatic disturbances.

5.6.3 Other form of ecohydrological systems

In this study, the MyRII protocol was tested on a river (zone A, B and C) which is a part of a larger detritic watershed ecosystem. Certainly, there are some other forms of ecohydrological ecosystem in Malaysia as highlighted in the Literature Review section.

In this study, it was clear that it may not be possible to formulate a standard physical assessment protocol that can be applied to all types of ecohydrological ecosystem. However, these ecosystems should not be ignored and researchers should strive to continue to create or readapt the appropriate assessment protocols for assessing various fluvial ecosystems. This study should also be viewed with some caution as the validation exercise was conducted on a small scale level in the Kampar River region due to resource constraints. The results may not be similar in other study sites due to variability in climate, ecosystem, species composition and anthropogenic pressure characteristics. The proposed MyRII protocol needs to be tested on more rivers for further refinement. It must be stressed that the protocol is not intended to replace the existing WQI protocol, rather the MyRII protocol may be used to produce a multi-disciplinary judgment that is more balanced to assess river integrity.

5.6.4 Geomorphology

It should be pointed out that this study had only generated the 2D geomorphometric data. Although the 3D geomorphometrics are not within the scope of this study, the data are equally important for characterizing the watersheds, especially for identifying areas of geomorphic hazards (i.e. erosion, landslide) that may disturb the hydrography pattern and volume of surface water discharge (Strahler, 1952; Barnard et al., 2001; Caumon et al., 2009). Large-scale landslides and erosion are common in Malaysia due to frequent intense rainfall induced by the tropical climate (Chen and Lee, 2003; Chan, 2005; Schulz et al., 2009). As shown in Figure 5.7, the tributary watersheds are vulnerable, especially the Ulu Kampar watershed that features more areas with slope exceeding 25°. Areas with >25° slope are often regarded as fragile and unstable (Johnson 1980; Angeli et al., 2000; Jongmans and Garambois, 2007).

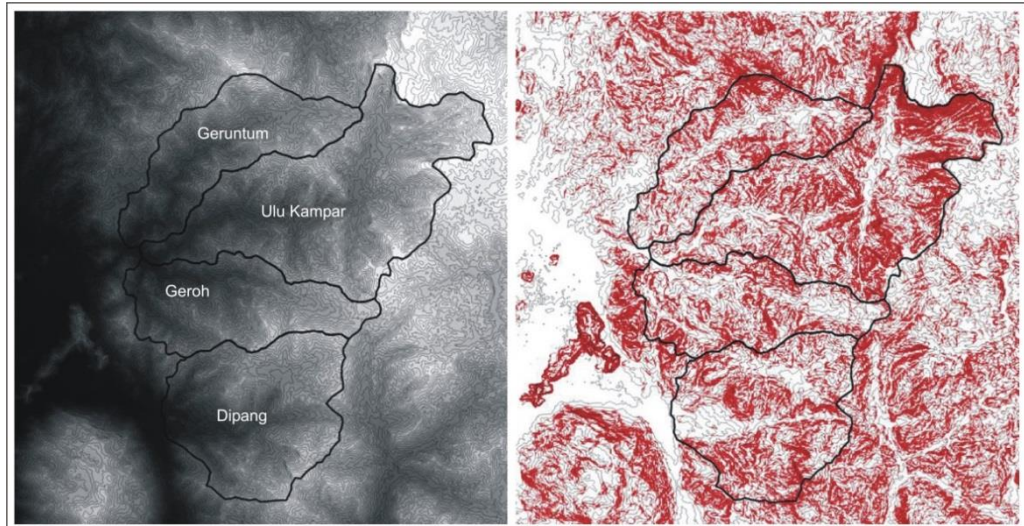


Figure 5.7: Visual data providing a reference for locating high-risk erosion and landslide areas in the four tributary watersheds. Note that the Ulu Kampar watershed has reasonably more area with $>25^\circ$ slope (red) in the eastern region

Besides geomorphometric data established by this study, Travelletti and Malet (2012) emphasize that there are four other key sources of data that should be investigated for characterizing the baselines, namely 1) kinematic data, 2) geological data, 3) geotechnical data, and 4) petro-physical data. These baselines should be generated by future studies to expand the body of knowledge on watershed integrity for water provision ES in Malaysia.

