River health monitoring in the Ayeyarwady river basin in Myanmar

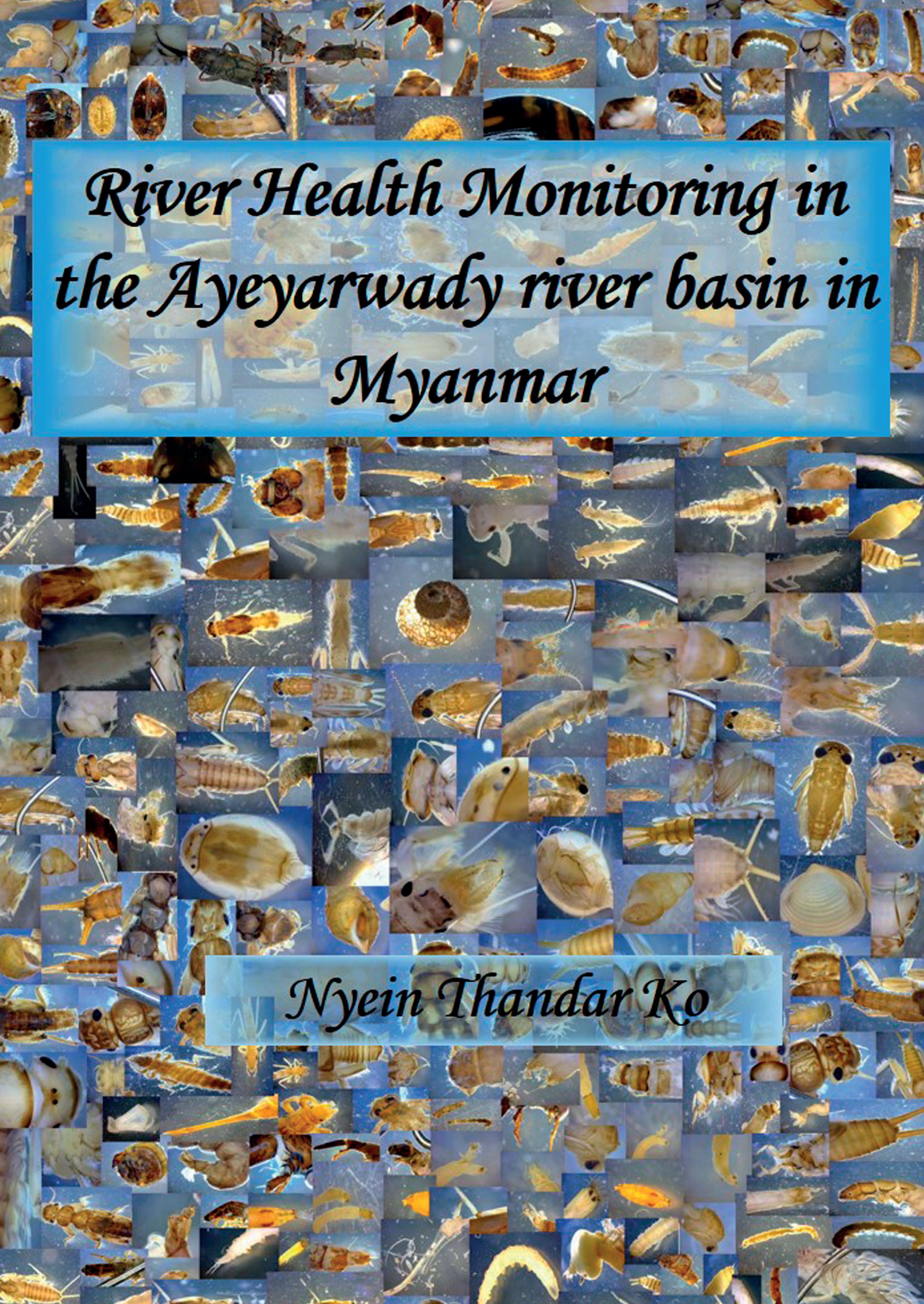
Ko, N.T.

DOI
10.4233/uuid:638f19f5-6282-41fc-ba7e-2b4598f7b56d

Publication date
2022

Document Version
Final published version

Citation (APA)
Ko, N. T. (2022). *River health monitoring in the Ayeyarwady river basin in Myanmar*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:638f19f5-6282-41fc-ba7e-2b4598f7b56d



River Health Monitoring in the Ayeyarwady river basin in Myanmar

Nyein Thandar Ko

River health monitoring in the Ayeyarwady river basin in Myanmar

River health monitoring in the Ayeyarwady river basin in Myanmar

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Wednesday 12 January 2022 at 10:00 o’clock

by

Nyein Thandar KO

Master of Engineering in Water Engineering and Management
Asia Institute of Technology, Thailand
born in Kyaikhto, Mon State, Myanmar

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairperson
Dr. T.A. Bogaard	Delft University of Technology, promotor
Dr. M.M. Rutten	Delft University of Technology, copromotor

Independent members:

Prof.dr.ir. M.K. de Kreuk	Delft University of Technology
Prof.dr. N. Fohrer	University Kiel
Prof.dr. M.E. McClain	IHE-Delft, Delft University of Technology
Dr. I. Nesheim	Norwegian Institute for Water Research
Prof.dr.ir. R. Uijlenhoet	Delft University of Technology, reserve member

Other members:

Dr. J. Conallin	Charles Sturt University

Dr. P. Suter has contributed greatly to the research and preparation of this dissertation.

The work presented in this thesis was performed at the Department of Water Management of the Faculty of Civil Engineering and Geosciences of Delft University of Technology. This research was funded by Nuffic NFS Fellowship program.

TU Delft Delft University of Technology

Keywords: Macroinvertebrates,Preliminary Myanmar Aquatic Biomonitoring Assessment Index, Myanmar, tropical rivers, irrigation channels, Hydropower generation dams, Flow regime,Water Management

Printed by:

Front & Back: Designed by Nyein Thandar Ko.

ISBN 978-94-6419-425-8

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

Summary

Freshwater is a finite resource. It offers goods and services of fundamental importance for the development of human societies. In the developing countries, water-related infrastructure developed rapidly, which will bring prosperity to an impoverished country but also risks compromising the sustainability of the environment. The scarcity of useful monitoring tools due to limited knowledge and capacity hinders informing management of the health on waterways in Myanmar, one of the developing countries. Therefore, we aimed to develop an approach to monitor the health of river ecosystems using remote-sensing satellite images and freshwater macroinvertebrate communities.

This doctoral thesis looks into the potential of remote sensing for monitoring the quality of surface water in Myanmar's rivers and it demonstrates how space datasets can be used to assess the water quality of rivers in Myanmar. We show that a remote sensing analysis using a space dataset can be successfully applied to detect the Suspended Sediment Concentration (SSC) and the water temperature of the Ayeyarwady River basin, in the central dry zone of Myanmar. Remote sensing information can offer a spatial and temporal view of the surface water quality in regard to suspended solids, and water temperature for larger bodies of water such as the Ayeyarwady and Chindwin Rivers.

A fascinating and remarkably varied array of small animals called aquatic macroinvertebrates live in freshwater, and each of them has its preferred environment associated with various types of river and stream substrates. Consequently, understanding the taxonomic composition and diversity of aquatic macroinvertebrates in rivers and streams has long been an important parameter to access the ecological status of a water body. Biomonitoring with the use of macroinvertebrates communities is widely used to assess ecological water quality due to low cost, reliability, and straightforward application by both scientists and non-scientists. However, biomonitoring using macroinvertebrates in tropical Asian countries is hindered by the absence of a standard key to identify aquatic macroinvertebrates at the species level. This is especially evident in Myanmar, where a concept portraying the aquatic ecosystem has been elusive.

This doctoral thesis reports on the development of standard illustrated taxonomic keys based on macroinvertebrates samples from eight rivers and six human-made irrigation channels in Myanmar to identify aquatic macroinvertebrates at family or morpho-species level. As there were no specific biomonitoring indexing tools in-place in Myanmar, this doctoral study started from three existing internationally accepted, rapid assessment indices: miniSASS, The Australian Waterwatch Method, and The Asia Foundation, with the vision of tailoring one of them for specific use in Myanmar. The three biomonitoring assessment methods were tested in a range of minimal-impacted rivers and streams and The Asia Foundation index method was found to be the most suitable biomonitoring assessment tool for Myanmar. We then modified this method to include Myanmar taxa not present in The Asia Foundation method.

This doctoral thesis introduces a new, low-cost, scientific reliable and easy to apply approach to assess river health in Myanmar. The method has been proven to have a lot of potential and can be a good foundation for the development of a professional bio-assessment method at a national scale in Myanmar. However, there are several perspectives for further research. Our current identification keys need to be modified at national scale because our taxa identification is geographically constraint and it is recognized that other taxa will be found when sampling additional streams in other parts of Myanmar. We also recommend additional testing of our current modified index method using sites on other rivers across the country to establish a more robust indexing method for the entire Myanmar.

Contents

1

Introduction

Freshwater is a finite resource, providing goods and services of fundamental importance for the development of human societies. In developing countries, water-related infrastructure is being built rapidly and will bring much prosperity to an impoverished country but also risks compromising the sustainability of the environment. The scarcity of useful monitoring tools due to lack of knowledge and capacity building hinders informing management of the health of all waterways in developing countries such as Myanmar. A fascinating and remarkably varied array of small animals called freshwater aquatic macroinvertebrates live in the water, and each of them has its preferred environment associated with various types of river and stream substrates. Consequently, understanding the taxonomic composition and diversity of aquatic macroinvertebrates in rivers and streams has long been an important parameter to access the ecological status of a water body. Biomonitoring with the use of macroinvertebrates communities is widely practicing to assist the ecological water quality due to low cost, reliable, and easy to apply by both scientists and non-scientists, and also provides a pathway for developing countries to monitor the health of their freshwater systems. However country specific tools and research is lacking and needed to inform management.

1

1.1. River Health: a new concept

Why is the monitoring of the health of a river so important? For human-beings, living a long and healthy life comes with caring for a healthy body and mind and, as such, undergoing regular medical check-ups. Similarly, we should also pay attention to the health of the rivers and the surrounding environment. The monitoring of the rivers informs us about river flow and -regime, gives insight into its quality and behaviour, and can provide a reliable basis for river management and consequential scientific research [1].

Rivers are finite freshwater resources and one of the most critical resources in the earth's eco system. A river can be viewed as a 'living structure'; meaning that it is more than just flowing water. Rivers are part of a larger network and have aquatic biodiversity values, including a variety of river life, aquatic macroinvertebrates, macrophytes [2], as well as aesthetic and cultural values [3]. Additionally, rivers serve social and economic benefits such as irrigation, power generation, drinking water and household water uses, fishing and recreation [4, 5, 6] .

For scientific research, rivers are traditionally classified based on standard chemical and physical water quality monitoring methods. River water quality assessment is a quantitative approach to determine how the water quality suits a variety of usages based on the physical, chemical or biological properties. These quantitative approaches may be adequately used to regulate river discharges and contaminant loads, and to protect human needs, but these measurements are not adequate to identify whether a river ecosystem is a natural, undisturbed and healthy river system [1]. Thus, the "desires" of the river itself have been overlooked.

Therefore, a new approach, the so-called "River Health," was introduced in regard to the management of rivers [4, 1, 7]. The concept of River Health includes research and knowledge whether a river's system and function are well enough to support human values and needs as well as to sustain its own ecological values [4]. The term "health" is frequently used in human society to express that the human organism and function are free from stresses and diseases. River systems and functions encompass not only the water and water composition but also the riverbed, riverbanks, floral and faunal communities. Hydraulically, the basic function of a river system is to convey water and sediment from upstream to the ocean. Continuous water- and sediment transport maintain not only riverbed morphology, but also purify and nourish and provide suitable habitats for the aquatic ecosystem [8].

Generally, rivers are healthy if there is enough water with the right quality and adequate habitat to support all benefits for all river users [4]. Thus, a healthy river is a river in which the river's natural functions and its social functions are well performed and compromised in a harmonious way [8]. Political and social-economic aspects are an integral part of the river health concept [9, 1]. Therefore, river health monitoring should be a holistic approach which includes a variety of quantitative and qualitative indicators, such as water quality, regime flow, channel stability and aquatic diversity [10].

Overpopulation is a worldwide concern and is a real threat on water resources globally, leading to a massive investment in water-related infrastructure development [11, 12, 13]. Numerous changes are caused by the rapid development of urbanisation, such as river channel modifications, flow alterations, changes in water quality, river's function alteration, deterioration of water environment and river connectivity. All these changes in quality and quantity negatively impact river habitats and aquatic biodiversity [10, 14]. Therefore, around the world the health of rivers is steadily declining through direct and indirect natural and human-related activities, especially in the developing countries of South East Asia [15, 5, 10, 14, 16].

Generally, there are three main threats by human influences upon tropical Asian rivers; 1) degradation of drainage basins due to deforestation and overgrazing, 2) river regulation and control by the development and planning of massive dam projects, and 3) river pollution primarily due to untreated sewage, industrial effluents and mining wastes [17, 16]. The consequences of these three threats also threaten riverine biodiversity, however, conservation efforts in tropical Asian rivers are constrained due to limited ecological knowledge and public awareness, and inadequate political commitment to environmental protection [18, 19, 16, 20, 21]. Therefore, the need to study the River Health and to find an effective monitoring approach to identify a healthy river ecosystem in S.E. Asia, particularly in Myanmar, is paramount.

1

1.2. Myanmar- Ayeyarwady River Basin

Myanmar, one of the developing countries from Southeast Asia (SE Asia). It is a lower-middle-income country. Myanmar has an area of 676,578 km^2 and located between latitude $9°28'0''$ N and $28°29'0''$ N and longitudes $92°10'0''$ E and $101°10'0''$ E. It is bordered by the Bay of Bengal to the southwest and by the Andaman Sea to South. The land borders are Bangladesh, India, China, Laos and Thailand. It is about 2,000 km, from North to South and about 900 km from east to west. The population was 53.708 million in 2018. The population growth rate is 7.56% over the last ten years (2008-2018) (The World Bank; http://datatopics.worldbank.org/world-development-indicators/themes/people.html).

There are four main rivers in Myanmar, namely the Ayeyarwady River (about 2210 km, long), the Chindwin River (about 900 km, long), the Thanlwin River (1224 km, long) and the Sittaung River (about 320 km, long) (Source: Irrigation Department, Hydrology Branch, Myanmar). The Ayeyarwady River catchment is situated for ninety-one percent (412,500 km^2) within Myanmar and discharges through a nine-armed delta into the Indian Ocean (Figure 1.1). The Ayeyarwady river basin includes the Chindwin river as a most significant tributary. The Thanlwin river originates from the Tibetan Plateau and through the south-east of Myanmar with 284,200 km^2 river basin. The total 34,950 km^2 catchment area of the Sittaung river basin lies in Myanmar [21].

The backbone of the country's economy is agriculture. Two-third of the total labour force is working in the agricultural sector [19]. The estimated cultivated area is 18.27 million ha which is about 55% of the total cultivatable area in Myanmar [19]. There are 180 irrigation reservoirs to supply irrigation water, and the water-food-nexus is essential for food security in Myanmar [21]. Also, irrigation channels are an essential part of the infrastructure for daily household water use in Myanmar.

Myanmar has abundant hydropower potential [20] . In Myanmar, out of the utilisation of available freshwater, 5% is for irrigation, domestic and industrial uses and 91% is reservoir and navigation usage, although this differs regionally and seasonally [21]. Many dams for hydroelectric generating and agriculture purpose are built in the tributaries of the Ayeyarwady River. Moreover, there are plans to construct many new dams and water control infrastructure in the near future [21].

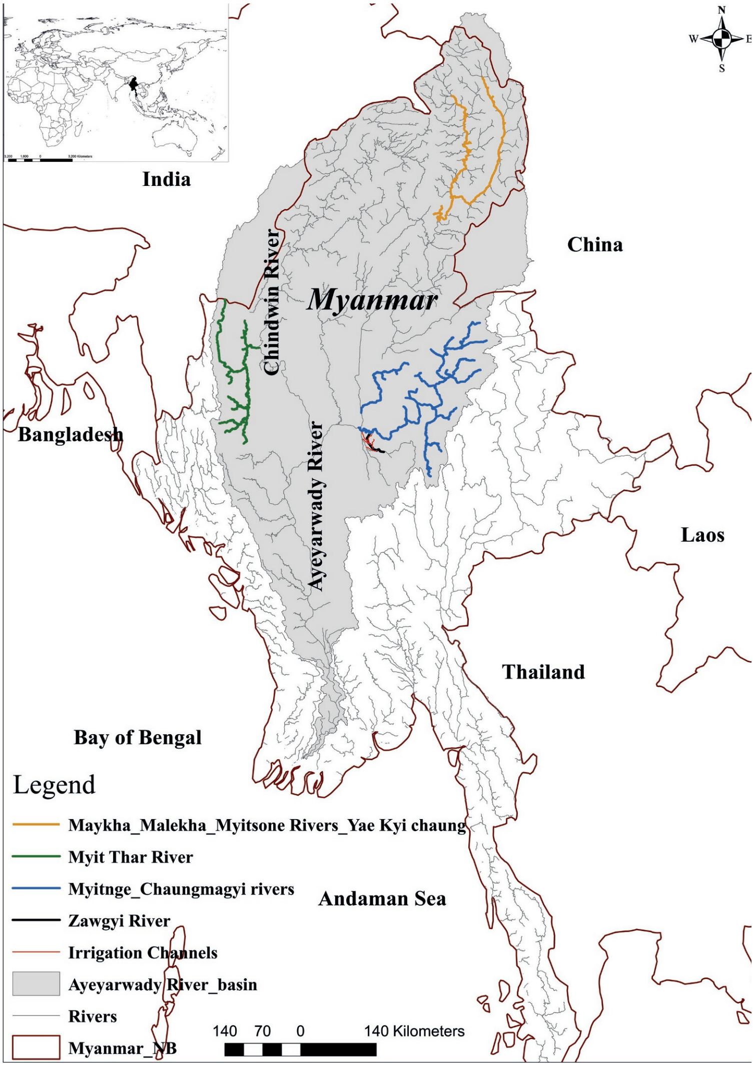


Figure 1.1: Locations of selected eight rivers and irrigation channels on the Ayeyarwady River Basin in Myanmar

1.3. Problem Statement

In Myanmar, the river water quality directly impacts millions of people in the need for river water for the daily uses [22]. Generally, Myanmar has abundant water resources, but water resources problems and challenges have already started to have a negative impact [21].

Currently, the potential human pressures on healthy river ecosystem and unsustainable usage by governmental organisations, commercial enterprises and local population exist, such as extensive hydropower dams constructions, direct domestic, industrial and solid wastes disposal, deforestation within watersheds, clearance of riparian vegetation, intensive agriculture, improper jade and gold mining activities [21]. However, we have limited data to quantify the real anthropogenic impact on water resources. For example, there is limited information on the effects of improper mining activities in Myanmar on surface water quality [23]. Furthermore, the scarce and scattered data sources that are available are not effectively shared among responsible institutions [19].

Besides, in Myanmar, the hydrological and meteorological monitoring stations are limited and the quality and data accessibility not always secured [24]. For water quality measurements, several campaigns in the main rivers (Ayeyarwady, Salween, Bago) have been initiated by governmental organisations and researchers. Only recently, Thatoe Nwe Win et al. [25] introduced a low-cost water quality monitoring program using a mobile phone application and a participatory "Citizen Science" approach for the Ayeyarwady and the Chindwin Rivers. However, overall there is a critical water resources data gap jeopardising reliable and effective water resources research in Myanmar [21].

Not only the main rivers, but also its tributaries and human-made channels, such as irrigation channels, play an essential role in socio-economic activities, also providing habitats for aquatic fauna and flora in agricultural countries like Myanmar. However, small water bodies and their quality are often overlooked in studies as compared to the larger natural and modified rivers. Therefore, there is an urgent need to find an innovative monitoring approach to assess the health of rivers and its tributaries, including human-made irrigation channels in Myanmar.

1.4. Indicators

Typically, the approach of River Health monitoring is similar to the approach of human health assessment [10]. For example, a medical doctor uses different indicators to assess the health of a patient such as testing of blood, urine, temperature, ultrasound etc. to check the patient's condition. Rivers have multifunctional physical, chemical and biological dynamics [1]. Therefore, we use different indicators to ensure a reasonable probability of a healthy river, e.g., physical and chemical water quality, ecological water quality, geomorphology and physical habitat [10].

The literature identified a healthy river ecosystem based on either physical and chemical indicators [26, 27] or biological indicators [28, 29] while other research used physical, chemical, and biological indicators in defining river health [13, 30].

Figure 1.2 shows an example of the different indicators with their variables in the monitoring of a healthy river. All physical, chemical and biological indicators play an essential role in the investigation of river health by supporting different data from different aspects. Consequently, there are various techniques or approaches to applying one of these indicators to address river health around the world.

Important criteria to select an indicator for river health assessment are that it should be scientifically reliable, easy to derive and relatively cheap to perform sufficient measurements [7].

1.4.1. Physical Indicators

Among all potential indicators, physical indicators became the primary regulatory indicators for regulating effluent discharges to protect water users and river ecology [1, 4]. There are 27 physical indicators listed by the International Union of Geological Sciences (IUGS) [1]. Among them, in Figure 1.2 we show the seven most critical physical indicators which are directly related to the condition of river systems [1, 4].

We selected surface water temperature and suspended sediment concentration as these parameters are essential water quality variables which directly or indirectly influence freshwater aquatic ecosystems [31, 32]. Furthermore, Robinson et al. [33] reported that the Ayeyarwady River is ranged as the river with the fifth-largest suspended load among all rivers around the world, making this a dominant variable for Ayeyarwady river health. Only since 2014, a start has been made for systematic

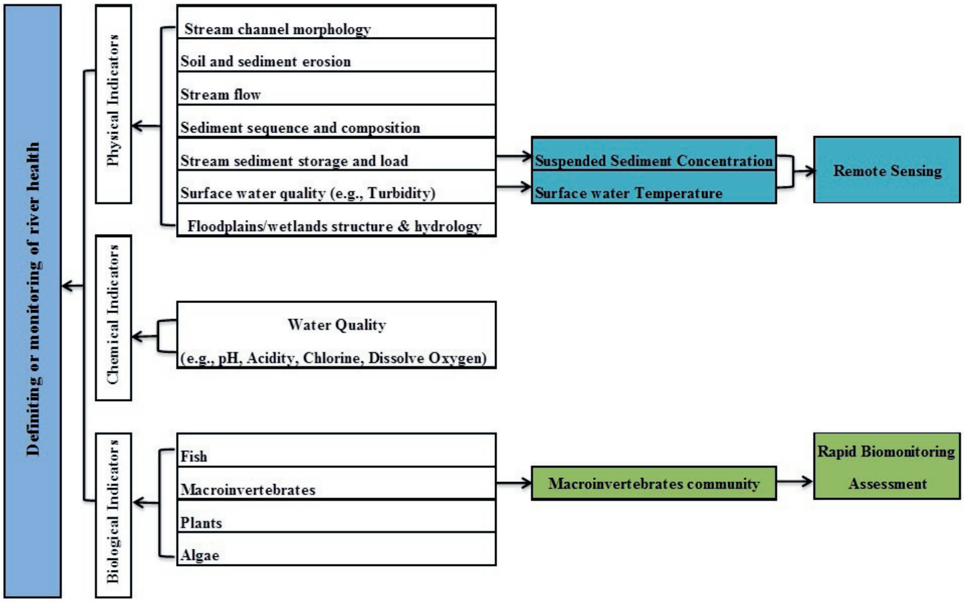


Figure 1.2: Framework of some example variables with different indicators to assess or monitor river health.

suspended sediment monitoring in the dry season consisting of one grab sample at 7 locations 2 times per year.