5.6.5 Water provision ecosystem service value

The estimated monetary value of the four tributary watersheds in this study was a conservative figure as the value is expected to be reasonably higher because the tariff code 21 which imposes a higher tariff is not taken into

account in this study due to the difficulty in obtaining water consumption data of the remaining 12% of consumer, namely from the commercial sector. The estimated figures were calculated with the assumption that the watersheds' geomorphological characteristics remain in stable until 2026. Any alteration and impairment of the existing condition would change the watersheds' economic value.

This study is by no means comprehensive and the pilot investigation in Malaysia so far has been on a small scale level to collect the baseline data for foothill-based geomorphology in Titiwangsa Mountain Range. It was only focused on water provision ES although the watersheds can offer flood prevention, ecotourism, aesthetic and even cultural ES values (Morton and Padgitt, 2005; Luck et al., 2009; Austin et al., 2010). Given that our findings were on based limited numbers of tributary watersheds, the results should be treated with some caution. More studies are necessary to reinforce the baseline data to drive planning and policy-making. Moreover, besides the “user pays” approach (i.e. MPM) adopted by this study, other approaches and projected scenarios should also be explored to underpin the economic baselines and communicate water tariff hike when the watershed ES is damaged or needs to be restored. Naturally, it is more cost effective to protect the watersheds from threats than to pay for restoration later.

CHAPTER 6

CONCLUSION

This study has successfully met its objective by pioneering the multi-disciplinary MyRII protocol for filling a gap identified by the Malaysian government and validated its ability to respond to different levels of zonal integrity along the Kampar River. The key strength of the protocol is that it complies with the existing local authorities' requirement (i.e. WQI) and expanded to include biological (i.e. IQI) and physical (i.e. RPQI) metrics that are able to respond to different time scales and a wide range of ecological processes during the 18 months' trial period. Although the result of MyRII is a single number that may range from 0 to 100, it is a summed response values of three critical indices (i.e. IQI, RPQI and WQI) which individually focus and highlight impairment of various degrees in finer scale. In other words, besides the MyRII value, the sub-indices and the corresponding multi-metrics provide the precise nature of impairment to inform and drive river restoration and management initiatives. As such, the MyRII protocol has emerged as an improved version when compared with the existing river assessment protocol which only focuses on water chemistry variables.

Evidence from this study has also provided first data and valuable insights of the dynamic interactions and correlations in the spectrum of metrics assessed in the context of Malaysian riverine ecology. Correspondingly, it has expanded the understanding of spatial and temporal variability and

disturbances that may occur in the tropical riverine ecosystem. Similar to most newly formulated assessment methods, the MyRII protocol is not without flaws, notably the deficiency in ichthyology body of knowledge and taxonomy skills available in the country which may hinder the deployment of the MyRII protocol. Also, further researches are needed to develop other sensitive assessment protocols to examine various types of fluvial system found in Malaysia. Certainly, this study was by no means comprehensive and the MyRII protocol was deduced mainly from a small-scale research in Kampar River watershed. The MyRII protocol may need more trials in other watersheds and rivers for further refinement and continuous improvement. However, as shown by the results of this study, the limitations are clearly overshadowed by the benefits. The protocol proposed herein can thus also offer a model for developing river assessment system in other countries within the Southeast Asian region and elsewhere with similar climate and geomorphology.

The MyRII protocol is a solid approach which should, at the very least, provide the necessary benchmark on whether a river's ecological integrity is increasing or decreasing. A river is an intricate web that cannot be understood by looking at one angle. The immediate issue at stake is, unless we begin to recognize the ecological interactions between biology, chemistry and physical components, and assess river integrity in a multi-disciplinary manner, we would only have partial or deficient data to drive restoration and management initiatives. This study adds to the mounting body of evidence that water resource stakeholders and policymakers must look at the big picture and adopt

the “balanced ecosystem” mindset when executing river assessment and conservation initiatives. Certainly, the concerns arising from this study suggest that there is much to learn. Nonetheless, the proposed MyRII protocol sets the foundation and offers a way forward.