Global satellite datasets could be used as an alternative. These allow for the estimation of water quality in a systematic, economical way, also in remote and inaccessible areas [34]. Numerous open-access datasets can be used for the assessment of suspended sediment concentration and other water quality variables. Currently, the highest spatial resolutions among accessible public satellites are Operational Land Image (OLI) Sensor (Landsat 8) and Multi-Spectral Images (MSI) (Sentinel-2) at 10 and 30 m respectively, with a lower signal-to-noise ratio [35]. We will demonstrate a combination of space datasets from OLI Sensor on board of Landsat 8 and in-situ monitoring datasets in the detection of spatial patterns of surface water temperature and suspended sediment concentration (SSC) on the Ayeyarwady River and the Chindwin River in the central dry zone of the country.

1.4.2. Biological Indicators: macroinvertebrates

Different biological representatives (fish, macroinvertebrates, plants, and algae) can be used for various research questions based on advantages and disadvantages [9, 36, 37]. To date, aquatic macroinvertebrates communities are the most well-known representative of aquatic biodiversity in the monitoring of a healthy river ecosystem.

Biomonitoring approaches using macroinvertebrates communities have been introduced in the developed countries (United States, Europe, Australia, Brazil, South Africa) [38, 37, 39]. On the contrary, there is little experience of using aquatic macroinvertebrates assemblage in river ecosystem studies in S.E. Asian countries, except for a few studies in Thailand, Vietnam, Malaysia, and Nepal [40, 41, 42, 43].

To our best knowledge, there is no systematic research on aquatic macroinvertebrates of rivers and streams in Myanmar, although initiatives are beginning. The Myanmar Healthy Rivers Initiative (MHRI) introduced biomonitoring using aquatic macroinvertebrates communities on the main streams of Ayeyarwady River, downstream of Mandalay in October 2015, and the lower Salween/Thanlwin River, 65 km from the sea in February 2016 [44]. They concluded that aquatic macroinvertebrates assemblies are not appropriate to use as an indicator to describe river health in the downstream part of these large Myanmar rivers due to the significant flow variation, high sediment loads and unsuitable substrates.

Dickens [44] concluded that biomonitoring using aquatic macroinvertebrates could be applied in small streams or tributaries where the riparian, marginal vegetation and flow regime are more stable as compared to large rivers. Eriksen et al. [45] proved that macroinvertebrates could be applied to identify river health in small streams based on their pilot sampling on the Bago River (331 km long).

This work will present a new biomonitoring method as scientifically reliable, low-cost, and easy to apply by both scientists and non-scientists. We will apply the biomonitoring approach using macroinvertebrates communities in the monitoring of river health and in the environmental impact assessment in different types of natural or impacted rivers and in artificial channels within the Ayeyarwady River basin. We selected a total of eight rivers in various regions of Myanmar: the northern region (Maykha, Malikha, Myitsone-Ayeyarwady, Yae Kyi), the northwest region (Myit Thar), and the central dry zone (Myitnge, Chuangmagyi, Zawgyi). Also, we collected macroinvertebrate samples in six irrigation channels of the Zawgyi River (Figure 1.1).

Macroinvertebrates are small animals without a backbone. They are visible to the human eyes without a microscope (for example, see in Figure 1.3). They live in both lentic and lotic water bodies depending on their preferred habitats, such as fast-flowing or slow-flowing waters [46]. Their life cycle ranges from weeks to years [47], they feed on fine particulate organic matter (FPOM), coarse particulate organic matter (CPOM), algae, and prey [2]. We can collect them using a simple net without expensive equipment [48].

Figure 1.3: Photo of collected Ephemeroptera-Mayflies from the downstream section of the Myitnge River, February 2017 (1:0.4 scale).

Different species have different tolerance levels to the quality of river water based on their preferred aquatic ecosystem. For example, Plecoptera – Stoneflies are the most sensitive and intolerant taxa to environmental changes because they need a high dissolved oxygen level with clean substrates [2]. On the other hand, Bivalvia– freshwater mussels are tolerant taxa and feed on phytoplankton, bacteria and other small organic matter [49].

Therefore, we can observe the current status of the river ecosystem and assess which pressures are affecting the health of the river ecosystem based on the macroinvertebrate diversity and feeding habits (Figure 1.4) [50, 51]. There are considerable numbers of publications worldwide which state how macroinvertebrate communities link to water quality, flow regime, hydro-morphology and different environmental gradients [52, 53, 54, 55].

Chessman [47] explained four reasons for selecting macroinvertebrates in a biological approach to assessing ecological water quality as follows:

1. The communities change with the changes in most of the pollution as they are omnipresent,
2. The species richness and abundance are essential to maintaining a healthy river ecosystem as their feeding habits are linked with the river ecosystem,
3. The present taxa can show the history of pollution or disturbance as the life cycle of macroinvertebrates ranges from the weeks to years,
4. The macroinvertebrates can be collected easily on a large spatial scale with low-cost equipment.

Therefore, we selected aquatic macroinvertebrates as an indicator to monitor river health in the Ayeyarwady River basin, and we aimed to develop a rapid bioassessment method to use in Myanmar.

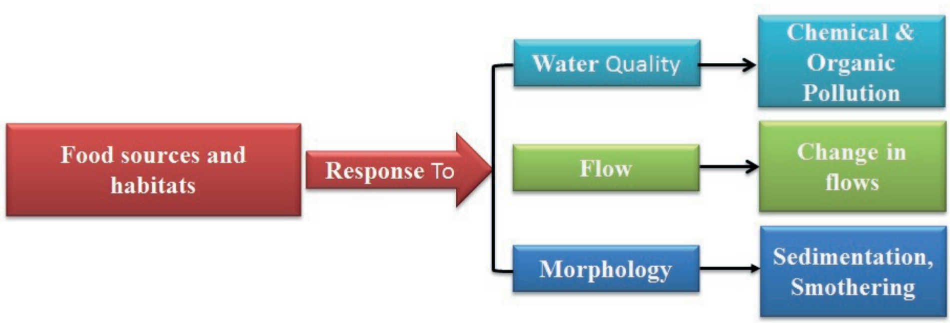


Figure 1.4: The relationship between aquatic macroinvertebrates communities food sources and their preferred habitats and quality and quantity of river ecosystem

1.5. Research Objectives

Our main objective was to test and develop monitoring methods to monitor river health of the Ayeyarwady River basin in Myanmar and assess environmental impacts using remote sensing satellite images and freshwater macroinvertebrates communities. As a pioneer study, field sampling is vital in providing the data to explore the suitability of these two methods for River Health in Myanmar. To do so, we performed one year of field water sampling and two years of field macroinvertebrates sampling as a basis for this research.

1.6. Research Questions

We proposed four research questions to meet our goal, as follow:

1. How reliable are space-based datasets as a system for monitoring suspended sediment concentrations and water temperature in the Ayeyarwady river,

2. Is it possible to develop a specific biomonitoring method for Myanmar based on recent biomonitoring assessment tools in SE Asia,

3. Can macroinvertebrate measurements be used as an indicator to study the potential impact of dams in Myanmar,

4. Can macroinvertebrate measurements be used to assess River Health in human-made channel systems?

1.7. Research Structure

We will address our research questions in the following six chapters (Figure 1.5).

Chapter 1 presents a general introduction of river health and introduces a different approach to monitoring river health. We highlight the current existing problem and background in the selected research area. The research objectives and associated research questions are indicated in this chapter.

Chapter 2 demonstrates the application of Operational Land Image (OLI) Sensor on the board of Landsat 8 in the monitoring of suspended sediment concentration and surface water surface on the Ayeyarwady River and Chindwin River. The data used in this chapter are in-situ field sediment concentration by our field sampling and water temperature data from the participatory water quality monitoring project by [25].

We aimed to provide illustrated keys to taxa found in Myanmar and to provide information on the ecology such as the habitats occupied and functional feeding groups of each of the dominant taxa. We collected macroinvertebrates samples from eight rivers and six human-made irrigation channels within the Ayeyarwady River basin. The keys are preliminary, based on the reference keys from Mekong River by [56] but will aid in the identification of the freshwater aquatic invertebrates of Myanmar in the future. Our current identification keys were reported in the supplementary material A in this thesis. The identification of macroinvertebrate communities used in the chapters (3, 4 and 5) is based on the illustrated keys from this supplementary material.

Chapter 3 focuses on method development at the local scale. We applied three rapid bioassessment techniques to establish a baseline using macroinvertebrates samples from minimal impact sites among all sampling sites of current research. Our vision was to modify one of them for ongoing use in Myanmar to answer the research question (2). We applied this modified method in chapter 4 and 5 to estimate ecological water quality.

Chapter 4 deals with the impact of the dam on the river ecosystem. In particular, macroinvertebrates samples associated with physicochemical and hydrological variables above and below the hydropower dam have been explored to see the impact on aquatic assemblage downstream of dams.

Chapter 5 presents a novel ecosystem and river ecosystem based on macroinvertebrates communities. This chapter deals with the results of macroinvertebrates sampling from human-made irrigation channels and their source river to address the research question (4).

Chapter 6 presents a synthesis of our research to discuss our main findings. This last chapter includes recommendations and potential further researches requirements.

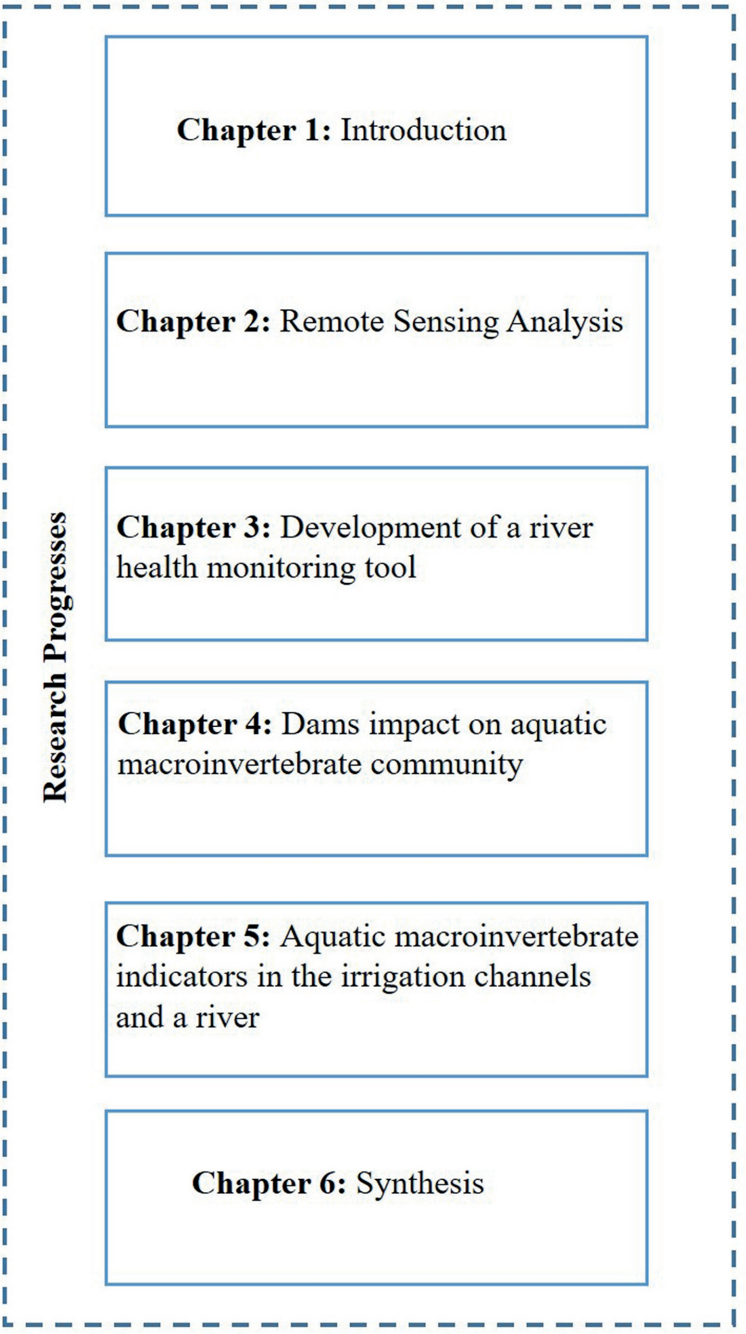


Figure 1.5: Research Structure with six chapters to answer four research questions

2

Remote Sensing Analysis

This study demonstrates that the Operational Land Image (OLI) Sensor on the board of Landsat 8 can be successfully applied for detection of spatial patterns of water temperature [°C] as well as suspended sediment concentration (SSC) [mg/L] using the Ayeyarwady River, Myanmar as a case study. Water temperature estimation was obtained from the brightness thermal Band 10 by using the Split-Window algorithm with a relative error in a range from 4.5% to 8.2%. An empirical equation was developed based on nineteen SSC points from a field survey and Landsat (133Path/45Roll) This equation was applied to another Landsat image (134Path/45Roll) to estimate SSC and to check the reliability of this equation Near infrared and red bands were found as the most responsive wavelength bands for retrieving SSC of the river in both Landsat images with a relative error in a range of less than 20%. Future studies should focus on the improvement of ground reference data points to become more reliable for this data scarce river basin

This chapter is based on [57]: Ko, N. T., Rutten, M., Conallin, J. (2017). Remote Sensing Analysis of Temperature and Suspended Sediment Concentration in Ayeyarwady River in Myanmar. Global Journal of Engineering and Technology Review., 2(3).

2.1. Introduction

A 30% of the total amount of sediment load released into global oceans comes from large Asian rivers, namely, the Ayeyarwady, Brahmaputra, Thanlwin, Mekong and Chang Jiang [58]. Among these rivers, the Ayeyarwady River is ranked as a fifth-largest suspended load around the world based on the original literature, which has been published in nineteenth-century [33]. A 20% of the sediment load from the Himalayan- Tibetan Plateau contributes to the Ayeyarwady (Irrawaddy) and Thanlwin (Salween) River system [58]. However, there are a steadily increasing water infrastructure developments such as dams on the tributaries of these rivers, that tend to decrease sediment load. Thus, currently, the Ayeyarwady River is probably ranked as third-largest contributor of sediment load around the world [33]. Unfortunately, there is little knowledge on the Ayeyarwady River's sediment because there is limited information on this issue.

In the original literature from 19^{th} century, the suspended sediment load of Ayeyarwady River was estimated at 261 $MT/year$ by Gordon for (52) weeks for the period from 1877 to 1878 by taking 100g of water and sediment samples for six days per week [33]. Gordon used the dry filter paper and a Fortin balance in his calculations, and he developed a relationship between the sediment concentration and discharge by using the ten years of sampling data (1869-1879).

Then, Robison et al. [33] revisited the original data of Gordon's study, and they found that Gordon's result was underestimated due to the minor calculation error in his discharge results and the effect of very fine sediment particles in the filter used. Then, the modified estimated discharge and sediment load were (379 ± 47 × 109 $m^3/year$ 364 ± 60 $MT/year$) respectively from the year 2005 and 2006 at the same selected area with Gordon.

More recently, a new estimation of the suspended sediment load of Ayeyarwady River by Furuichi et al. [59] has been reported as 325 ± 57 $MT/year$ based on the study of [33] and daily discharge data from 1969 to 1996 collected at Pyay station which is located in the basin toward the delta. Furuichi et al. [59] used the discharge- sediment load equation derived from measurements of sediment concentration at different water depths. Data validation for data quality control could not be included in their study due to lack of information about sediment load of Ayeyarwady River.

In 2014, Governmental organization; Directorate of Water Resources and Improvement of the river system (DWIR) under the Ministry of Transportation, started to monitor suspended sediment concentration along the Ayeyarwady and Chindwin Rivers. The suspended sediment transport is observed twice per year at five stations on Ayeyarwady River and two stations on the Chindwin River, respectively (Figure 2.1). However, the frequency and data coverage for the whole Ayeyarwady and Chindwin Rivers are still quite limited.

The above literature shows that previously, information on river sediment concentration or sediment load was limited in Myanmar, although, it is an important water quality variable which directly or indirectly influences freshwater aquatic ecosystems [31, 32]. Detailed information on water quality parameters is important in water resources planning and development to better manage rivers ecosystem and rivers users [60].

However, experimental based water quality measurements such as suspended sediment concentration, total dissolved solids, are costly as well as time-consuming for low-income countries, like Myanmar due to lacking adequate funding, capacity and techniques. Therefore, the use of global satellites data-set in the estimation of water quality has received attention worldwide due to copyright-free and public accessibility, such as the U.S. Geological Survey (USGS).

The previous study of Hellweger et al. [34] has reported three advantages of the use of space data-set in water quality measurements.

1. The near-continuous spatial coverage of satellite data-set can estimate water quality over a large scale range.

2. The global coverage of satellites can be possible to estimate water quality in remote and inaccessible areas.

3. The long historical record of satellites imagery, for example, Landsat was launched since the 1970s, can provide an estimation of historic water quality in data scare regions, especially where the ground measurements cannot be performed.

The studies completed up to now indicated great potential in the use of space data-set such as airborne spectral imagery (CASI), MODIS space-borne sensor, SPOT ASTER satellite images, Operational Land Image (OLI) Sensor (Landsat 8), in the estimation of sediment concentration of rivers and river water quality [31, 61, 62]. Among openly and freely public accessible satellites, the signal-to-noise ratio (SNR) radiometric performance of OLI sensor is better than other sensors due to more bits than other sensors, which can give better land cover characterization [63]. Remote sensing techniques make it possible to measure water quality variables by developing power relationship between in-situ data and irradiance reflectance recorded by sensors aboard satellites in visible and near-infrared (NIR) spectral regions [61, 64].

Therefore, the objective of this study is to test the potential use of Landsat 8 images by remote sensing technique in Ayeyarwady and Chindwin Rivers in Myanmar. We selected suspended sediment concentration and surface water temperature as water quality parameters in this research. We will use both the collected data from DWIR and in-situ data by field sampling on the Ayeyarwady and Chindwin Rivers before the confluence of these two rivers at the central dry zone of Myanmar.

2.2. Methods and Materials

2.2.1. Study area

Myanmar has an area of 676,578 km^2 and is situated between latitudes N:$9°28'0''$ and N:$28°29'0''$ and longitudes E:$92°10'0''$ and E:$101°10'0''$. It is bordered in the south by the Bay of Bengal and the Andaman Sea. It has land borders with Bangladesh, India, China, Laos and Thailand. It is about 2,000 km from north to south and about 900 km from east to west. There are four main rivers in Myanmar, namely Ayeyarwady River, Chindwin River, Thanlwin River and Sittaung River. Among them, the Ayeyarwady River is the largest river of Myanmar, and it flows through Myanmar from the north to the south (about 2210 Km long) and empties through a nine armed delta into the Indian Ocean. Moreover, it is an essential commercial waterway, and the river basin covers 62% of Myanmar (412,500 Km^2) (Figure 2.1) [19].

2.2.2. In-situ Temperature

We used the in-situ weekly surface water temperature (March, April and May 2016) collected at five stations on Ayeyarwady and two stations on Chindwin Rivers, respectively by Thatoe Nwe Win et al. [25] for data validation with satellites temperature (Figure2.1). Water surface temperature is measured every Tuesday at 10:00 am at all stations by non-expert volunteers using a mobile phone application (Akvoflow caddisfly).

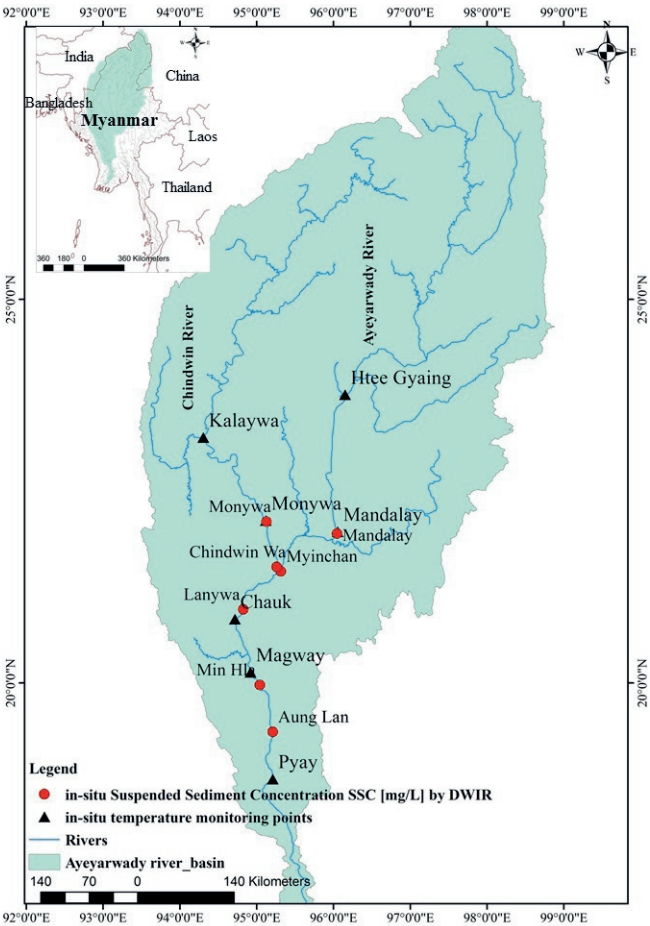


Figure 2.1: Location of in-situ temperature and suspended sediment concentration (SSC) by DWIR on the Ayeyarwady River Basin

2

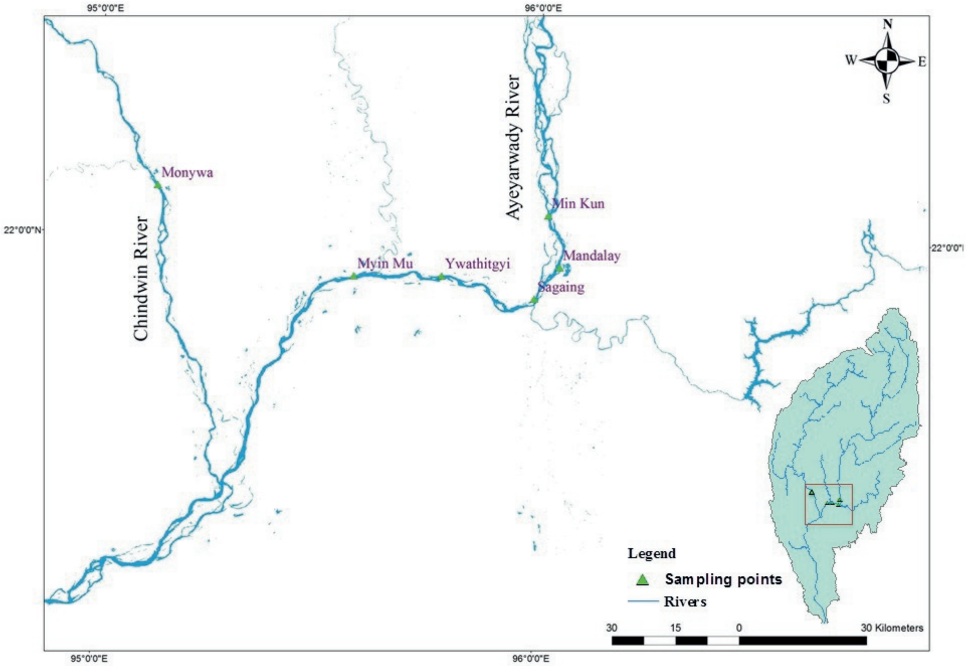


Figure 2.2: Field observation points for suspended sediment concentration (SSC) on Ayeyarwady and Chindwin Rivers

2.2.3. In-situ suspended sediment concentration, SSC [mg/L]

For in-situ SSC, this study was carried out with two in-situ data sets from DWIR and our field observation.

DWIR measured SSC using $0.45\,\mu m$ filter paper and filtering equipment in their departmental laboratory. The water samples are taken from the surface and 2-meter depth of the river from the surface during low water season; within January to March and within October to December. We used SSC data recorded by DWIR from the period of January, February, and March 2014 for data evaluation and validation for Ayeyarwady and Chindwin Rivers in this study.

Table 2.1: Used Landsat Data in this study

Spatial data for estimation of water surface temperature			
Data	Frequency	Dates	
Landsat 8 images (14 images) Path/Roll 1. 133/49 2. 133/48 3. 133/47 4. 134/46 5. 134/45 6. 133/45 7. 133/46 8. 134/44 9. 133/44 10.134/43 11.133/43 12.134/42 13.133/42 14.133/41	OLI (Operational Land Imaginer) multispectral Bands 1-7,9: 30-meters OLI panchromatic band 8: 15-meters	15-April-2016 (No: 4,5 & 8 images) 08-Apil-2016 (No: 3,6 & 9) 10-May-2016 (No:1 to 7, 10, 11, 13 & 14)	USAGS Global Visualization Viewer http://glovis.usgs.gov/
Spatial data: for estimation of Suspended sediment concentration			
Path/Roll	Frequency	Dates	
1. 133/47	OLI multispectral Bands 1-7: 30-meters	13-Jan-14	USAGS Global Visualization Viewer http://glovis.usgs.gov/
2. 134/46		04-Jan-14	
3. 134/45		05-Fe-2014 12-Jan-17 28-Jan-17 13-Feb-17 01-Mar-17 17-Mar-17	
4. 133/45		02-Mar-14 05-Jan-17 21-Jan-17 06-Feb-17 22-Feb-17 10-Mar-17	

2.2.4. Field Campaign in Ayeyarwady and Chindwin Rivers on the same dates of Landsat capture Time (January, February and March 2017)

The purpose of the field campaign was to improve the amount of in-situ data by DWIR due to minimal points for analysis as well as to be able to compare between field monitoring data and Ministry recorded data. We selected five sampling sites on Ayeyarwady River (Myin Mu, Ywarthigyi, Sagaing, Mandalay Mingone) and one on Chindwin river (Monywa) (Figure 2.2) before the confluence of these two rivers at the central dry zone of Myanmar. We collected water samples at the same dates when satellite images were captured in the study area in January, February and March 2017 (every-16 days). Three or four water sample points were taken (based on the width of the river) at the surface of the river and 2 meters deeper from water surface at each site. The measurement of the weight of the suspended sediment concentration was done using a filtering apparatus with filter paper in the lab. .

2.2.5. Landsat Data

In this study, we selected Operational Land Image (OLI) Sensor on the board of Landsat 8 to estimate surface water temperature and suspended sediment concentration on Ayeyarwady and Chindwin Rivers at the central dry zone of

2

Myanmar. The swath size of OLI is 178 km and can revisit the same spot on the equator at every 16 days [35]. The OLI sensor gives one to nine Bands, in which spatial resolution for multi-spectral Bands (1-9) is 30 m except for panchromatic Band (Band 8), which is 15 m. Among the nine spectral bands, a deep blue visible channel (band 1) can be used for water resources and coastal zone investigation, and a new infrared channel (band 9) allows detecting for cirrus clouds. The two new Bands (10 and 11) by TIRS sensor have 100 m resolution (https://lta.cr.usgs.gov/L8,USGS2016). We used Landsat 8 images OLI (http://glovis.usgs.gov/) on the list of dates in Table 2.1 to estimate water temperature and suspended sediment concentration. The list of data used in this study is shown in Table 2.1.

2.2.6. Remote Sensing of Water Temperature[°C]

Interpretation of thermal remote sensing of water temperature in rivers is required to correct for atmospheric conditions as atmospheric transmission and absorption of radiation between sensor and water surface can impact on the measurement of remote sensing water temperature [32]. In the case of Landsat 8, the two thermal bands (10 and 11) can be used to study the remote sensing of water temperature in rivers [65]. We used brightness temperature of Band 10 from Landsat 8 images to assess the water temperature from the spatial patterns, for the whole Ayeyarwady river.

The validation was done with the weekly in-situ temperature of March, April and May 2016, including data, measured one day at two stations (Chauk and Magway) in February. Satellites capture times were not precisely aligned, but in-situ temperature measurements at three stations in March and at one station in April were on the same date with the satellites capture time. There were 14 Landsat images to process for the whole catchment of Ayeyarwady River. Framework for the estimation of surface temperature based on Allen et al. [66] is shown in Figure 2.3.

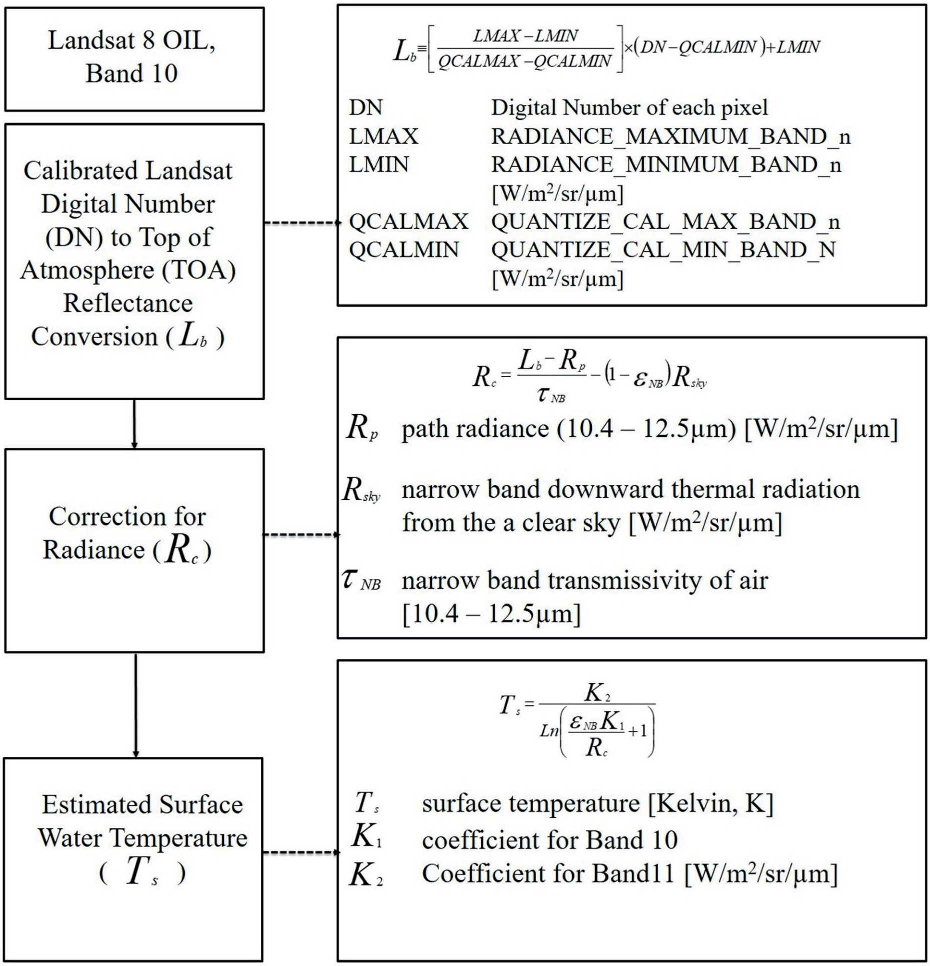


Figure 2.3: Framework for estimation of surface water temperature based on [66] (Pages – 21, 31 33)

2.2.7. Remote Sensing of Suspended Sediment Concentration, SSC $[mg/L]$

Sensors aboard satellites can measure the optical properties (i.e. reflectance) of water, which depend on the water clarity and dissolved organic matter at various wavelengths [34]. Remote sensing technique can derive the reflectance values of water from the satellites images. These reflectance values can correlate with the in-situ data set, which can draw a regression line to develop power relationship for spatial coverage measurements [66]. However, the accuracy of remote sensing of water quality information such as suspended sediment and chlorophyll depend

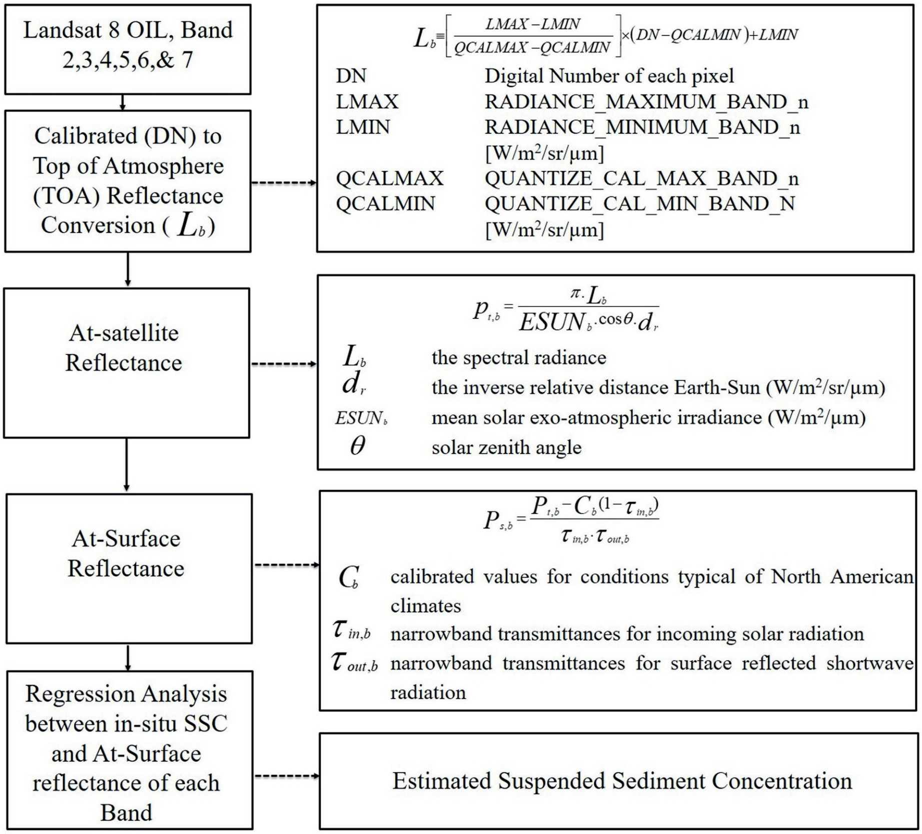


Figure 2.4: Framework for estimation of suspended sediment concentration based on [66] (Pages – 21, 23 25)

on water-leaving radiant which is the capacity of water penetration captured by a sensor [67]. The depth of penetration varies with the type of water quality information and their concentration level (e.g. turbidity) [67].

The availability of both Landsat images and in-situ SSC is the essential key for this study. The images used in the estimation of SSC are listed in Table 2.1. In this calculation, Band 2, 3, 4, 5, 6 and Band 7 were used for image processing in the estimation of surface reflectance base on the following procedure of Allen et al. [66] (Figure2.4).

Table 2.2: Comparison between in-situ temperature and remote sensing temperature collected on the same dates

Collected Date	In-situ temperature [°C]	Remote sensing temperature [°C]	Relative Error (%)	Station
14-Mar-16	28.1	28.01	0.3	Chauk
14-Mar-16	27.6	28.84	-4.5	Magway
07-Mar-16	26.5	27.76	-4.8	Pyay
04-Apr-16	29	31.37	-8.2	

2.3. Results

2.3.1. Remote Sensing Temperature [°C]

The estimated surface water temperatures by the use of 14 Landsat 8 images with remote sensing on the whole Ayeyarwady and Chindwin Rivers range from 20 to 45 °C (Figure 2.5). For data validation, we compared in-situ water temperature at five stations on Ayeyarwady River (Htee Gyaing, Mandalay, Chauk, Magway and Pyay) and two stations on Chindwin River (Monywa and Kalaywa) with remote sensing water temperature. Table 2.2 shows the comparison of in-situ temperature and remote sensing temperature on the same dates at Chauk, Mayway and Pyay. The results show that remote sensing temperature is overestimated by 4.5% at Magway and 4.8% at Pyay in March and by 8.2% at Pyay in April (Table 2.2).

We compared remote sensing temperature of 16 days equatorial revisit frequency and weekly temperature from March to May 2016 (Figure 2.5). For Monywa stations, the estimated temperature is closer to the in-situ temperature even the collected dates are not the same (Figure 2.5). Indeed, on 14^{th} March (in-situ temperature) and 16^{th} March (remote sensing temperature), the difference is 2°C within two days. In May, the difference between the temperature on 1^{st} May (estimated) and temperature on 2^{nd} May (in-situ) is 2.26 °C. The insignificant difference in temperature was found not only in Monywa station but also in most of the stations, except Htee Gyaing station (Figure 2.5).

At Htee Gyaing station, the remote sensing temperature on 10^{th} May is 19.32°C, but the in-situ temperature on 9^{th} May is 28.4 °C that could be explained by the satellite image of May which over this station had cloud cover and not a clear image.

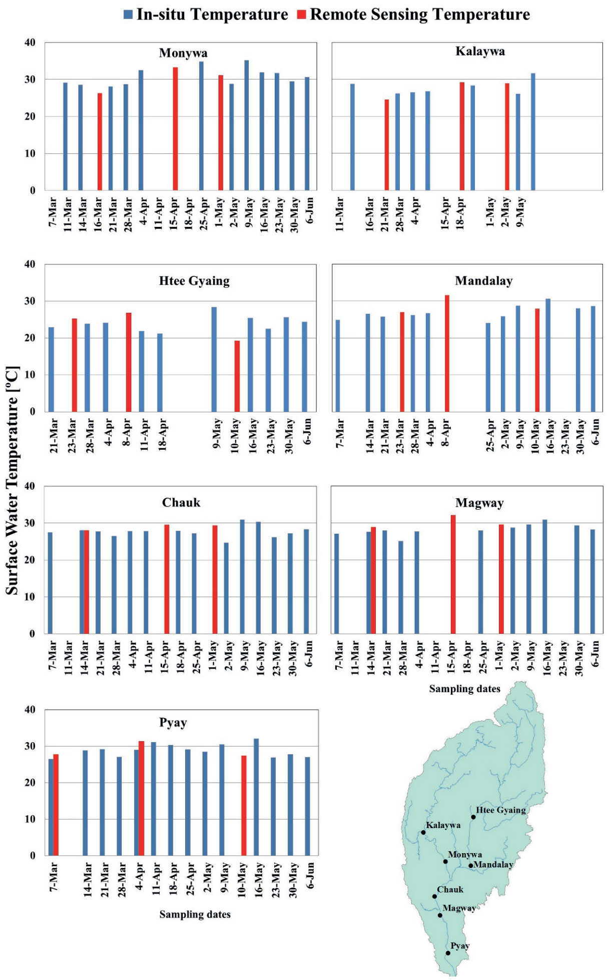


Figure 2.5: The in-situ temperature and the remote sensing temperature at seven locations on the Ayeyarwady and Chindwin Rivers during March and June 2016

2.3.2. Suspended Sediment Concentration , SSC $[mg/L]$

Validation of in-situ SSC $[mg/L]$

When we make a correlation between reflectance and SSC data on Band 4, SSC estimated from filed sampling observation were almost lower than SSC collected by DWIR (Figure 2.7.a). We cannot explain the reason due to the lack of information about Ministry measurements. Therefore, we looked at all possible uncertainties of both field SSC and DWIR SSC to select reliability of SSC data which will correlate with the reflectance of satellite image to estimate spatial coverage of sediment

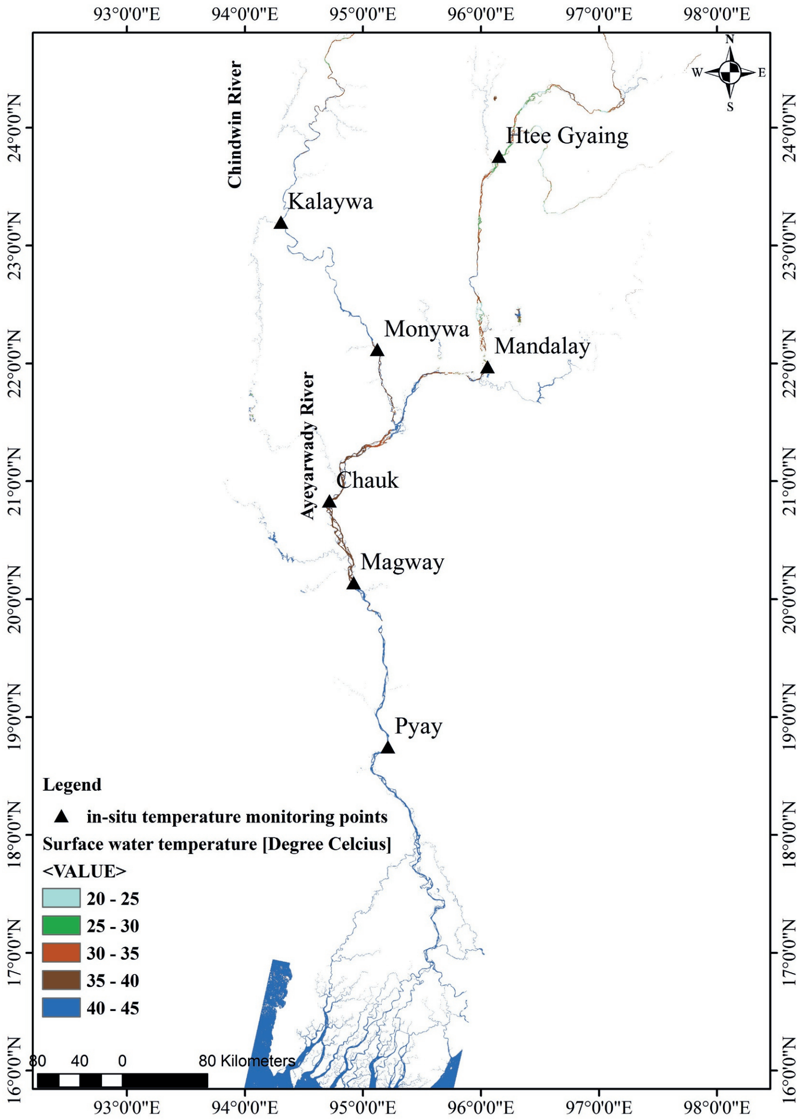


Figure 2.6: Estimated remote sensing temperature in Ayeyarwady and Chindwin Rivers in May 2016

data on Ayeyarwady and Chindwin Rivers.

Firstly, we re-analyzed the data with a previous study of Furuichi et al. [59] to verify the possible uncertainty of the DWIR SSC. Furuichi et al. [59] studied sediment transport at Pyay station using discharge-sediment load equation (Eq.2.1) developed by rating curve of daily discharge. We used this equation 2.1 to estimate SSC at Pyay station with daily discharge [m^3/s] collected at the same station by Department of Meteorological and Hydrology (DMH) Myanmar. We compared with estimated SSC by equation 2.1 at Pyay station with DWIR SSC at Aunglan station which is located 66 km upstream of the Pyay (locations are shown in Figure 2.1) because we do not have data at the same station at this current time. The results show that DWIR SSC is higher than the estimated SSC by Furuichi, Win Wasson [59] (Figure2.7.b).

$$L = 0.0127 * Q^{1.4264} \tag{2.1}$$

Where, L is the sediment load (kg/s) and Q is the daily discharge (m^3/s).

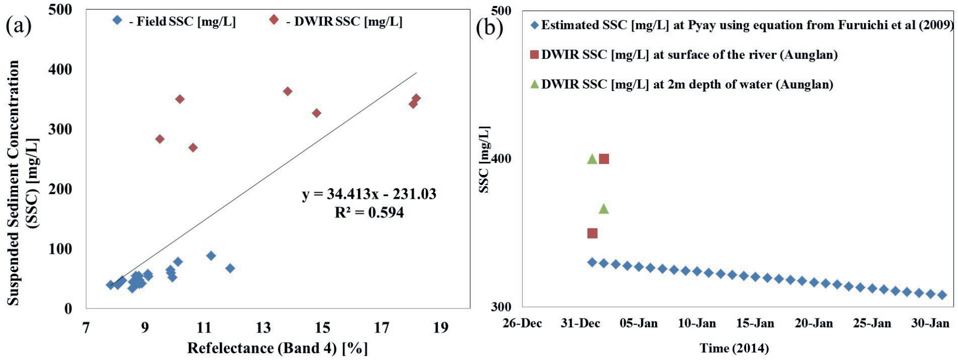


Figure 2.7: (a):Regression analysis between reflectance at Band 4 and suspended sediment concentration (SSC) by filed sampling and by DWIR, (b): The comparison of estimated SSC [mg/L] by an equation of Furuichi et al.[59] at Pyay compared with the SSC [mg/L] collected by DWIR at Aunglan for 2014

Validation of Landsat images

Secondly, we checked the uncertainty of the Landsat images to investigate why the SSC values were lower in 2017 (field) and why the SSC values were higher in 2014 (DWIR). The two Landsat images from 2014 and 2017 were analyzed to check if image quality was affecting the river sediment concentration or not. We compared all the reflections from the land use from the image of 2014 and the image of 2017 to see how the land use changed, which can have a possible effect on the river sediment concentration. Here, we did not see noticeable changes for land use in two Landsat images at the same pixel points (Figure 2.8). We used the same satellite with the same band, and these images are clear of cloud cover. Finally, we concluded that the Landsat image quality was not affecting the estimation of SSC in this study.