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APPENDICES

APPENDIX A

Papers published

Ng, C.K.C., Ooi, P.A.C., Wong, W.L. and Khoo, G., 2019. First development of the Malaysian River Integrity Index (MyRII) based on biological, chemical and physical multi-metrics. *Journal of Environmental Management*, 255, 109829.

Ng, C.K.C., Ooi, P.A.C., Wong, W.L. and Khoo, G., 2019. Adaptation of an assessment system for establishing a River Physical Quality Index (RPQI) and testing its effectiveness with fish-based metrics in Malaysia. *River Research and Applications*, pp. 1 – 14.

Ng, C.K.C., Ooi, P.A.C., Wong, W.L. and Khoo, G., 2018. Ichthyofauna checklist (Chordata: Actinopterygii) for indicating water quality in Kampar River catchment, Malaysia. *Biodiversitas*, 19, pp. 2252 – 2274.



Ng, C.K.C. et al., 2018. Water quality variation during a strong El Niño event in 2016: A case study in Kampar River, Malaysia. *Environmental Monitoring and Assessment*, pp. 190: 402.

Ng, C.K.C., Ooi, P.A.C., Wong, W.L. and Khoo, G., 2017. A review of fish taxonomy conventions and species identification techniques. *Journal of Survey in Fisheries Sciences*, 4 (1), pp. 54 – 93.

Ng, C.K.C., Ooi, P.A.C., Wong, W.L. and Khoo, G., 2017. An overview of the status, trends and challenges of freshwater fish research and conservation in Malaysia. *Journal of Survey in Fisheries Sciences*, 3 (2), pp. 7 – 21.

APPENDIX B

Official memo for the feedback and dialogue meeting at the Department of Irrigation and Drainage on 12th July 2019 highlighted in item 5.5.1.

	MEMO JABATAN PENGAIRAN DAN SALIRAN NEGERI PERAK DARUL RIDZUAN		
Daripada	Penolong Pengarah Kanan Bhg. Sungai, JPS Perak		
Kepada	Timbalan Pengarah, JPS Perak Ketua Penolong Pengarah, BPME Ketua Penolong Pengarah, Saliran Pertanian dan Pantai Ketua Penolong Pengarah, Bhg. Korporat Penolong Pengarah Kanan, Bhg. Saliran Bandar dan Tebatan Banjir Penolong Pengarah, Bhg. Hidrologi dan Sumber Air Penolong Pengarah, Bhg. Ukur Bahan Jurutera Projek, Pejabat Projek Persekutuan PLSB Sg. Perak		
Bilangan Fail Kami	Tarikh	Bilangan Surat Tuan	Tarikh
Bil. () dlm	10 Julai 2019		

Tuan/Puan,

Taklimat Kualiti Air

Dengan segala hormatnya saya merujuk kepada perkara di atas.

2. Dimaklumkan bahawa taklimat tersebut akan diadakan pada tarikh, masa dan tempat seperti berikut :-

Tarikh : 12 Julai 2019 (Jumaat)
Masa : 8.30 pagi
Tempat : Bilik Mesyuarat (BPSP)
Tingkat 5, JPS Perak.
Pengerusi : Timbalan Pengarah, JPS Perak.

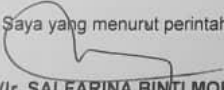
3. Sehubungan dengan itu, Tuan / Puan adalah dijemput bersama Penolong Jurutera masing-masing untuk menghadiri taklimat tersebut.

4. Kehadiran Tuan / Puan amat dihargai dan didahului dengan ucapan terima kasih.

Sekian.

" BERKHIDMAT UNTUK NEGARA "

Saya yang menurut perintah,


(Ir. Salfarina Binti Mohd Sharif)
b.p : Pengarah
Jabatan Pengairan dan Saliran,
Perak Darul Ridzuan.

APPENDIX C

The meeting on 12th July 2019 was for gathering feedback from the officers of Department of Irrigation and Drainage (DID) involved in river management. Assistant Director Puan Ir. Salfarina Mohd Sharif presented the author with a token of appreciation after the dialogue and feedback session.