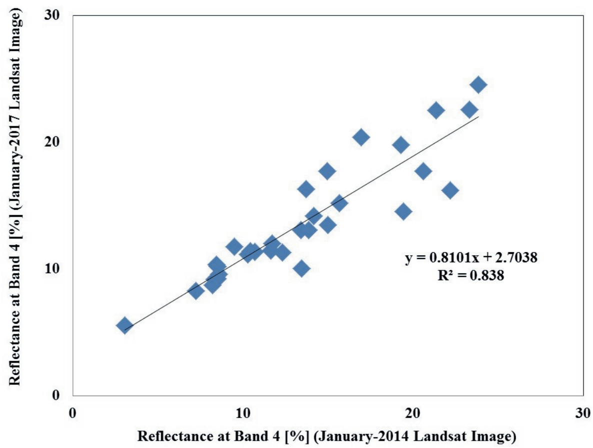


Figure 2.8: Comparison of surface reflectance of the Landsat image in 2014 and surface reflectance of the Landsat image in 2017

Results from Field Observations

After the validation for in-situ SSC and satellites images, DWIR SSC was out of the range of previous study [59] and our field values. Moreover, the collected dates by DWIR are not the same dates of satellites images, whereas, we collected samples at the same dates with satellites equatorial revisit frequency dates. Therefore, we decided to use our field SSC values to develop a regression line based on the relationship between field data and reflection from the satellites image.

The correlation between reflectance from the above water surface and below the water surface is different at the same wavelength of the visible and near-infrared bands as the surface reflectance is influenced by surface conditions [68]. In this study, the coefficient of determination of the relationship between SSC from the surface and SSC from 2 m depth was just 0.35 (Figure 2.9). We tested regression analysis between reflectance from the Landsat 8 and two different SSC (SSC measured at the surface and average SSC of surface and 2 m depth of water).

We found that the average SSC of surface and 2 m depth of water shows good regression line than SSC measured at the surface of the water. Bhatti et al. and

Doxaran, Cherukuru Lavender [68, 69] found that the water quality measurements above the surface of the river were strongly influenced by surface waves, the wind and resulting sun glint on the water surface within a given sensor field of view, especially on a windy day [68, 69]. In this analysis, we used average SSC $[mg/L]$ from a surface and 2 m depth of the river which is in line with the other works of literature [67, 68, 69].

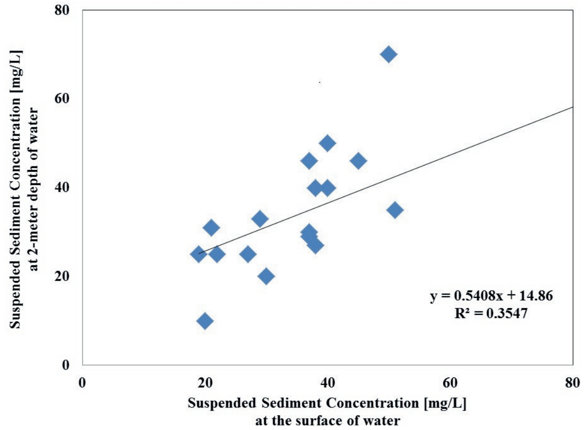


Figure 2.9: Comparison of SSC $[mg/L]$ from the surface and from the 2-meter depth of Ayeyarwady River

Variations of reflectance band 2, 3, 4 5 were analyzed to identify which bands have the best relationship between the reflectance and in-situ SSC values. The linear regression line between in-situ data and reflectance of the Landsat image in Band 3 shows a good fit with an R^2 value of 0.6; however, the trend line was bunched. The Band 2 (Blue) and Band 4 (Red) have similar trends that the reflectance increases with increasing SSC at most of the points and the R^2 of their relations were similar (Figure 2.10). Here, the reflectance at Band 4 was selected for remote sensing SSC estimation as P-value (0.00003) and 66% R^2 according to the results of R^2 and P-value among all possible Band.

Therefore, we developed the following algorithm, which was derived from the regression line between the reflectance of Band 4 and selected in-situ SSC. We then used this algorithm to retrieve suspended sediment concentrations on spatial coverage on Ayeyarwady River. Figure 2.11 shows the comparison of estimated SSC using algorithm and SSC collected in the field and their residual plot.

$$SSC[mg/L] = 544 * B_4 - 23.564 \tag{2.2}$$

Where, B4 is the water reflectance from band Red.

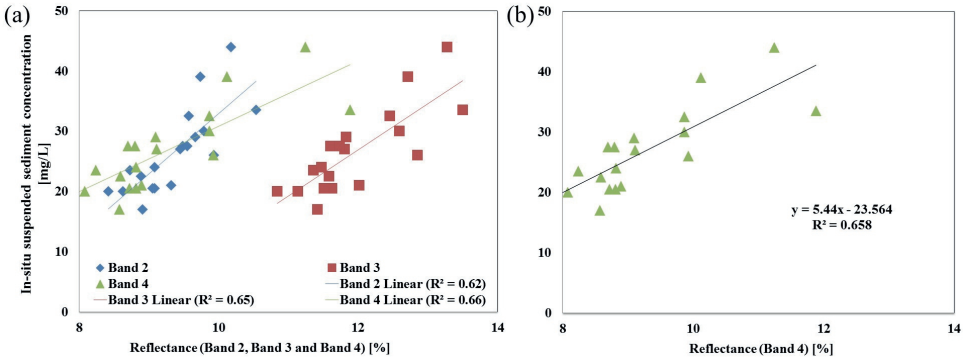


Figure 2.10: (a) Regression analysis between reflectance (Band 2, Band 3 and Band 4) [%] and in-situ suspended sediment concentration; SSC $[mg/L]$, (b) regression analysis between reflectance at Band 4 and in-situ SSC $[mg/L]$

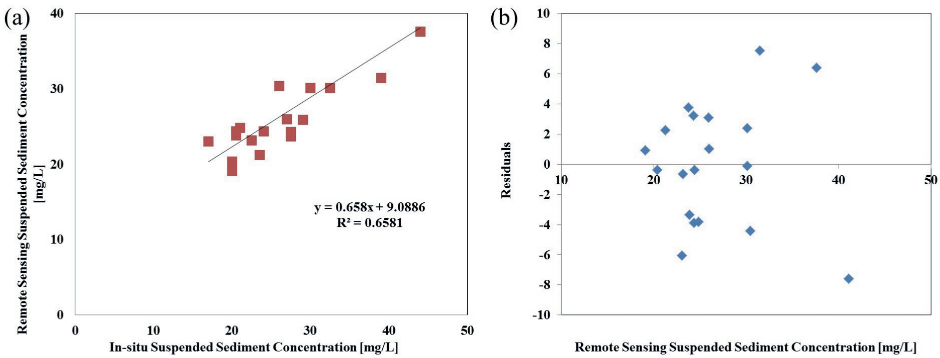


Figure 2.11: (a) Comparison of remote sensing suspended sediment concentration and in-situ suspended sediment concentration on Ayeyarwady River, (b): the residual plot of remote sensing suspended sediment concentration

Reliability of empirical formula developed by the relationship between reflectance and field SSC

The empirical equation (Equation 2.2) developed by the relationship between field SSC and surface reflectance on Landsat (133Path/45Roll) collected on 22^{nd} February 2017 were used to retrieve SSC for another Landsat image

Table 2.3: Relative error percentage of between the estimated SSC and field SSC of band 2, 3, 4 5

Sampling points	Relative error % of B2	Relative error % of B3	Relative error % of B4	Relative error % of B5
1	-26	-65	-64	3
2	-9	-43	-41	18
3	-24	-61	-61	4
4	-22	-59	-58	6

(134Path/45Roll) on 13^{th} February 2017. The same Landsat 8 OIL was used to retrieve SSC using equation 2.2 to check the reliability of the empirical equation of this study, then compared with the SSC obtained by the field observation. However, there were only four field SSC points in this Landsat image (134Path/45Roll).

The relative error percentage between the estimated SSC by equation (2.2) and four field SSC of band 2, 3, 4 5 are shown in Table 2.3. In this case, the optimal wavelength was found in band 5 (NIR) as it had less relative error percentage than relative error percentage of the other bands. The results show that the range of SSC in the field is higher than the range of SSC in satellites images because pixel points are larger than the sampling point in the field, see in Figure 2.12.

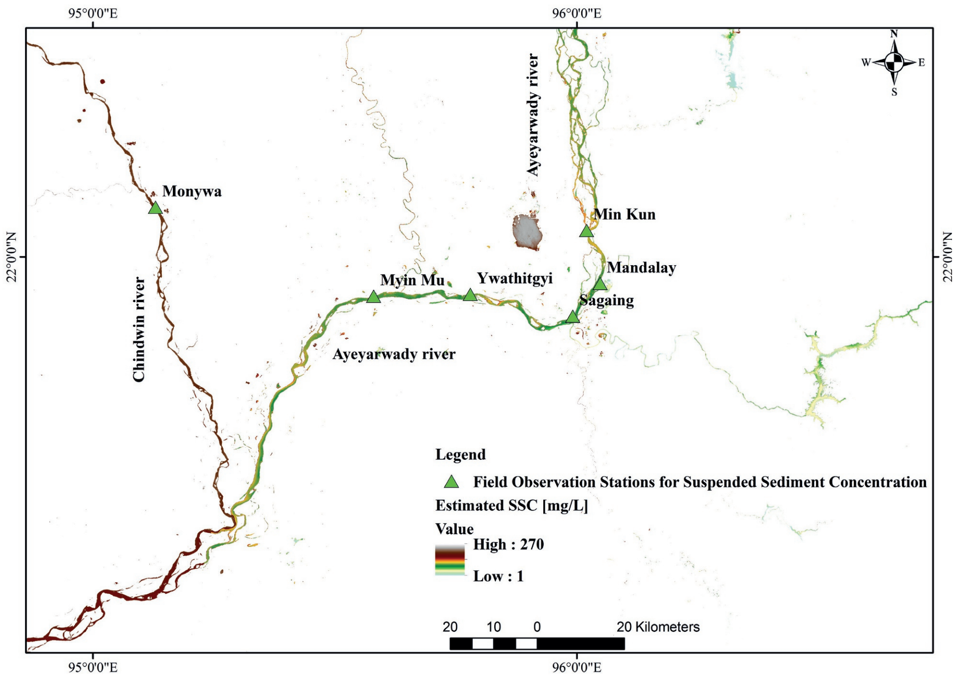


Figure 2.12: Estimated Remote Sensing SSC $[mg/L]$ map for Landsat images (134Path/45Roll) and (133Path/45Roll) on the Ayeyarwady and Chindwin Rivers at the central dry zone of Myanmar

2.4. Discussion

In this study, the digital image classification with remote sensing and GIS has demonstrated its ability to provide water quality parameters such as surface water temperature and suspended sediment concentration. For data validation, an effort was made to validate using in-situ weekly temperature, and the results were good with less than 10 per cent of relative error of radiant surface temperature. The current results show that satellites images can provide reliable water surface temperature measurement using remote sensing techniques over a large range of areas, for example, the whole Ayeyarwady River.

We developed an empirical equation from the power relation of band 4 with nineteen in-situ SSC range from 10 to 50 mg/L. The selected wavelength band (Band 4) was within most suitable wavelength to retrieve SSC values by a previous study of Ritchie, Schiebe McHenry [70] who indicated that the optimum value of wavelength for specifying SSC in the surface water is between 700 and 800.

Our findings show that the empirical equation developed from Landsat image of (133Path/45Roll) collected on 22^{nd} February 2017 can be applied to estimate SSC for another Landsat image of different time and space (134Path/45Roll) on 13^{th} February 2017 if the river characteristics are a similar condition. This finding is in agreement with the study of [71] that the reflectance values of satellite images acquired on different dates can be used together to develop in situ SSC and reflectance relationship.

We found that a single band reflectance of Landsat image (Band 5) appears to be a good indicator for estimation of SSC ranging from 130 to 160 mg/L with a relative error of less than 20%. This result is in good agreement with the previous study of Curran and Novo [72]; thus, near-infrared Band has a relatively high correlation with the in-situ SSC, especially for high sediment concentrations. However, we have only four in-situ SSC points for validation in this new Landsat image. Due to the low number of replicates, in the case of P-value of regression analysis, P-value from the power relation of four field SSC was higher than P-value of power relation of nineteen field SSC. Thus, when larger in-situ data points are used in the regression analysis, the P-value can be smaller.

Therefore, the better regression line to derive a reliable empirical equation for SSC estimation can be made by adequate in-situ data sets [73]. For example, Wang et al. [31] and Suif et al. [73] used 24 and 42 in-situ data points, respectively. Although more in-situ data gives a better regression line, the current study has limited in-situ data sets (19 sampling points on one Landsat image) due to available research budgets and time during field samplings. Therefore, for accuracy and reliability, more in-situ sampling points are recommended for further study.

According to the estimated SSC on two Landsat images, we found that the Chindwin River has a higher sediment transport than sediment transport by the Ayeyarwady River (Figure 2.12). These results are confirmed for old study in 1940, which reported that approximately half of the sediment load in the lower Ayeyarwady River basin comes from the Chindwin River [74]. Robinson et al. [33] also support our finding that the sediment concentration of Chindwin River is higher than those values in Ayeyarwady River.

Based on our knowledge, this high sedimentation in Chindwin River probably is due to the inflow from the mining activities at the upstream sections near Homalin Township where a lot of gold mining exist and also due to the difference in geological factors, catchment size, etc. However, there is limited information about the wetland's inflow from mining activities in Myanmar, and we do not have any empirical data before mining began in the upstream of the Chindwin River. Therefore, we want to recommend for further study to analyze the upstream of the both Ayeyarwady and Chindwin Rivers and after the confluence of these two rivers below Mandalay regions to find the source of sedimentation.

Although satellites data-set can provide valuable information for water resources researches, there are some limitations. For example, the ability to classify water quality, the sampling depth from the surface, and current spatial and temporal resolution are limited [34]. Thus, various water quality parameters such as toxins, nutrients, biochemical and chemical oxygen demand cannot directly be detected from space data-set [35]. Therefore, the research on water quality associated with remote sensing information with ground monitoring is vital in water resource management and planning [34].

2.5. Conclusion

Modern technologies make easy life. This study demonstrated the use of such space data-set to assess water quality of rivers in Myanmar. We showed that the Operational Land Image Sensor on the board of Landsat 8 could be successfully applied to detect surface water temperature and suspended sediment concentration in Ayeyarwady River basin at the central dry zone. However, the more available in-situ data-set would improve the performance of the regression analysis between in-situ data points and the reflectance of the satellites images. We recommended building the more in-situ observations to validate with the results of space data-set for further study, especially upstream of both Ayeyarwady and Chindwin Rivers and after the confluence of these two rivers. Currently, we concluded remote sensing information can be successfully applied in the estimation of surface water temperature and sediment concentration on a large range of area but filed observations are need to some extent to become effective analysis in the future in Myanmar.

3

Development of a river health monitoring tool

Anthropogenic pressures such as river infrastructure, agriculture and power generation are rapidly increasing in Southeast Asia, aimed at providing food security within the region. However, this will lead to unintended river health consequences, and, currently, most Southeast Asian countries have no country-specific tools for monitoring river health. In Myanmar, one of Southeast Asia's poorest and most rapidly developing countries, no country-specific tools exist, and there is an urgent need to provide tools that can inform better management and trade-off decision making. This research evaluated three rapid macroinvertebrate bioassessment methods under Myanmar conditions. The objective of the research was to assess the applicability of existing internationally accepted indexing methods for use in Myanmar. Through taxa identification in the laboratory and statistical analysis, it was concluded that the method with the best fit for Myanmar taxa is The Asia Foundation index method, although differences were small. This Asia Foundation method is comparable to the Australian Waterwatch method but includes a family present in our samples that is not included in the

This chapter is based on [75]: Ko, N.T.; Suter, P.; Conallin, J.; Rutten, M.; Bogaard, T. The Urgent Need for River Health Biomonitoring Tools for Large Tropical Rivers in Developing Countries: Preliminary Development of a River Health Monitoring Tool for Myanmar Rivers. Water 2020, 12, 1408.

Waterwatch method. We then modified this method to include Myanmar taxa not recorded in The Asia Foundation method. The modified index method could be further developed into a Myanmar specific tool for widespread use potentially in combination with the also tested miniSASS, a much easier order-based method better suitable for non-professionals. We recommend additional testing using sites on other rivers across the country to establish a professional indexing method for Myanmar.

3.1. Intorduction

Anthropogenic activities in developing countries such as river regulation and pollution have a potentially negative cumulative impact on rivers and wetlands water quantity and quality, hence negatively impacting on river-dependent people, often the poorest people in a region [76, 77]. Dudgeon [2] pointed to the fact that the deterioration in river water quality is increasing in developing countries, particularly in Southeast Asian (SE Asia) countries. Hughes [78] also found that SE Asia is a popular global hotspot of biodiversity, but also known as the most biologically threatened region by anthropogenic activities. Additionally, the scarcity of useful monitoring tools hinders informing managers of the health of all waterways and possible management actions required [40].

A growing interest in low-cost river health monitoring approaches has introduced different rapid assessment methods using aquatic macroinvertebrates communities [79, 80]. The idea of designing these approaches was to make a scientifically reliable, rapid and low-cost technique that could be an alternative to physical and chemical methods to monitor river water quality by both scientist and non-scientist [81, 48].

The most frequently used methods are scoring based that involve identifying the present taxa with or without their abundance to calculate the ecological water quality index or class [82]. The score of individual taxa indicates the level of tolerance to water quality [48]. The scoring system approach calculates the ecological water quality index based on average score per taxon (ASPT). ASPT can be calculated by dividing the sum of score per present taxa by the total number of scoring taxa. The highest number of taxa with the highest number of abundance gives the high value of ASPT which can classify a better level of river water quality [83].

Although there are some assessments of biomonitoring protocols using species-level taxonomy [84], most scoring methods rely on identification to family-level taxonomy [37]. Family level identification has the issue of reducing the information which can be extracted from the macroinvertebrate community data compared with species identification. Each species has an ecological range of tolerances to environmental conditions, whereas, at the family-level, there is a much wider range of tolerances.

Consequently, there is considerable literature comparing the two levels of identification, with some arguing that the family-level loses information and is not as robust as species-level identification [85]. Armitage et al. [82] declared that the community-based family level rapid approaches based on score systems could lose detailed ecological information, but it has value because local citizens can use it so they can be involved in regional water resources management decisions. A review of the literature showed that there is no particular index value which can satisfy all requirement for universal application as they have been developed at the local scale for a specific country [82, 86], for example Britain biotic indices (Biological Monitoring Working Party (BMWP)) and Australian biotic indices (Stream Invertebrate Great Number Average Level (SIGNAL)).

Transferability of methods developed in one area and applied in another, although cost and time efficient, depends on a number of factors and testing within the local conditions is critical [87]. When considering transferring methods from one country or river type to another, species are often different and may not occur in a specific research area, which complicates universal use in areas where methods do not exist [88]. Therefore, it is essential to know the transferability of existing international standard methods to new areas where they have not yet been tested [40]. There are various national-scale biomonitoring protocols which were developed independently for different regions in the USA, Europe, South Africa, Australia, New Zealand and South Korea based on the objectives and requirements of the various countries [37]. However, there has been limited development for a method for the SE Asian region, except The Asia Foundation method [89].

Myanmar is a SE Asian developing country experiencing rapid growth and it is expected to increase in the coming decades. Negative impacts through water control infrastructure, water abstraction, mining and pollution all have the potential to significantly impact ecosystem integrity in a country where millions are reliant on the ecosystem services that healthy rivers and wetlands provide [90]. Currently, there is no systematic research on aquatic macroinvertebrates of rivers and streams in Myanmar.

To our best knowledge, only a few initial, piloting studies have been performed using biomonitoring. There has been an initial study on aquatic macroinvertebrates by Myanmar Healthy Rivers Initiative (MHRI) in the main stream of the Ayeyarwady River, downstream of Mandalay, and in the lower Salween (also called Thanlwin River), 65 km upstream from the sea [44]. These early studies concluded that aquatic macroinvertebrates communities are not appropriate to use as an indicator to describe river health in the downstream reaches of Myanmar's large rivers due to the significant flow variation, high sediment loads and unsuitable substrates. Dickens et al. [44] recommended using aquatic macroinvertebrates as an indicator in small streams or tributaries where the riparian, marginal vegetation and flow regime are more stable as compared to large rivers. Eriksen et al. [45] proved that macroinvertebrates could be applied to identify river health in small streams based on their pilot sampling in the Bago River basin.

Therefore, this research was focused on testing a number of internationally developed macroinvertebrate-based rapid assessment methods and evaluating their applicability in Myanmar. The chosen methods included miniSASS (mini Stream Assessment Scoring System) developed in South Africa (www.minisass.org), The Asia Foundation method developed from work in Mongolia and Lao PDR (http://asiafoundation.org), and The Australian Waterwatch developed in Australia (www.nswwaterwatch.org.au/resources). These three methods are widely used techniques in their respective regions. All three methods are rapid field-based score index methods. All methods are similar in that they score macroinvertebrate families in relation to their sensitivity to anthropogenic activities. The scores generally relate to categories related to natural or unmodified condition, with scores progressing downwards to largely modified and poor river health conditions.

The overarching objective of this research was to determine which of the existing internationally accepted indexing methods is most appropriate for use in Myanmar. Hereto, we divided our work into four parts: (1) determine if enough macroinvertebrates across a number of taxa could be collected for further analysis using both rapid assessment methods and laboratory analysis for statistical comparison; (2) access how applicable internationally accepted methods for rapid bioassessment to use in Myanmar; (3) show if modifications would be needed to adapt the method for use in Myanmar; and (4) recommend further development and research of biomonitoring tools required for successful and nation-wide application of biomonitoring in Myanmar, including as citizen science tools.

3.2. Materials and Methods

3.2.1. Study area

It is required to use data from pristine or least disturbed sites because data from impacted sites can give reduced diversity, which can bias the data to communities [91]. However, many of the rivers in Myanmar have already been disturbed by the construction of dams and, unfortunately, political and safety issues often hinder accessibility. Finally, we selected two rivers in Myanmar, namely the Myitnge and Chaungmagyi Rivers (Figure 3.1), 528 and 100 km long and with 29,630 km^2 and 5,720 km^2 catchment area, respectively. The Myitnge River flows from the hills of eastern Hseni and through Shan state and Mandalay region.The Chaungmagyi River originates from the Shan Plateau of Eastern part of Myanmar and flows to the central part of the country. There are hydropower dams on the Myitnge and Chaungmagyi Rivers of 790 and 25 Megawatt (MW), respectively, in the downstream reaches before they end into the Ayeyarwady River near the Mandalay plain at the central dry zone of the country (Figure 3.1). The average annual inflows of the Myitnge and Chaungmagyi Rivers are 24 and 2.7 $\times$ 10^9 $\mathrm{m}^3/year$, with min and max monthly discharge of 167.06 and 1,069.84 m^3/s for Myitnge River and 14.17 and 107.52 m^3/s for Chaungmagyi River [92].

We collected samples from three sampling sites on upstream sections of both rivers where anthropogenic impacts were minimal to represent our reference sites for analysis. There were two sampling sites on the Myitnge River (MT-1, $22°42'55.39''$ N, $97°20'55.33''$ E, and MT-2, $22°1'36.09''$ N, $96°57'49.74''$ E) and one sampling site on the Chaungmagyi River (CM-1, $22°49'28.62''$ N, $96°33'32.78''$ E). Sites MT-1 and MT-2 are located at 432 and 259 m a.s.l., respectively and Site CM-1 is situated at 680 m a.s.l. We selected sampling sites which had a rocky substrate with vegetation along the edge of the river where suitable habitat for macroinvertebrates is likely to remain even under low water levels. At each site, three samples were collected and this was repeated during two sampling occasions.

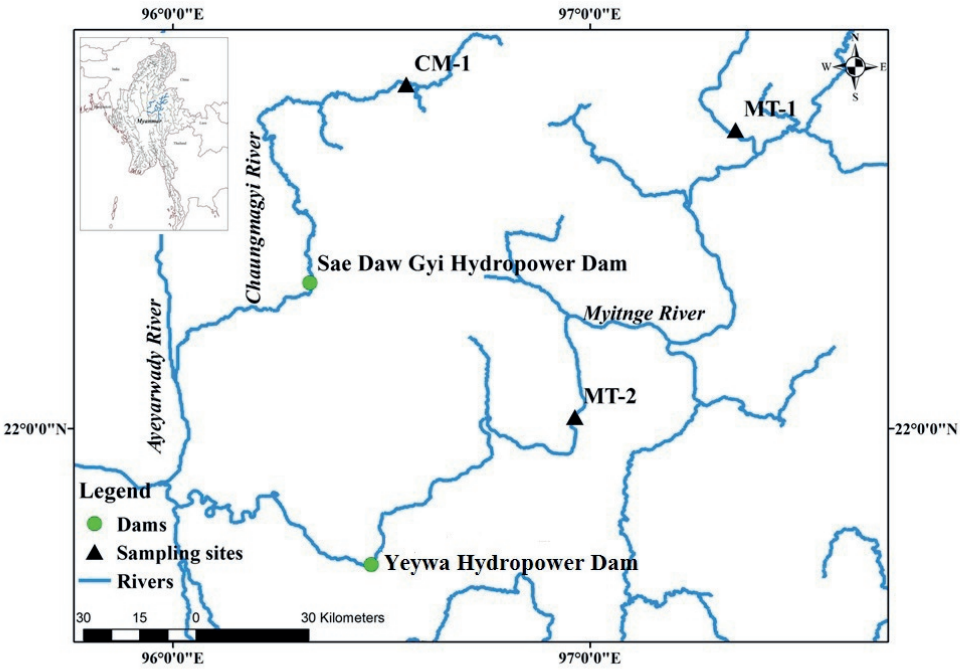


Figure 3.1: Locations of selected sampling sites on Myitnge and Chaungmagyi Rivers in Myanmar; MT-Myitnge R, CM- Chaungmagyi R

3.2.2. Physico-chemical water quality variables

We measured four physico-chemical water quality variables at all sampling sites at the time of sampling. We used a pH test strips with a range of 4.5–9.0 and water clarity tubes for in situ monitoring of pH and turbidity (NTU: Nephelometric Turbidity Unit). In addition, we measured electrical conductivity (EC - $\mu S\,cm^{-1}$) and water temperature (Temp - °C) using a multiparameter meter.

3.2.3. Macroinvertebrates sampling and identification

In the period of November–December 2016, three macroinvertebrate samples were collected from each of the three sites. This exact sampling regime was repeated again at each site between February and March 2017. In total, 18 macroinvertebrates samples were available for analysis. At each site, samples were collected from a 5-m transect parallel to the riverbank. We used a kick or sweep net method [37] to collect samples of macroinvertebrates with a five side nylon net (500 and 1000 MU mesh). We held the kick net vertically on the riverbed and disturbed the substrate by kicking the cobbles or by using hands to disrupt the stones so that the macroinvertebrates were washed into the net by the stream flow. We first placed the macroinvertebrates samples in a white plastic tray (30 cm × 30 cm) filled with water. We 'live-pick' sorted the macroinvertebrates for the first sample on site. We used the first sample to conduct the rapid assessment using each of the three methods, and then preserved each of the three samples in 70% ethanol for later identification in the laboratory.

3.2.4. Rapid Assessment Index methods – Field-based testing

In the field at each site, we conducted a live pick and tested against each of the three international rapid biomonitoring methods: miniSASS, The Asia Foundation and Australian Waterwatch. These methods vary in the taxonomic level they use and thereby the complexity. The miniSASS is order based, whereas the Asia Foundation and the Australian Waterwatch methods are based on the score of family level counting. Macroinvertebrates samples collected were identified at family level as one of the protocols for each method. Collected taxa were scored based on a prescribed score per taxon of individual approaches to calculate ASPT. These were then recorded for each method to visualize any major differences while using the different methods in the field and to assess if enough macroinvertebrates were collected to apply the different methods.

Method 1, miniSASS is a community monitoring tool for river health designed by The Water Research Commission of South Africa (www.minisass.org) based on Stream Assessment Scoring System (SASS) [48]. Chutter [93] developed SASS by adjusting and modifying the Biological Monitoring Working Party (BMWP) score system as an abiotic index for South Africa [86]. The individual sensitivity score ranges from 2 to 17 for 12 taxonomic groups (see in http://www.minisass.org/en/map/). They identify water quality conditions into five categories; the natural or unmodified condition (>7.2), good or few modifications condition (from 6.2 to 7.2), fair or moderately modified state (from 5.7 to 6.1), poor or largely altered state (from 5.3 to 5.6), and very poor or severely altered condition (<5.3) based on average score per taxon, ASPT.

Method 2, is The Asia Foundation method was developed as a Community

Water Quality Monitoring (WQM) method by The Asia Foundation organization (http://asiafoundation.org/). This method included 45 taxonomic groups with the range of individual sensitivity score value from 1 to 10. The water quality level divided into four groups based on the Ecological Water Quality Index; average score per taxon ASPT; 1 to 2.9 means "Poor quality," 3.0 to 6.9 means "Fair quality," and 7.0 to 10.0 means "Good quality."

Method 3, involved the use of the Australian Waterwatch Water bug detective guide (http://www.waterwatch.org.au/) developed by the state governments primarily for use by citizens to determine waterway health. They used (Stream Invertebrate Great Number Average Level) SIGNAL 2 [94] to establish individual score per taxon which range from 1 to 10. It has 30 taxonomic groups to identify four-stream pollution indices; less than three means "Poor," between 3 and 4, and between 4 and 6 mean "Fair" and "Good," and more than 6 are "Excellent" water quality condition.

We calculated the ecological water quality index of rivers with the sum of the individual score of collected taxa divided by the total number of those taxa as the following equation of method 1 and 2.

$$\text{Ecological Water Quality Index; ASPT} = \frac{\sum(\text{Individual score of present taxa})}{\sum(\text{Total number of scoring taxa groups})} \tag{3.1}$$

However, the Australian Waterwatch method takes into account the abundance of taxa present (See in https://www.nswwaterwatch.org.au/resources). Therefore, we calculated the ecological water quality index with the following equation for Australian Waterwatch method.

$$\text{Ecological Water Quality Index; ASPT} = \frac{\sum(\text{Individual score of present taxa} \times \text{weight factor})}{\sum(\text{Weight factor of scoring taxa groups})} \tag{3.2}$$

Where; weight factors range from 1 to 5 based on the number of abundances found. The weight factors reached 1 for one or two taxa, 2 for 3 or 5 individuals, 3 for between 6 and 10 individuals, 4 for between 11 and 20 individuals, and 5 for greater than 20 individuals.

3.2.5. Index and Statistical analysis

Due to macroinvertebrate keys not existing in Myanmar to date, keys within the texts "Identification of Freshwater Invertebrates of the Mekong River and its Tributaries" by [56] and "Tropical Asian Streams" by [2] were used to key species for identification. To be able to assess which of the three international methods was most appropriate for use as an assessment tool for Myanmar, we created a list of family level data derived from laboratory identification to calculate ASPT. Firstly, we did not consider taxa, which were absent in the current three indices methods in the estimating of indices of the three methods.

Samples were analysed using the statistical analysis program PRIMER v6 [95]. We constructed an indices matrix without transformation. We computed the resemblance matrix using Bray-Curtis similarity. Non-metric multidimensional scaling (MDS) was used to display rank order correlation plot with stress values. The MDS plot was used to show rank order distance among samples (dis)similarity calculated by Bray-Curtis [96]. One way analysis of similarity (ANOSIM) and similarity analysis (SIMPER) was carried out using a resemblance matrix by Bray-Curtis similarity. We applied ANOSIM to examine if the indices resemblance matrix differed among all sampling sites. ANOSIM provided a statistical coefficient Global R-value, which highlighted variables separations between the sites [95]. SIMPER was used to analysis the percentage of (dis)similarity between indices variable as a function of sampling sites within the same river, and between different rivers. More importantly, SIMPER also computed the contribution of each indexing method. These contributions were used to show which variables (Indexing methods) supported the percentage of (dis)similarity. All statistical significance for Bray-Curtis, ANOSIM, and SIMPER were to a 0.001 level [95].

To find which indexing method is the most likely to be appropriate with macroinvertebrates of Myanmar, we used the Biota and Environment matching routine (BEST) from PRIMER v6. BEST (Bio-Env) was used to estimate the rank correlation between two resemblance matrices (taxa and indices) [96]. BEST was used to find the best subset of environmental (Indexing methods) variables, which shows strong correlation between the biotic resemblance matrix and the environmental Euclidean distance matrix. We applied the 99 random permutations (probability of 0.01) for the null distribution to find the optimal rank correlation values.

3.3. Results

3.3.1. Physico-Chemical water quality variables

The physico-chemical water quality variables at all sampling sites for two sampling periods (November-December 2016 and February-March 2017) are given in Table 3.1. The pH values ranged from 5.5 to 7.6 across all sites. We found the highest turbidity of 307.8 NTU in the Chaungmagyi River during the first sampling campaign (November-December 2016). The surface water temperature varied from 22 to 29 °C among all sampling sites. The electric conductivity (EC) ranged from 65 to 427 $\mu S\,cm^{-1}$. We found that the level of EC was higher in the Myitnge River than in the Chaungmagyi River for both November-December 2016 and February-March 2017 sampling campaigns.

Table 3.1: Collected number of all taxa and Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO) with their abundance data and four physico-chemical variables at each sample at each site of both study rivers for two sampling occasions.

Site Observation	Occasion	Locations	Samples	Total Taxa		Total Abundance		pH	Turbidity [NTU]	EC [$\mu S\,cm^{-1}$]	Temp [°C]
				All	EPTO	All	EPTO				
Myitnge River	November-December 2016	MT-I-1	MT-I-1.1	5	5	50	50	7.5	14.0	289	23
			MT-I-1.2	4	4	25	25				
			MT-I-1.3	12	7	32	22				
		MT-I-2	MT-I-2.1	4	4	29	29	6.5	14.0	354	29
			MT-I-2.2	4	4	25	25				
			MT-I-2.3	5	5	16	13				
	February-March 2017	MT-II-1	MT-II.1.1	17	13	119	55	7.3	4.3	327	22
			MT-II-1.2	9	9	380	380				
			MT-II-1.3	13	13	267	267				
		MT-II-2	MT-II-2.1	14	13	304	300	6.8	6.0	427	23
			MT-II-2.2	8	7	33	30				
			MT-II-2.3	4	2	12	6				
Chaungmagyi River	November-December 2016	CM-I-1	CM-I-1.1	1	0	1	0	5.5	307.8	72	24
			CM-I-1.2	10	9	124	123				
			CM-I-1.3	12	10	103	96				
	February-March 2017	CM-II-1	CM-II-1.1	19	17	148	146	7.6	108.0	65	23
			CM-II-1.2	19	15	245	236				
			CM-II-1.3	9	8	38	37				

3.3.2. Macroinvertebrates richness and abundance

The result of identification from all 18 macroinvertebrate samples was a total of 10 orders with 36 families and 58 different species. Table 3.1 shows the a number of all taxa, and sensitive taxa (Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO)) with the abundance data per sample at each sampling site on both study rivers. The number of different aquatic macroinvertebrates taxa ranged from 3 to 17, with the abundance ranging from 12 to 380 individuals from the samples collected in the Myitnge River. In the Chaungmagyi River, the number macroinvertebrates taxa ranged from 1 to 19, with the abundance ranging from 1 to 245 individuals from the samples collected. The highest contribution of taxa among all sampling sites were sensitive taxa, EPTO (Table 3.1). The most abundant taxa among EPTO at each sample in both rivers were Ephemeroptera. Table 3.2 shows a detailed list of collected family and morphospecies-level taxonomy.

Table 3.2: Collected abundance and their original and modified scores of The Asia Foundation Index and Stream Invertebrate Great Number Average Level (SIGNAL 2) Grades.

			The Asia Foundation		SIGNAL 2	Rivers	
Order	**Family**	**Species**	**Original**	**Modify**	**Grades**	**Myitnge**	**Chaungmagyi**
Ephemeroptera *	Baetidae * *	*Platybaetis* sp 1	5	5	5	67	189
		Baetis sp 1	5	5	5	814	183
		Procloeon sp 1	5	5	5	6	0
	Prosopistomatidae **	*Prosopistoma* sp 1	N.A	4	4	4	0
	Ephemeridae **	*Ephemera* sp 1	6	6	N.A	3	0
	Heptagenidae **	*Asionurus* sp 1	10	10	N.A	18	27
		Asionurus sp 2	10	10	N.A	0	9
	Caenidae **	*Caenis* sp 1	4	4	4	2	0
	Leptophlebiidae **	*Chloroterpes* sp 1	10	10	8	20	3
		Chloroterpidae sp 1	10	10	8	2	0
	Potamanthidae **	*Potamanthindus* sp 1	5	5	6	0	1
	Polymitarcyidae **	*Ephoron*	N.A	6	6	0	31
	Isonychiidae **	*Isonychia*	N.A	8	8	0	1
	Ephemerellidae **	*Torleya*	10	10	9	0	1
		C.gosei sp 1	10	10	9	0	3
Plecoptera *	Perlidae **	*Neoperla* sp 1	10	10	10	11	14
		Neoperla sp 2	10	10	10	3	1
		Neoperla sp 3	10	10	10	0	1
		Etrocorema sp 1	10	10	10	1	1
		Etrocorema sp 2	10	10	10	9	1
		Togoperla sp 1	10	10	10	0	12
		Togoperla sp 2	10	10	10	0	1
		Togoperla sp 3	10	10	10	0	23
Trichoptera *	Hydropsychidae **	*Potamyia* sp1	5	5	6	105	27
		Oestropsyche sp 1	5	5	6	1	0
		Macrostemum sp 1	5	5	6	40	35
		Amphipsyche sp 1	5	5	6	0	1
		Parpsyche sp 1	5	5	6	0	1
		Trichomacronema sp 1	5	5	6	0	46
	Helicopsychidae **	*Helicopsyche* sp 1	10	10	8	1	0
	Odontoceridae **	*Marilia* sp 1	10	10	7	18	3
	Dipseudopsidae **	*Pseudoneureclipsis* sp 1	10	10	9	4	6
	Molannidae **	*Molanna* sp 1	10	10	N.A	7	0
	Leptoceridae **	*Triplectides* sp 1	10	10	6	1	0
	Stenopsychidae **	*Stenopsyche* sp 1	10	10	N.A	0	5
		Stenopsyche sp 2	10	10	N.A	0	2
Odonata *	Gomphidae **	Gomphidae sp 1	6	6	5	61	7
	Megapodagrionidae **	Megapodagrionidae sp 1	6	6	5	3	2
	Euphaeidae **	Euphaeidae sp 1	6	6	5	0	1
Megaloptera	Corydalidae **	Corydalidae sp 1	10	10	7	6	8
Diptera *	Chironomidae	Orthocladinae sp 1	3	3	3	36	0
	Ceratopogonidae	Ceratopogonidae sp 1	3	3	4	1	0
	Tipulidae (L)	Tipulidae (L)	3	3	5	1	0
	Tipulidae-Limoninae	TipulidaeL-imoninae sp 1	3	3	5	0	4
	Tipulidae	*Antocha*	3	3	5	0	1
	Athericidae	Athericidae sp 1	N.A	8	8	0	1
Coleoptera *	Noteridae **	Noteridae sp 1	7	7	4	1	0
	Gyrinidae **	Gyrinidae sp 1	7	7	4	1	0
	Elmidae (L)**	Elmidae (L) sp 1	8	8	7	20	1
		Elmidae (L) sp 3	8	8	7	0	1
		Elimidae (A)	8	8	7	1	0
	Psephenidae **	Psephenidae sp 1	7	7	6	1	0
Lepidoptera *	Crambidae	*Eoephyla*	5	5	3	0	1
Hemiptera *	Naucoridae **	Naucoridae sp 1	10	10	2	2	3
	Aphelocheirus **	*Aphelocheirus* sp 1	10	10	N.A	12	0
	Micronectidae	Micronectidae sp 1	1	1	2	0	1
Mesogastropoda *	Thiaridae **	Thiaridae sp 1	1	1	4	6	0
	Viviparidae **	Viviparidae sp 1	1	1	4	2	0
Total abundance						1291	659
Number of sites						2	1
Nymber of occasion						2	2

Note: N.A is no data, sp means species, L is larval, A is adult. (*) is miniSASS taxa, (**) is Australian Waterwatch taxa.

3.3.3. Ecological water quality index and statistical analysis

Laboratory identification was used to calculate ASPT following the three different methods to calculate the ecological water quality indices of each sample for both rivers (Figure 3.2). The estimated water quality indices using the three methods generally showed fair conditions and above water quality conditions across all samples (Figure 3.2).

Dimensionless MDS ordinations plots for the non-transformed ecological water quality indices by three methods were calculated. Based on Bray–Curtis similarity between the Myitnge and Chaungmagyi Rivers, the stress calculated at 0.04 (<0.05) (Figure 3.3.a), indicating that rank order correlation is a good representation of indices similarity matrix by Bray–Curtis between the Myitnge and Chaungmagyi Rivers. This indicates that the three different scoring methods provide similar ecological trend results in relation to water quality conditions in both rivers. The Global R test plot calculated close to zero (−0.096) (Figure 3.3.b), which mean that there was overlap between indices of the three methods. The dark vertical line on the plot (Figure 3.3.b) is not separated from the distributions. Therefore, the null hypothesis is correct that there is no significant difference between all indices derived by the three methods among all sites in both rivers.

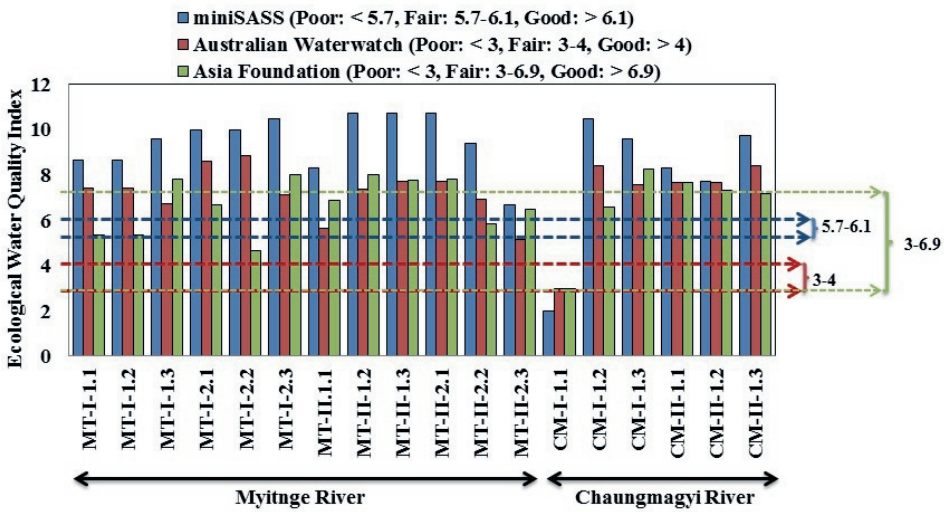


Figure 3.2: Estimated ecological water quality indices by three methods at each sample on Myitnge and Chaungmagyi Rivers for two occasions.

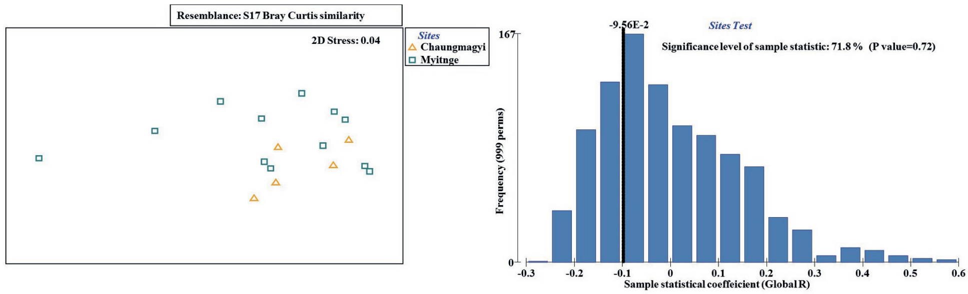


Figure 3.3: (a): Matching of indices by three methods between two study rivers by non-metric multidimensional scaling(MDS) plot, and (b): matching of indices by three methods among all sampling sites by Global R statistic test by one way analysis ANOSIM

The similarity analysis routine SIMPER provided the percentage of (dis)similarity of indices of the three methods within the same river and between the two rivers. The similarity of indices among sampling sites within the Chaungmagyi River was 96 % and between sampling sites within the Myitnge River was 92%. Table 3.3 shows the detailed results of SIMPER with the percentage of contribution of each index method.

According to the results of the MDS plot, ANOSIM, and SIMPER, the three methods all calculated similar ecological water quality conditions among all sampling sites of both studied rivers. The correlation plot between each indexing method was calculated and was 0.6 between miniSASS and the Australian Waterwatch; the highest correlation (0.9) was between The Asia Foundation index method and Australian Waterwatch index method (Figure 3.4). Rank correlations calculated using BEST (Bio-Env) showed The Asia Foundation indexing method produced the highest rank correlation (0.774) between taxa resemblance matrix and Euclidean distance matrix for the indices, followed closely by the rank correlations of The Australian Waterwatch indexing method (0.772) and miniSASS (0.683).

The miniSASS is a less rigorous method designed for school children and community groups. This method is an 'Order' based method (12 order/taxa groups) rather than using detailed family groups. The Australian Waterwatch method is also designed for community monitoring but is a more rigorous method than miniSASS with 30 family/taxa groups. On the other hand, the Asia Foundation method is a rigorous scientific method designed for scientists or government organizations using 45 family/taxa groups.

In addition, We collected 58 aquatic macroinvertebrates families across all sites, in which four families are absent in The Asia Foundation score grades, and five families are absent in Australian Waterwatch score grades (see Table 3.2). Although arguments could be made for the use of any of the three methods, based on the above results and considerations, we finally selected The Asia Foundation index for further refinement for Myanmar. The Asia Foundation index method was developed in Lao PDR (Mekong River basin) and Mongolia where climate and watershed characteristics have more similarity with Myanmar than the other methods, and had more macroinvertebrate taxa representative of Myanmar than the other two methods (Australia and South Africa). We then modified the Asia Foundation method by adding four new taxa of Myanmar to see how much the ecological water quality index changed compared to the original method without the new taxa.

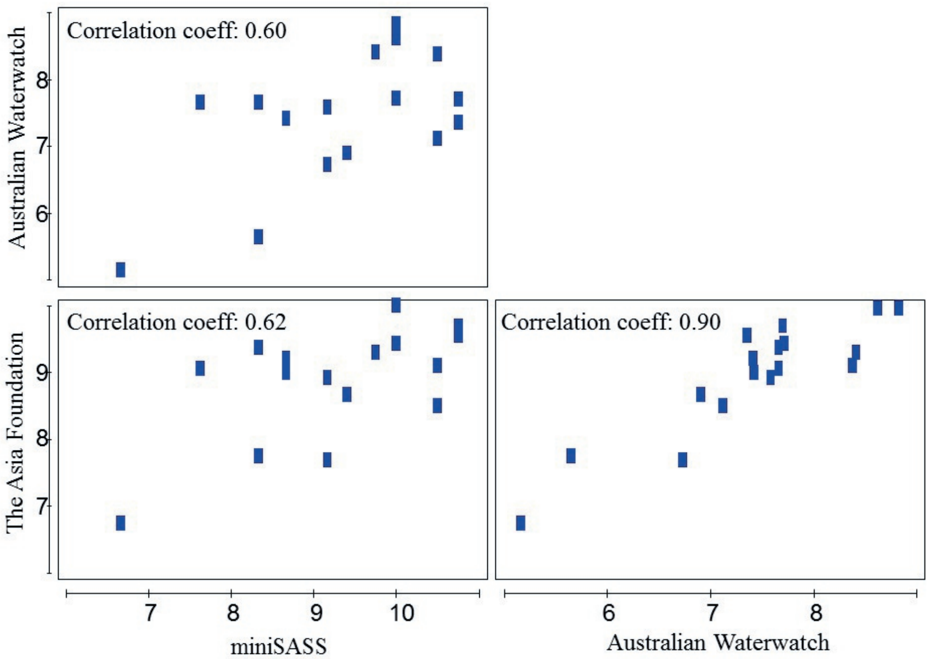


Figure 3.4: Correlation values between three index methods

Table 3.3: The results of Average (dis)similarity percentage and contribution variables by similarity analysis SIMPER routine of PRIMER v6

Group CM						
Average similarity: 95.92						
Species	Average Abundance	Average Similarity	Similarity/standard deviation	Contributiom %	Cumulative.%	
The Asia Foundation	9.15	34.55	30.73	36.02	36.02	
miniSASS	9.08	31.9	14.96	33.26	69.28	
Australian Waterwatch	7.94	29.47	35.17	30.72	100	
Group MT						
Average similarity: 92.43						
Species	Average.Abundance	Average.Similarity	Similarity/standard deviation	Contributiom %	Cumulative.%	
miniSASS	9.41	34.17	13.38	36.97	36.97	
The Asia Foundation	8.85	32.36	17.64	35.01	71.98	
Australian Waterwatch	7.22	25.9	12.69	28.02	100	
Groups CM & MT						
Average dissimilarity = 6.13						
	Group Chaungmagyi	Group Myitnge				
Species	Average Abundance	Average Abundance	Average Dissimilarity	Dissimilarity/standard deviation	Contribution%	Cummulative %
miniSASS	9.08	9.41	2.5	1.34	40.83	40.83
Australian Waterwatch	7.94	7.22	2	1.11	32.72	73.55
The Asia Foundation	9.15	8.85	1.62	1.12	26.45	100

3

3.3.4. Method development and modification – Myanmar modified The Asia Foundation Index

During laboratory testing, it was found that a number of families found in the Myanmar streams were not represented in The Asia Foundation Method. These include three taxa of Ephemeroptera (Prosopistomatidae, Polymitarcyidae and Isonychiidae) and one family of Diptera (Athericidae). Not including these families would reduce the precision of the method for Myanmar and could cause confusion if they were identified but not able to be used in the method. All other families were included in the original index method. Therefore, we modified The Asia Foundation method by including the extra four families with an appropriate sensitivity score. To derive sensitivity scores, we used SIGNAL 2 as the score range is consistent with the score of an individual taxon (ranging from 1 to 10) for The Asia Foundation index [94]. Using the SIGNAL 2 index, we added grade scores for the four missing family groups.

The Prosopistomatidae were given a grade score of 4 because they are less sensitive to water quality changes than other families of mayflies [97]. Polymitarcyidae were given a grade score of 6 due to their similar habitat requirements of other burrowing mayflies (e.g., Ephemeridae) in the original Asia Foundation index [2]. Both SIGNAL 2 grades and the original Asia Foundation did not include Isonychidae–*Isonychia*; however, this family of macroinvertebrates behave ecologically similar to the Australian genus Coloburiscidae, which filters organic material from the water column with hairs on the legs, and both are weak swimmers. These two families were originally placed in the same family but have since been separated [98]. The Isonychidae–*Isonychia* from Myanmar was therefore given the same score as Coloburiscidae in SIGNAL 2 grades (i.e., grade 8) in the modified index. The Athericidae in SIGNAL 2 has a grade of 8, indicating it is a sensitive family. Hence, Athericidae was placed in a pollution sensitive grade (8).

The ecological water quality indices of the original and modified Asia Foundation method were calculated for each sample where the additional four families occurred (Figure 3.5). The difference in indices between the modified method with the additional four taxa and the original method without the four taxa are not significant, for example, for samples CM-II-1.1 and CM-II-1.2 where the intolerant family (Athericidae) and mid-range tolerant family (Polymitarcyidae) were found.

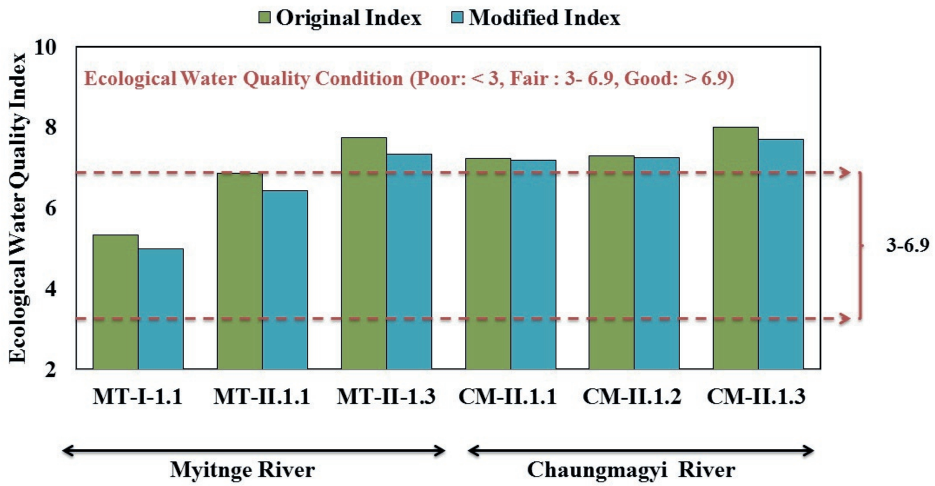


Figure 3.5: Ecological water quality indices of six samples based on the original Asia Foundation Method and Myanmar Modified Method. Dotted line shows Fair condition according to the index. Dotted line shows Fair condition according to the index.

3.4. Discussion

There are various approaches for assessing river water quality using physical, chemical and biological indicators [99, 9]. Among these, biological indicators are well suited for assessing river water quality because they can detect the level of impact and identify which pressures may be causing the impact. Algae, bacteria, fish and aquatic macroinvertebrates are popular biological assemblages in different biomonitoring approaches, all with advantages and disadvantages [1]. Biomonitoring using aquatic macroinvertebrates have diversified and have been extensively applied internationally to monitor river water quality since the 1980s. Macroinvertebrate-based river health monitoring tools hold potential for developing countries to be able to monitor the health of their rivers and wetlands using rapid and relatively low cost technology, but methods developed outside of the country need to be tested and modified to be locally applicable [37].

This study aimed to investigate the potential use of a biological monitoring method suitable with enough taxa data to monitor river health at the local scale for Myanmar. Hereto, we selected minimally impacted sites in the upstream part of two rivers. Unfortunately, there is human disturbance on all water resources around the world [100]. Therefore, although we selected sites with minimal anthropogenic pressure in both rivers, some human influences may exist, for example direct household waste disposal. However, our results show that the current sampling sites had a similar dominance of aquatic insects consistent with other Asian countries (such as Thailand, Nepal and Malaysia). Six species from five families of Trichoptera [101] and 30 families of all taxa were the same as found in Thailand [40]. Four out of seventeen families of Odonata were the same found in Nepal [102] and the six dominant families of EPT in Peninsular Malaysia found by Abdo, Rawi, Ahmad and Madrus [42] were all recorded in the study. Based on collected taxa-richness and their abundance, it was concluded that macroinvertebrates could be collected in numbers across different taxa to warrant the trialing of the different rapid assessment methods.

Our main objective was to find an appropriate macroinvertebrate-based index method based on the three different international standardized index methods under Myanmar taxonomic condition and then to modify the index for use in Myanmar. At all sites tested (except one site on one sampling occasion), an adequate number of macroinvertebrates were able to be collected to test the three methods. The three different methods trialed gave slightly different results, which is not surprising as they use data of different taxonomic level and are developed for different areas of the world. Differences were not significant and both the proposed modified version of The Asia Foundation method and miniSASS may play a role in river health monitoring in Myanmar.

Generally, the lower is the taxonomic level used, the more specific is the understanding of river health that can be expected in temporal and spatial sense but also more training is needed to apply such a method. Out of the three methods we tested, the Asia Foundation method and the Australian method had a comparable level of detail. The miniSASS is much easier as it uses only order level. In our samples, the Asia Foundation method had the least number of families missing (four) compared to five missing in the Australian method. We chose to modify this method to better represent Myanmar conditions. The addition of the four missing families did not alter the score results for these unmodified waters substantially, but makes the method more Myanmar specific and the detection of river health degradation easier in the country.

An important aspect of biomonitoring is the characterization of the water quality at time of sampling and even the pollution in the period before the sampling, as it has a strong influence on the results. We collected basic physico-chemical analysis of the water in-situ at time of sampling. All in-situ levels were within acceptable standards for ecological integrity based on the references [103, 99], but we did not measure any organic pollution levels. No information on the historical water quality in the Myitnge and Chaungmagyi Rivers is known. However, concerns have been raised on the water quality downstream of the industrial concentration of the Mandalay and Sagaing urban areas [90]. However, these sampling points were all upstream of the major urban and industrial concentrations. Furthermore, the land use in the upstream catchments is mainly forest and agriculture, where the latter is known for low application of fertilizers and pesticides, but the negative effects currently unknown [90].

Biomonitoring programs are not always linked to public involvement for raising awareness and citizen science approaches for river water quality monitoring. However, there is a well-known trade-off between the number of families required for accurate assessment and determination problems by non-scientists [83]. Our research suggests that the adjusted index with an additional four families improved the performance of the index slightly. The inclusion could also lessen confusion for both experts and citizen scientists when utilizing the method, as, if they were left out but then identified, there would be no category for them. The current state of the Myanmar biomonitoring assessment tool should be improved by more use and testing in different river types and adjusted accordingly. The miniSASS method may be valuable for wider application by citizens next to the modified index proposed.

There is currently no surface water quality monitoring network in place in Myanmar. Only initial steps in developing a water quality monitoring network for the Ayeyarwady have been presented using a low-cost sensor network [25]. Furthermore, towns along rivers are growing larger with inadequate pollution control infrastructure and more water control infrastructure including hydropower dams are planned [104]. Assessing river health is therefore of utmost importance but at the same time absent in Myanmar where the water resources are central to the Myanmar economy [90].

The presented results are promising at a localized scale, but at the same time we recognize the need for rapidly extending to reach a national wide biomonitoring system [37]. We are aware that this study is a pioneering start with a modest dataset collected in challenging conditions. We studied two large tributaries of the Ayeyarwady using three locations and sampling in two seasons, which is inadequate to establish a system wide monitoring tool, but the tool can be trialed and improved as more data become available. The method can be considered representative for this region, but it is important to also determine the rest of the country, which will take a more comprehensive sampling regime across all river types. We recognize that the dataset is limited but these preliminary results are encouraging and additional sampling of impacted sites and minimal impacted sites is warranted.

Currently, we conclude that this modified index is useful as an initial assessment to develop a professional biomonitoring method at a national scale where no baseline research exists potentially in combination with an easier biomonitoring tool for citizens such as miniSASS. However, from a utility and reliability perception, we recommend further comprehensive study in other rivers of Myanmar to investigate its value in detecting impacts from human activities. This can be done using the tool in the field, but also testing in the laboratory to better refine the method.

4

Dams impact on Aquatic Macroinvertebrate Community

Intensive and incessant disruptions in watercourses such as dams are taking place due to the growing demand for hydroelectric generation, and can result in severe deterioration of ecosystem integrity. This research concentrates on the impact of dams on macroinvertebrate communities downstream of two hydropower dams on tributaries of the upper Ayeyarwady River basin (Myitnge and Chaungmagyi Rivers) in Myanmar. A total of 52 and 49 aquatic invertebrate taxa with a total abundance of 2743 and 1356 were collected from the Myitnge and Chuangamgyi Rivers respectively. We found the natural flow regime had changed in both study rivers after the construction of the dams. Analysis of similarity (ANOSIM) indicated the communities of morphospecies of taxa and the very sensitive insects (Ephemeroptera, Plecoptera, Trichoptera, and Odonata, EPTO) were significantly different between upstream and downstream of both dams. We used the preliminary

This chapter is based on [105]: Ko, N. T., Suter, P., Conallin, J., Rutten, M., Bogaard, T. (2020). Aquatic Macroinvertebrate Community changes downstream of the Hydropower generating dams in Myanmar-Potential negative impacts from increased power generation Dams impact on Aquatic Macroinvertebrate Community. Frontiers in Water, 2, 57.

Myanmar Aquatic Biomonitoring Assessment Index (MABA) detect ecological water quality. The MABA analysis using all taxa at family-level showed that upstream of the dams was rated as good quality whereas downstream of the dams was rated as fair quality. Our research showed that macroinvertebrates communities can be used as a bioindicator to detect the impact of human influences on river health such as dams. We concluded that the novel biomonitoring assessment tool recently developed for Myanmar is a promising monitoring tool as further river development occurs in Myanmar, which could also be linked to citizen science projects.

4.1. Introduction

Dams provide considerable social and economic benefits to human society, such as those produced by irrigation and hydroelectric power [106]. Although dams bring prosperity, they are cited as the most significant and incessant threat to freshwater ecosystems globally [107, 108]. Dams alter natural flow regimes, sediment transport, water quality, channel morphology, stream temperature, and nutrient cycles, and they also obstruct dispersal and the migration of macroinvertebrates and fish communities [54, 109, 110].

In developed countries the rate of dam construction has been reducing and in some cases dams have been de-commissioned to restore the river ecosystem [111, 112]. In South East Asia (SE Asia), the construction of new dams is accelerating in order to facilitate those countries' economic growth [113], especially in Myanmar. Dudgeon [2] pointed out that the biodiversity of rivers in tropical Asia is already threatened by existing dams.

Myanmar, a developing country in SE Asia, has abundant hydropower potential [20]. The existing installed capacity of Myanmar ranges from 10 Megawatt (MW) to 1,000 Megawatt (MW) for medium to large-scale hydropower projects, and the target is to reach a total of 16,665 MW of installed capacity by 2030 [21]. In Myanmar, most of the dams are multipurpose, used for both generating electricity and irrigation. The effects of dams are evident when researching the physical, chemical, and hydrological gap-free time series data before and after barrier construction [114, 115]. Unfortunately, the availability of robust hydrological and meteorological datasets is relatively limited in Myanmar [19, 21]. Therefore, in Myanmar, studies on the impact of dams, in general, are limited.

The use of aquatic macroinvertebrate communities has received interest as a biological indicator to detect human's influence on river ecosystems, due to it being scientifically reliable, low-cost, and easy to apply by both scientists and non-scientists [48, 40, 37, 51]. We can collect macroinvertebrate samples on a large spatial scale relatively easily with a simple net [47, 37]. Macroinvertebrates play an essential role in freshwater ecosystems because they break down and transfer organic matter, which assists in the cycling of nutrients in stream ecosystems [116, 117, 118]. Also, macroinvertebrates are a primary food source of fishes and predators, meaning they are essential in the food web [54]. The level of impact and pressure on a river can be observed by identifying the taxa present in different sites, upstream and downstream, in potentially impacted sites [52].

There are a significant number of studies on the impact of dams on the diversity and abundance of macroinvertebrate communities [119, 36, 43, 120, 121, 122, 114, 55]. Most of the studies reported changes in the taxonomic composition of macroinvertebrates between sites upstream and downstream of a dam [43, 120]. These studies found changes in macroinvertebrate communities downstream of a dam, consisting of changes in either the abundance or diversity of taxa and species.

Bredenhand and Samways [121] found that the species richness of macroinvertebrate communities was 50% lower downstream of a dam compared to upstream of a dam. Indeed, the sensitive insects (Ephemeroptera, Plecoptera, Trichoptera, EPT) are abundant upstream of a dam while they were rare downstream of a dam. Likewise, Vaikasas et al. [122] stated that the abundance of macroinvertebrates was significantly reduced downstream of a hydropower dam compared to control sites (dam-unaffected), which was especially evident with more sensitive EPT taxa.

It is not only changes to the flow regime that are important. For example, the composition of benthic communities downstream of a barrier can be extensively impacted by the accumulation of organic and inorganic material in the reservoir of a dam. Similarly, a change in nutrient resources downstream of a dam can affect the taxa richness and abundance [43]. Thus, the long-term reduction in downstream movement of organic and inorganic loads can have an impact on availability of organic material as a food source for macroinvertebrates. In addition the dam and reservoir can act as barrier to drift or aerial colonisation by macroinvertebrates [123]. Therefore, the differences in species richness upstream compared to downstream of dams are not only due to the difference in flow regime, but also the change in nutrient availability due to the accumulation of sediment and blocking of migration [50].

In Myanmar, the use of aquatic macroinvertebrate communities in the assessment of human influences on aquatic ecosystems like rivers, streams, and lakes is lacking. Previous research has been conducted on the Ayeyarwady River (about 2,210 km long) in the central dry zone of Myanmar and the lower Thanlyin River (1,224 km long), 65 km from the Andaman sea. This initial study stated that macroinvertebrates cannot be used as an indicator to define healthy river ecosystems in large rivers in Myanmar, where there are high flow fluctuations and sediment loads which can create unsuitable substrates for macroinvertebrate communities [44]. However, they suggested that there were tributaries upstream of Mandalay, that more suitable for macroinvertebrate sampling [44] and that macroinvertebrates may be suitable for water quality assessment. A study on the Bago River (331 km long) in Myanmar also showed that macroinvertebrates can be collected in tributaries and therefore able to identify healthy river ecosystems [45].

Recently, the preliminary development of river health biomonitoring using macroinvertebrates has been reported [75]. Due to the inexistence of biomonitoring methods in Myanmar, the preliminary development method was based on the existing Asian indexing method using taxa information from undisturbed or least-impacted sites in the upstream reaches of the Myitnge and Chuangmagyi Rivers. The study by Ko et al. [75] shows that an indexing method using aquatic macroinvertebrate communities works well in estimating ecological river water quality, and the study recommends applying it in impacted sites (downstream) to access human influences. In the current study, we used this Myanmar-modified method to estimate ecological river water quality both upstream and downstream of dams, to see the impact of dams on river water quality.

Therefore, the objective of this research is to study the impact of two hydroelectric dams on aquatic assemblages in the Myitnge and Chaungmagyi Rivers in Myanmar.

4.2. Materials and Methods

4.2.1. Study area and sampling locations

We selected two hydropower dams on different rivers, namely Myitnge (MT), and Chaungmagyi (CM) Rivers; two main tributaries of the Ayeyarwady River. The Ayeyarwady River is about 2,210 km long, and 91% of its river basin (412,500 km^2) lies within Myanmar [21]. The Myitnge River is 528 km long which begins from the hills of eastern Hseni and through Shan state and Mandalay region. The Chaungmagyi River is 100 km long and flows from the Shan Plateau of Eastern part of Myanmar and through to the central part of the country. Both study rivers have 29,630 km^2 and 5,720 km^2 catchment area, respectively and end into the Ayeyarwady River near the Mandalay plain at the central dry zone of the country.

The first study dam is the Yeywa Dam-($21°40'32.42''$ N and $26°28'27.94''$ E), located in the east of Mandalay city on the Myitnge (MT) River. Its construction started in 2001 and was finished in 2010. Although the gross hydropower potential is 790 MW with four generators, currently, only approximately 25-30% of its capacity is being used [124].

4

The second study dam is Sae Daw Gyi multipurpose dam ($22°20'56.76''$ N and $96°19'21.13''$ E), located near Madaya city in the Mandalay region on Chaungmagyi (CM) River. The dam operation has been started to work in 1989. The priority of dam operation rule is irrigation water supply. And, two generators (2 x 12.5 MW) have been installed to generate hydroelectricity [125].

Sampling sites were selected which enabled good and safe accessibility and were suitable for macroinvertebrate sampling with two upstream sites (US-1 and US-2) and two downstream sites (DS-1 and DS-2) of both dams. The first upstream sites (MT-US-1 and CM-US-1) were approximately 253 km and 115 km upstream of the dams and 432 m a.s.l and 680 m a.s.l in the Myitnge and Chaungmagyi Rivers respectively. The second upstream sites (MT-US-2 and CM-US-2) were situated at 98.5 km and 115 km upstream of the dams with 259 m a.s.l and 680 m a.s.l respectively.

Sampling sites around 5.5 km and 6 km downstream of the dams (MT-DS-1 and CM-DS-1) (89.25 m a.s.l and 81.40m m a.s.l, respectively) were chosen. The second downstream sampling sites for the dams were selected at 40.5 km and 8 km from Yeywa dam and Sae Daw Gyi dam respectively (Figure.4.1). All sampling sites had cobble and sandy substrate.

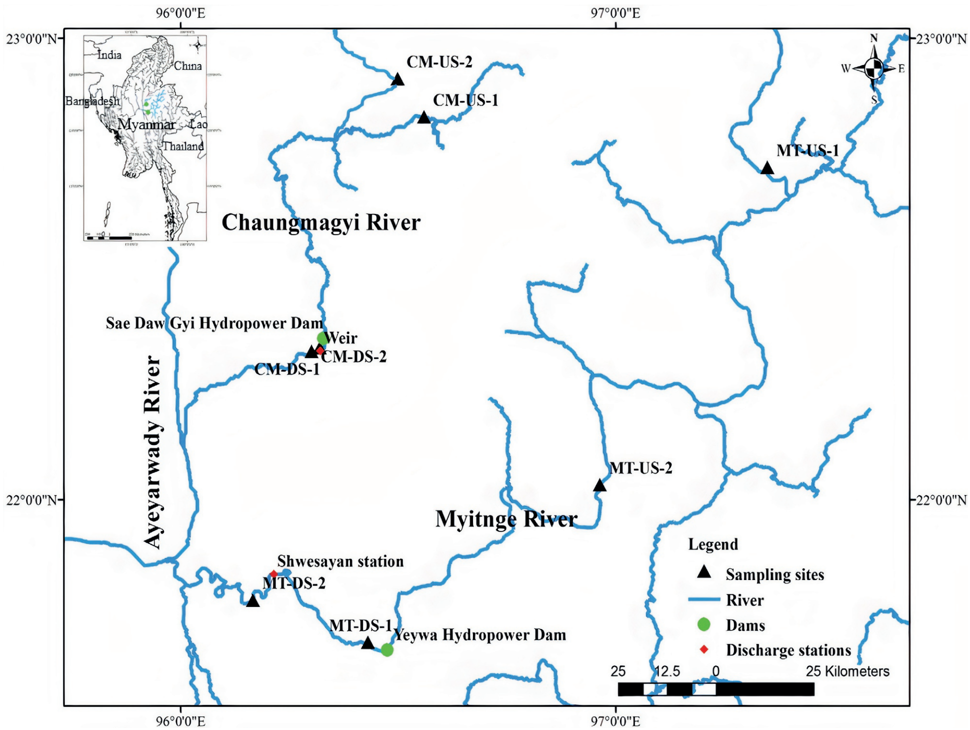


Figure 4.1: Locations of the sampling sites upstream and downstream of the two hydropower dams (US - upstream, DS –downstream) on Myitnge (MT) and Chuangmagyi (CM) Rivers

4

4.3. Description hydrological and biomonitoring analysis

4.3.1. Hydrological Analysis

We applied the Indicator of Hydrologic Alteration (IHA) version 7.1 [126] to analyse the changes in natural flow regimes from the pre-impact period to post-impact period based on a daily streamflow series.

RVA analysis using IHA software gives a series of Hydrologic Alteration (HA) factors with 33 parameters (Table.4.1) to show how natural flow regimes have been altered from the pre-impact period to the post-impact period. The change in frequency from pre- to a post-impact period of each parameter can be determined into three RVA category boundaries; Low, meaning HA is less or equal to 33% from median values, Middle is between 33% and 67%, and High HA includes all values greater than 67% [127]. We selected the non-parametric analysis (percentile values) for this study to calculate three different categories of values [127].

The following equation is used to calculate all RVA values for each of the 33 parameters;

$$\text{Hydrologic Alteration Factor} = \frac{\text{Observed Frequency -Expected Frequency}}{\text{Expected Frequency}} \quad (4.1)$$

where the expected frequency is the expected frequency in the post-impact period if it is the same flow pattern as pre-impact period, the observed frequency is the observed frequency in the post-impact period. Positive HA shows increased frequency values from pre- to post-impact period (with a maximum value of infinity), whereas negative HA shows decreased frequency values (with a minimum value of -1) [127].

We used daily flow data from 1981 to 2016 at Shwesayan discharge station (Figure 4.1), which was approximately 35.5 Km downstream of the MT-DS-1. We used this discharge data for the pre-impact period (1981-2001), transition period (2001-2010) and the post-impact period (2010-2016) for the Yeywa dam in the Myitnge River to quantify the changes in the frequency, duration, magnitude, and flow fluctuations due to the impact of the dam.

For Chaungmagyi River, we used historic daily flow data (1969-2016) recorded at the weir, which is four kilometers downstream of the Sae Daw Gyi dam. There is a large data gap, so we used ten years of daily discharge from 1969 to 1978 as pre-impact period and 21 years of daily discharge from 1996 to 2016 as a post-impact period without a transition period for analysis of the Sae Daw Gyi multipurpose dam.

4.3.2. Physico-chemical parameters

Spot samples of pH, turbidity, water temperature and electrical conductivity were collected at the time of macroinvertebrate sampling at each sampling site. We used a Simplex Health pH test strips (ranged 4.5-9.0), Ground Truth water clarity tubes, and Greisinger, GMH 3400 series meter to measure pH, turbidity [Nephelometric Turbidity Units, NTU], water temperature [°C] and electrical conductivity (EC) [μ S cm^{-1}].

4.3.3. Biological Sampling

At each site three macroinvertebrate samples were collected [128] each from a five-meter transect parallel to the riverbank. A sweep-net/kick sampling method was used by disturbing the substrate by kicking. We used Nylon net 500 μm mesh size to be sure the aquatic macroinvertebrates can be retained in the net as discussed by Buss et al. [37]. Each sample was preserved with 70% ethanol on-site for later laboratory identification. The three samples were treated as discrete sample.We did two sampling occasions with the same sampling regime in low flow conditions during November-December 2016 and February-March 2017.

4.3.4. Ecological water quality Index

We estimated the ecological river water quality at all sampling sites in both study rivers using Myanmar Aquatic Biomonitoring Assessment Index (MABA) method by Ko et al. [75] based on all collected taxa of three macroinvertebrates samples at each site. We calculated the ecological river water quality index using all collected and identified taxa in the laboratory with the following equation of MABA [75];

$$\text{Ecological Water Quality Index} = \frac{\sum(\text{Individual score of present taxa})}{\sum(\text{Total number of scoring taxa groups})} \quad (4.2)$$

The score of individual taxa ranges from 1 to 10 in the MABA method. The MABA method classifies three different ecological river water quality level based on the calculated index; between 1 to 2.9 means poor water quality, between 3.0 to 6.9 means fair water quality, and between 7.0 to 10.0 means good water quality [75].

4.3.5. Statistical Analysis

For statistical analysis, we used the statistical program PRIMER v6 [95]. Taxa matrix was constructed using a square root transformation. Then, the taxa resemblance matrix was computed using Bray-Curtis similarity using 999 random permutations as a function of sampling sites (upstream and downstream) and sampling season. We used dimensionless non-metric multidimensional scaling (MDS) plot to check the difference in macroinvertebrate composition among sampling sites and time. MDS plots display the rank order distance correlation among the resemblance matrix produced by Bray-Curtis similarity [96]. MDS plots show stress value which ranges from 0 to 1.0. Stress value with smaller than 0.05 means a near-perfect representation of ordination space, meaning there is no overlap between sample variables [96].

We used a one-way analysis of similarity (ANOSIM) to test the null hypothesis of no community differences between sites upstream and downstream of the dams and between sampling time. A Bray-Curtis similarity resemblance matrix was calculated using 999 permutations [95].

To check the percentage of similarity/dissimilarity of communities, we used similarity analysis (SIMPER) routine of PRIMER v6 [95]. SIMPER provides the percentage of the contribution of individual taxa which support the percentage of (dis)similarity of communities between upstream and downstream, and between different sampling periods. We used the feeding traits of the macroinvertebrates as indicators in SIMPER to examine the contribution of each feeding behavior. We determined the feeding traits for each taxon using the functional feeding groups in [2, 129].

All analyses were undertaken using two methods, firstly using the lowest taxonomic level of identification (morphospecies) for all collected taxa and secondly the only Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO) taxa.

For taxa identification we used the identification keys from the Mekong River and tributaries [56] where climate and watershed characteristics are similar to Myanmar's rivers. We identified collected taxa into family and morphospecies level of taxonomy in this study.

Table 4.1: Summary of IHA parameters [130]

IHA Parameter (Group)	Hydrologic Parameters	Ecosystem influences
1.The magnitude of Monthly water conditions	Mean or median value for each calendar month	1. Availability of habitat- -for aquatic organisms 2. Availability of soil moisture for plants 3. Availability of water 4. Reliability of water supplies for wildlife 5. Effects of water temperature- -and dissolved oxygen
2.Magnitude and duration of- -annual extreme water conditions	Annual minima, 1-days mean Annual minima, 3-days means Annual minima, 7-days means Annual minima, 30-days means Annual minima, 90-days means Annual maxima, 1-days mean Annual maxima, 3-days means Annual maxima, 7-days means Annual maxima, 30-days means Annual maxima, 90-days means Number of zero-flow days Baseflow index: (7-day minimum flow/mean flow for a year)	1. Balance of competitive- -and stress-tolerant organisms 2. Creation of sites for plant colonisation 3. Structure of river channel morphology- -and physical habitat conditions 4. Soil moisture stress in plants 5. Dehydration in wildlife 6. Duration of stressful conditions 7. Distribution of plant communities
3. The timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	1. Predictability and avoidability- -of stress for organisms 2. Spawning cues for migratory fish
4. Frequency and duration of high and low pulses	Number of high pulses within each water year Number of low pulses within each water year Mean or median duration of high pulses (days) The mean or median duration of low pulses (days)	1. Frequency and magnitude of- -soil moisture stress for plants 2. Availability of floodplain- -habitat for aquatic organisms 3. Effects of bedload transport- -and channel sediment distribution,- -and duration of substrate disturbance
5. Rate and frequency of water condition changes	Rise rates: (Mean or median of all positive differences between consecutive daily values) Fall rates: (Mean or median of all negative differences between consecutive daily values) Number of hydrologic reversals	1. Drought stress on plants 2. Desiccation stress on low mobility- -stream edge organisms
	Total of 33 parameters	

4

4.4. Results

4.4.1. Hydrological Analysis

The results of IHA using historic daily discharge data before and after the construction of the dams are shown in Figure.4.2. The flow regime changed after the construction of the barriers in both rivers. However, in the Myitnge River the post-impact flows were reduced from June to November and increased in January to May but the seasonality of flow was maintained (Figure 4.2.a). In the Chaungmagyi River the seasonal pattern was lost and magnitude of flows was greatly reduced throughout the year (Figure 4.2.b).

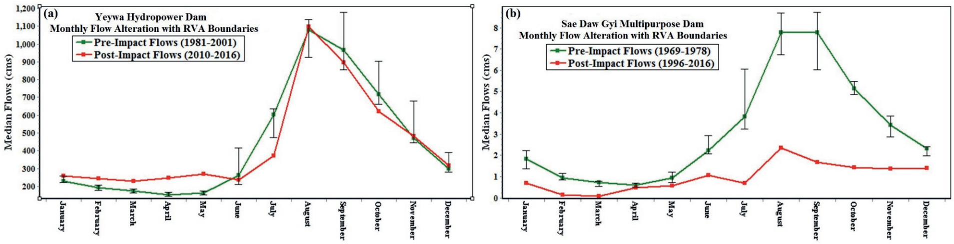


Figure 4.2: Monthly flow alteration of pre- and post-impact periods on the Myitnge River downstream of Yeywa dam (a), and on the Chaungmagyi River downstream of Sae Daw Gyi dam (b).

Indeed, the RVA analysis for the Myitnge River showed an increase in the magnitude of monthly median flows in high RVA category from pre-to post impact period in the period of January to May within the high RVA category (Figure 4.2.a). The highest flow alterations occur in April and May with 64% and 67% increase in magnitude during post impact period. The alteration in the magnitude of monthly median flows in other months were not significant, except in July, which showed 38% decrease in magnitude in post impact period (Figure 4.2.a).

In Myitnge River, there was an increase in the frequency of values in high RVA range for both minimum (the annual 1-day, 3-day, 7-day, 30-day, and 90-day) and maximum flows (the annual 1-day, 3-day, and 7-day) but the frequency of values for the annual 30-day and 90-day maximum flows decreased with middle RVA range (Figure 4.3.a).

On the other hand, in the Chaungmagyi River, the magnitude of monthly median flows and the duration and frequencies of minimum and maximum flow

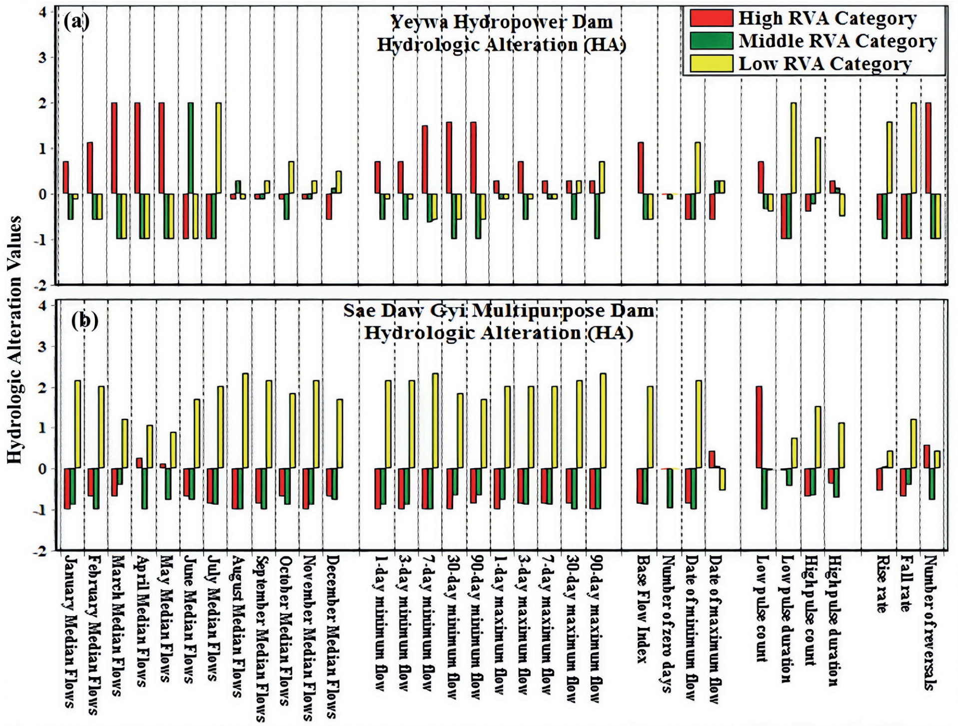


Figure 4.3: The Results of Hydrologic Alteration (HA) with three different RVA categories in Myitnge (Yeywa) (a) and Chaungmagyi (Sae Daw Gyi) (b) Rivers; positive HA values indicate a higher frequency, magnitude, and duration of values in the given range of RVA (Low, Middle, High)

(the annual 1-day, 3-day, 7-day, 30-day, and 90-day) decreased in the whole year after the construction of Sae Daw Gyi multipurpose Dam with high and medium RVA being close to the theoretical minimum value of -1 (Figure 4.3.b).

The base flow index has gone up 47% in Myitnge River and down in Chaungmagyi River with almost 100% (close to the theoretical minimum value of -1) during post-impact period. The number of zero flow days in Myitnge River was negligible in both pre- and post-impact period whereas the number of Julian dates of zero flow has increase from 0 to 49 from pre-to post-impact period in the Chaungmagyi River with RVA categories being close to -1.

The Julian dates of minimum and maximum flows were earlier in Myitnge River during post-impact period with 16% and 5% differences, respectively. In Chaungmagyi River, the Julian dates of minimum flows were 75% earlier from pre-to post-impact period with high RVA categories being close to -1, but the Julian dates of maximum flows were 10% late from pre-to-post-impact period.

Both the number and duration of low and high pulses have increased in the post-impact period in the Myitnge and Chaungmagyi Rivers, except that the duration of the high pulse has decreased with high RVA in the Myitnge River.

The flow rise rate has decreased by 38% and the flow fall rate has increased by 233% from pre-impact to the post-impact period s in the Myitnge River where water has been stored and released for the generation of hydroelectric power. On the other hand, both rise and fall rate of the flow regime have gone down by 97% in the post-impact period in the Chaungmagyi River where irrigation water supply was a priority for the dam operation.

Lastly, the number of reversals has significantly increased by more than 120% in Myitnge River during post-impact period whereas the number of reversals has gone up by only 2% in the Chaungmgagyi River after the construction of Sae Daw Gyi dam.

4.4.2. Physico-chemical Water Quality Parameters

We collected four physico-chemical water quality parameters to see the water quality conditions at the time of sampling in all sampling sites (Table 4.2). Turbidity of the water in the Myitnge River ranged from 4.0 to 7.0 [NTU]. In contrast, the turbidity in the Chaungmagyi River ranged from 4 to 498 [NTU] with the highest values of 307.8 and 498 [NTU] at the upstream site (CM-US-I-1 and CM-US-I-2).

The EC values differ little between upstream and downstream of the Yeywa Dam. The EC values were similar upstream and downstream of the Yeywa Dam (ranging from 289–390 μ S cm^{-1} in November-December 2016 and 323–427 μ S cm^{-1} in February-March 2017) although upstream values were generally lower than downstream. In the Chaungmagyi River the EC ranged from 72–199 μ S cm^{-1} in November-December 2016 and 65–146 μ S cm^{-1} in February-March 2017. CM-US-I was less than 72 μ S cm^{-1} on each sampling occasion.

The pH values at all sampling sites were above 6 with the exception of the site upstream of the Sae Daw Gyi dam (CM-US-I-1) with a pH of 5.5 in November-December 2016.

Temperature in the upper tributary of the Myitnge River (MT-US-I) was near 22 °C on both sampling occasions but in the lower catchment upstream and downstream of the dam the water temperature was near 29 °C in November-December 2016 and near 23 °C in February March 2017, although the most downstream site (MT-DS-II-2) was some 5 °C warmer. In the Chaungmagyi River the November-December 2016 temperature in the upstream sites ranged from 17–24 °C and at downstream sites ranged from 27–28 °C. In February-March 2017 the upstream site was 21.7 °C and downstream sites were near 24 °C.

Table 4.2: Collected abundance and taxa richness of all macroinvertebrates taxa and EPTO with four Physico-chemical water quality parameters at each sampling site in Myitnge and Chaungmagyi Rivers for two sampling periods

River	Time	Name of sites	Abundance		Total taxa		pH	Turbidity [NTU]	EC [µS/cm]	Temp [°C]
			All Taxa	EPTO	All Taxa	EPTO				
Myintnge River	November-December 2016	MT-US-I-1	107	101	15	11	7.52	4.2	289	22.6
		MT-US-I-2	70	67	7	6	6.5	6.6	354	29.3
		MT-DS-I-1	67	55	9	4	7.76	4.4	329	29.5
		MT-DS-I-2	432	320	12	6	7.67	4	390	28.5
	February-March 2017	MT-US-II-1	766	702	25	18	7.25	4.3	327	22
		MT-US-II-2	349	335	20	15	6.75	5.9	427	22.8
		MT-DS-II-1	171	24	14	5	6.75	4.3	391	22.9
		MT-DS-II-2	781	728	18	11	6.75	4.3	388	27.3
Chaungmagyi River	November-December 2016	CM-US-I-1	228	227	20	19	5.5	307.8	71.8	24
		CM-US-I-2	0	0	0	0	7.5	498	199	17.4
		CM-DS-I-1	53	52	10	9	6.75	4	157.9	27.3
		CM-DS-I-2	125	124	14	13	6.5	4	143.1	28
	February-March 2017	CM-US-II-1	431	423	30	23	7.64	108	65.1	21.7
		CM-DS-II-1	33	31	7	6	7.61	26.3	146.5	24.6
		CM-DS-II-2	487	457	21	17	7.62	18	144.9	24.1

4

4.4.3. Macroinvertebrate Analyses

We found a total of 52 and 49 aquatic invertebrate taxa (morpho-species) from the Myitnge and the Chaungmagyi Rivers, respectively (Table.4.3) with 27 EPTO taxa in the Myitnge River and 35 in the Chaungmagyi River. Total number of families was 37 and 27 in the Myitnge and Chaungmagyi Rivers, respectively. Insects dominated the species richness at all sites with 50 taxa in the Chaungmagyi River and 45 morpho-species in the Myintnge River. There were six mollusc taxa and 1 crustacean in the Myitnge River, but these groups were not found in the Chaungmagyi River.

Table 4.2 shows the number of total abundance and taxa of all taxa and sensitive taxa (Ephemeroptera, Plecoptera, Trichoptera, Odonata: EPTO) at all sampling sites including physico-chemical water quality parameter in both rivers. The second upstream site of Chaungmagyi River (CM-US-I-2) showed zero macroinvertebrates in the November-December 2016 sample.

We recorded the highest species richness of all taxa and EPTO from upstream of the Sae Daw Gyi dam (CM-US-I-1 & CM-US-II-1) during both sampling occasions (20 & 30 all morpho-species, and 19 & 23 EPTO taxa). We found the highest abundance of both all and EPTO taxa (432 & 781 individuals all taxa, and 320 & 728 individuals EPTO) from the downstream sites of Myitnge River (MT-DS-I-2 & MT-DS-II-2). We found the lowest abundance of all taxa and EPTO in sampling sites just downstream the hydropower dams; 53 and 33 individuals of all taxa in site CM-DS-I-1 and CM-DS-II-1, and 55 and 24 individuals of EPTO in site MT-DS-I-1 and MT-DS-II-1 (Table 4.2).

The abundance of macroinvertebrates ranged from 31 to 457 individuals per sample in the Chaungmagyi River and 24 to 728 in the Myitnge River, respectively. Mean taxonomic richness per sample was 11.5 and 8.75 taxa at upstream sites and 8.4 and 6.4 taxa at downstream sites on the Chaungmagyi and Myitgne Rivers, respectively. The mean abundances per sample at upstream sites and the downstream sites were 109.8 and 107.7 individuals at upstream sites and 69.7 and 145.1 at downstream sites on the Chaungmagyi and Myitgne Rivers, respectively.

Table 4.3: Collected total abundance and their score of The Myanmar Aquatic Biomonitoring Assessment Index (MABA) by [75].

			MABA method	Rivers	
Order	**Family**	**Species**	**Score**	**Myitnge**	**Chaungmagyi**
Ephemeroptera	Baetidae	*Platybaetis* sp 1	5	72	266
		Baetis sp 1	5	822	325
		Procloeon sp 1	5	6	0
	Prosopistomatidae	*Prosopistoma* sp 1	4	4	0
	Ephemeridae	*Ephemera* sp 1	6	3	0
	Heptagenidae	*Asionurus* sp 1	10	952	172
		Asionurus sp 2	10	0	89
	Caenidae	*Caenis* sp 1	4	112	37
	Neoephemeridae	*Potamanthellus edmundsi*	4	0	0
	Leptophlebiidae	*Chloroterpes* sp 1	10	25	95
		Chloroterpes sp 2	10	2	0
	Potamanthidae	*Potamanthindus* sp 1	5	0	1
	Polymitarcyidae	*Ephoron*	6	0	31
	Isonychiidae	*Isonychia*	8	0	1
	Ephemerellidae	*Torleya*	10	0	4
		Cincticostella gosei sp 1	10	0	15
Plecoptera	Perlidae	*Neoperla* sp 1	10	12	21
		Neoperla sp 2	10	5	9
		Neoperla sp 3	10	0	1
		Etrocorema sp 1	10	2	5
		Etrocorema sp 2	10	9	6
		Etrocorema sp 3	10	2	0
		Togoperla sp 1	10	0	12
		Togoperla sp 2	10	0	1
		Togoperla sp 3	10	0	23
Trichoptera	Hydropsychidae	*Potamyia* sp1	5	107	42
		Oestropsyche sp 1	5	1	0
		Macrostemum sp 1	5	76	41
		Amphipsyche sp 1	5	6	4
		Parpsyche sp 1	5	0	1
		Trichomacronema sp 1	5	0	46
	Helicopsychidae	*Helicopsyche* sp 1	10	1	0
	Odontoceridae	*Marilia* sp 1	10	22	9
	Dipseudopsidae	*Pseudoneureclipsis* sp 1	10	4	12
	Molannidae	*Molanna* sp 1	10	7	0
	Leptoceridae	*Triplectides* sp 1	10	1	0
		Oecetis sp 1	10	0	2
		Ecnomus sp 1	10	0	4
	Stenopsychidae	*Stenopsyche* sp 1	10	0	5
		Stenopsyche sp 2	10	0	2
	Hydroptilidae	*Hydroptila*	10	0	6
Odonata	Gomphidae	Gomphidae sp 1	6	65	8
	Cordulidae	Corduliidae sp 1	6	1	1
	Megapodagrionidae	Megapodagrionidae sp 1	6	3	2
	Protoneuridae	Protoneuridae sp 1	6	1	0
	Euphaeidae	Euphaeidae sp 1	6	0	1
Megaloptera	Corydalidae	Corydalidae	10	6	8
Diptera	Ephydridae	Ephydridae	3	6	0
	Chironomidae	Orthocladinae sp 1	3	77	3
		Tanypodinae sp 1	3	1	0
		Chironominae (L)	3	2	24
		Chironomidae (P)	3	0	2
	Ceratopogonidae	Ceratopogonidae sp 1	3	3	0
	Tipulidae (L)	Tipulidae (L)	3	75	1
	Tipulidae (P)	Tipulidae (P)	3	17	0
	Tipulidae-Limoninae	Tipulidae-Limoninae sp 1	3	0	4
	Tipulidae	*Antocha*	3	0	1
	Diptera (P)	Diptera (P)	3	10	0
	Athericidae	Athericidae sp 1	8	0	1
	Noteridae	Noteridae sp 1	7	1	0
	Gyrinidae	Gyrinidae sp 1	7	1	0
	Elmidae (L)	Elmidae (L) sp 1	8	0	1
	Elmidae (L)	Elmidae (L) sp 2	8	0	0
	Elmidae (L)	Elmidae (L) sp 3	8	32	1
	Elmidae (L)	Elimidae (A)	8	1	0
	Psephenidae	Psephenidae sp 1	7	1	0
Lepidoptera	Crambidae	*Eoephyla*	5	2	1
Hemiptera	Naucoridae	Naucoridae sp 1	10	2	3
	Aphelocheirus	*Aphelocheirus* sp 1	10	13	1
	Micronectidae	Micronectidae sp 1	1	2	5
Veneroida	Corbiculidae	*Corbicula*	3	53	0
Mesogastropoda	Thiaridae	Thiaridae sp 1	1	64	0
	Thiaridae-Melanoides	*Melanoides*	1	19	0
	Bithyniidae	Bithyniidae sp	1	17	0
	Viviparidae	Viviparidae sp 1	1	2	0
Basematophora	Planorbidae	Planorbidae sp 1	1	1	0
Decapoda	Palaemonidae	*Macrobrachium*	8	12	0
		Total abundance		2743	1356
		Number of sites		4	4
		Nymber of occasion		2	2

Note: sp means species, P is pupae, L is larval, A is adult.

4.4.4. Multivariate Analyses

All statistical analyses were carried out using all taxa and only EPTO taxa to find the difference in communities between sampling sites and time on both study rivers.

a) Myitnge River - (Yeywa Hydropower Dam) – Morphospecies-level of all aquatic macroinvertebrates taxa

All taxa resemblance matrices were calculated using Bray-Curtis similarity as a function of sampling sites (upstream and downstream) and sampling periods (November-December 2016 and February-March 2017). The calculated MDS stress values for both functions of sampling sites and time were high at 0.22 (Figure 4.4.a and b). The MDS plot showed that there was no overlap in multidimensional space by the spread of points between upstream and downstream sites, and the ANOSIM analyses indicated significant differences in community structure between sampling sites. The p-value was smaller than 0.001 according to the Global R test with 1000 permutations. The separation between the two sampling periods was not significant (p=0.9).

SIMPER analysis between the upstream and downstream sites showed six taxa accounted for 91% of the community upstream of the dam and five taxa accounted for 91% downstream of the dam (Table 4.4). Of these taxa, only two were common to the two zones, *Platybaetis* sp1 (Average abundance of 1.84 upstream and 0.44 downstream) and *Asionurus* sp1 (Average abundance of 0.81 upstream and 6.29 downstream) yielding an 88.57% dissimilarity between upstream and downstream sites.

Upstream of the dam there were three functional feeding groups represented, namely collector-gatherers, filter feeders, and predators. Collector-gatherers which feed mainly on detritus and fine particulate organic material included the two baetid mayflies *Baetis* and *Platybaetis*. The filter feeders which also feed on suspended detritus included the hydropsychid caddis fly *Potamyia* (coarse to fine particulate organic material) and the heptageniid mayfly *Asionurus* which is a burrower feeding on fine organic material. The predators were the dragonfly Family Gomphidae and the true bug (Hemiptera) *Aphelocheirus*. Downstream the same functional feeding groups were represented but usually by different taxa. The collector–gatherers, were the mayfly *Baetis* and the caenid mayfly *Caenis*. Filter feeders included the burrowing mayfly *Asionurus* which was most abundant and the bivalve mollusc *Corbiculina*. The predator was the Odontocerid caddisfly *Marilia*.

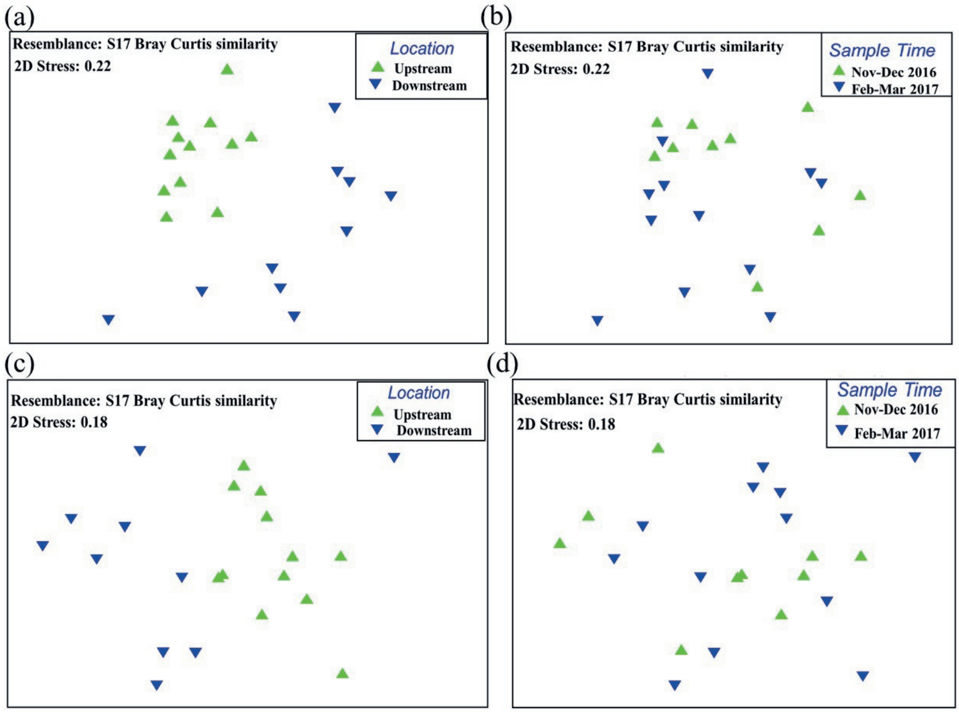


Figure 4.4: Non-metric Multidimensional Scaling (MDS) plots for comparison of sampling sites (upstream and downstream) and sampling period (Nov-Dec 2016 and Feb-Mar 2017) in Myitnge River, (a): the comparison of all taxa communities between sampling sites, (b): the comparison of all taxa communities between sampling periods, (c): the comparison of EPTO taxa communities between sampling sites, (d): the comparison of EPTO taxa communities between sampling periods.

Table 4.4: The percentage of contribution of all taxa with their average abundance between sampling locations (upstream and downstream)of the Yewar hydropower dam on Myitnge River (88.57% dissimilarity in communities between upstream and downstream sites)

Taxon	Upstream		Downstream	
	Average. Abundance	**% Contribution**	**Average Abundance**	**% Contribution**
Baetis sp1	5.94	43.21	0	0
Potamyia sp1	2.15	17.89	0	0
Platybaetis sp1	1.84	15.87	0.44	6.78
Gomphidae sp1	1.72	9.27	0	0
Asionurus sp1	0.81	2.86	6.29	72.51
Aphelocheirus sp1	0.55	2.04	0	0
Caenis sp1	0	0	1.75	5.09
Corbicula	0	0	1.26	4.77
Marilia	0	0	0.34	2.51

Table 4.5: The percentage of contribution of EPTO taxa with their average abundance between sampling locations (upstream and downstream) of the Yewar dam on the Myitnge river (78.19% dissimilarity in EPTO communities between upstream and downstream sites)

Taxon	Upstream		Downstream	
	Average. Abundance	% Contribution	Average. Abundance	% Contribution
Baetis sp1	2.2	39.35	0	0
Potamyia sp1	1.21	18.51	0	0
Platybaetis sp1	1.09	14.85	0.42	10.61
Gomphidae sp1	1.05	10.73	0	0
Asionurus sp1	0.62	4.23	2.06	71.25
Neoperla sp1	0.47	3.12	0	0
Caenis sp1	0	0	0.72	4.35
Marilia	0	0	0.32	4.24

4

b) Myitnge River (Yeywa Hydropower Dam) – Morphospecies-level of Ephemeroptera, Plecoptera, Trichoptera, and Odonata, (EPTO)

There is a distinct separation of the EPTO communities between upstream and downstream of the dams demonstrated by MDS with the stress level of 0.18 and no overlap in ordination space (Figure 4.4.c). ANOSIM Global R test showed the EPTO communities were significantly different between upstream and downstream at the P-value of 0.001 with 1000 permutations. However, the sample time (November-December 2016 and February-March 2017) for the upstream and downstream the dam sites showed overlap in multidimensional space, indicating there was no difference between the sampling dates (Figure 4.4.d) with P-value of 0.9.

SIMPER analysis based on the sampling location (Table 4.5) showed six species accounted for 90% of the community upstream of the dam and four taxa accounted for 90% downstream of the dam. *Platybaetis* sp1 (average abundance of 1.09 upstream and 0.42 downstream) and *Asionurus* sp1 (average abundance of 0.62 upstream and 2.06 downstream) accounted for a percentage dissimilarity of 78.19 between upstream and downstream sites (Table 4.5).

The functional feeding groups were similar upstream to those identified in the total taxa analysis. Downstream the EPTO taxa were the same as in the total taxa analysis.

c) Chaungmagyi River (Sae Daw Gyi Multipurpose Dam) – Morphospecies-level of all aquatic macroinvertebrates taxa

The MDS plot demonstrated that there was a distinct separation of the macroinvertebrate communities upstream and downstream the dam. The stress level was 0.16 indicating the separation is a reasonable representation of differences between the two communities (Figure 4.5.a). ANOSIM P-value by the Global R test showed significant differences between upstream and downstream (p=0.015). The sample time (season) for the upstream and downstream the dam sites showed no overlap in multidimensional space, indicating there was a difference between the sampling dates (stress = 0.16) (Figure 4.5.b). ANOSIM P-value by the Global R test showed that there was a difference between sampling dates (p=0.008).

SIMPER analysis indicated that six taxa accounted for over 90% of the community upstream of the dam, and eight taxa accounted for over 90% downstream of the dam. Three mayflies were common in upstream and downstream sites, *Platybaetis* sp1 (Average abundance of 1.68 upstream and 1.34 downstream), *Baetis* sp1 (Average abundance of 1.77 upstream and 1.2 downstream) and *Asionurus* sp1 (Average abundance of 0.75 upstream and 1.3 downstream) with 73% dissimilarity between zones (Table 4.6).

SIMPER analysis between the different sampling dates showed five taxa accounted for over 90% of the community in November–December 2016 and 13 taxa accounted for over 90% of the community in the February–March 2017. Of these taxa four mayfly taxa were common to the two sampling periods, *Platybaetis* sp1 (Average abundance of 1.67 in 2016 and 1.16 in 2017), *Baetis* sp1 (Average abundance of 1.19 in 2016 and 2.12 in 2017), *Asionurus* sp1 (Average abundance of 0.79 in 2016 and 1.53 in 2017), and *Caenis* sp1 (Average abundance of 0.38 in 2016 and 0.73 in 2017) with 71.06% dissimilarity between dates (Table 4.7).

Three functional feeding groups were collected upstream of the Sae Daw Gyi multipurpose dam in the Chaungmagyi River. Collector-gatherers included the two baetidae mayflies *Baetis* and *Platybaetis*. The filter feeders included the hydropsychid caddisfly *Potamyia* and the heptageniid mayfly *Asionurus*. The predators were the gomphid dragonfly, and the perlid stonefly *Neoperla*.

Only two functional feeding groups were found downstream of the dam. The baetid mayflies *Baetis* and *Platybaetis*, the caenid mayfly *Caenis* and the leptophlebiid mayfly *Chloroterpes* were dominant for collector-gatherers. Filter feeders included two species of the burrowing mayfly *Asionurus* and the hydropsychid caddisflies *Macrostemum* and *Amphipsyche*.

Samples in November–December 2016 had three functional feeding groups represented. Collector-gatherers included the two baetidae mayflies *Baetis* and *Platybaetis*, the caenid mayfly *Caenis* and the leptophlebiid *Chloroterpes*. Filter feeders included the same families with sampling sites comparison (*Potamyia* and *Asionurus*). The gomphid dragonfly was the predator.

Samples in February–March 2017 had four functional feeding groups represented. The collector–gatherers, were same as in the November-December 2016 samples. Filter feeders included two species of the burrowing mayfly *Asionurus*, the polymitarcid mayfly *Ephoron*, and the caddisfly *Pseudoneuroclipsis* The predators were the stoneflies *Neoperla* and two species of *Togoperla*. The mayfly, *Cincticostella gosei* is a shredder feeding on large particulate organic material such as leaves.

The MDS plot demonstrated that there was a distinct separation of the macroinvertebrate communities upstream and downstream the dam. The stress level was 0.16 indicating the separation is a reasonable representation of differences between the two communities (Figure 4.5.a). P-value by Global R test also showed significant differences between upstream and downstream ($p=0.015$). The sample time (season) for the upstream and downstream the dam sites showed no overlap in multidimensional space, indicating there was a difference between the sampling dates (stress = 0.16) (Figure 4.5.b). P-value by Global R test gave the same story with the outcome of site comparison that there was a separation between communities upstream and downstream the dam in different sampling time ($p=0.008$).

According to the result of SIMPER analysis, six taxa accounted for over 90% of the community upstream of the dam, and eight taxa accounted for over 90% downstream of the dam. Three mayflies were common in upstream and downstream sites, *Platybaetis* sp1 (Average abundance of 1.68 upstream and

1.34 downstream), *Baetis* sp1 (Average abundance of 1.77 upstream and 1.2 downstream) and *Asionurus* sp1 (Average abundance of 0.75 upstream and 1.3 downstream) with 73% dissimilarity between zones (Table 4.6).

Then, SIMPER analysis between the different sampling dates showed five taxa accounted for over 90% of the community in November–December 2016 sampling and 13 taxa accounted for over 90% if the community in the February–March 2017 sampling. Of these taxa four mayfly taxa were common to the two sampling periods, *Platybaetis* sp1 (Average abundance of 1.67 in 2016 and 1.16 in 2017), *Baetis* sp1 (Average abundance of 1.19 in 2016 and 2.12 in 2017), *Asionurus* sp1 (Average abundance of 0.79 in 2016 and 1.53 in 2017), and *Caenis* sp1 (average abundance of 0.38 in 2016 and 0.73 in 2017) with 71.06% dissimilarity between dates. This result means the communities were different at different sampling times (Table 4.7).

We collected three functional feeding groups, collector-gatherers, filter feeders, and predators upstream of Sae Daw Gyi multipurpose dam in Chaungmagyi River. Collector-gatherers included the two baetidae mayflies *Baetis* and *Platybaetis*. The filter feeders included the hydropsychid caddisfly *Potamyia* (coarse to fine particulate organic material) and the heptageniid mayfly *Asionurus*. The predators were the dragonfly in the Gomphidae, and the perlid stoneflies *Neoperla*.

We found only two functional feeding groups downstream of the dam, collector-gatherers and filter feeders. The baetid mayflies *Baetis* and *Platybaetis*, the caenid mayfly *Caenis* and the leptophlebiid mayfly *Chloroterpes* were dominant for collector-gatherers. Filter feeders included two species of the burrowing mayfly *Asionurus* and the hydropsychid caddisflies *Macrostemum* and *Amphipsyche*.

Samples in November–December 2016 had three functional feeding groups represented, namely collector-gatherers, filter feeders, and predators. Collector-gatherers included the two baetidae mayflies *Baetis* and *Platybaetis*, the caenid mayfly *Caenis* and the leptophlebiid *Chloroterpes*. Filter feeders included the same families with sampling sites comparison (*Potamyia* and *Asionurus*). The Gomphidae sp1 was the predator.

Samples in February–March 2017 had four functional feeding groups represented, the collector–gatherers, filter feeders, predators and shredders. The collector–gatherers, were the baetid mayflies *Baetis* and *Platybaetis*, the caenid mayfly *Caenis* and the leptophlebiid mayfly *Chloroterpes*. Filter feeders included two species of the burrowing mayfly *Asionurus*, the polymitarcid mayfly *Ephoron*, and the caddisfly *Pseudoneuroclipsis* The predators were the stoneflies *Neoperla* and two species of *Togoperla* while *Cincticostella gosei* is a shredder feeding on large particulate organic material such as leaves.

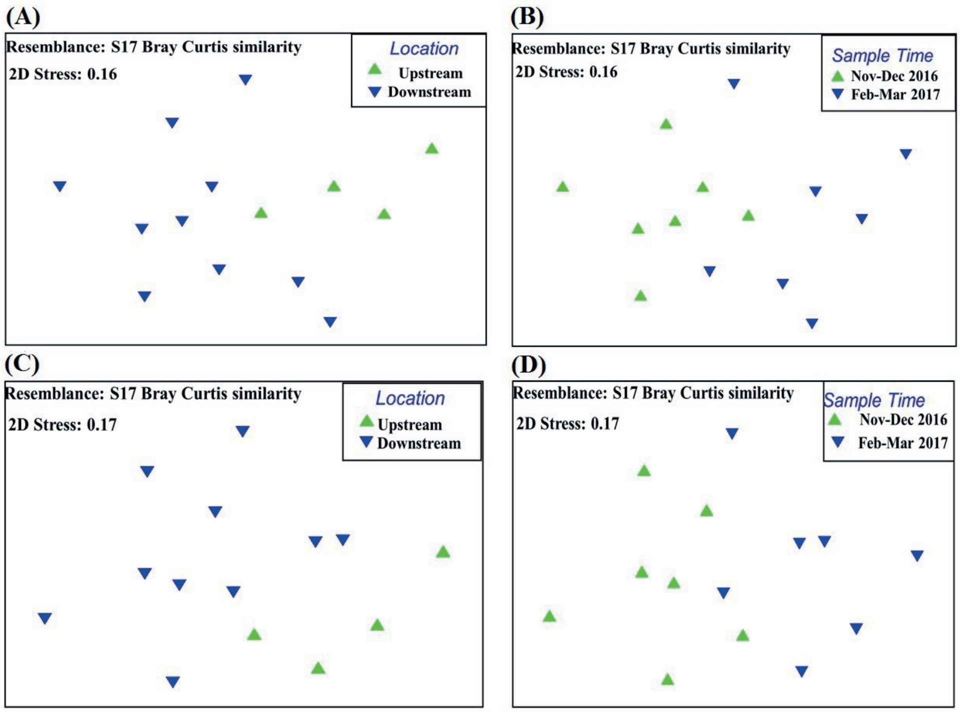


Figure 4.5: Non-metric Multidimensional Scaling (MDS) plots for comparison of sampling sites (upstream and downstream) and sampling period (Nov-Dec 2016 and Feb-Mar 2017) in Chaungmagyi River, (a): the comparison of all taxa communities between sampling sites, (b): the comparison of all taxa communities between sampling periods, (c): the comparison of EPTO taxa communities between sampling sites, (d): the comparison of EPTO taxa communities between sampling periods.

Table 4.6: The percentage of contribution of all taxa with their average abundance between sampling locations (upstream and downstream) of the Sae Daw Gyi multipurpose dam on Chaungmagyi River (73% dissimilarity in communities between upstream and downstream sites)

Taxon	Upstream		Downstream	
	Average. Abundance	**% Contribution**	**Average Abundance**	**% Contribution**
Baetis sp1	1.77	29.53	1.2	12.73
Neoperla	0.75	6.44	0	0
Platybaetis sp1	1.68	25.72	1.34	29.69
Potamyia sp 1	1.19	19.12	0	0
Asionurus sp1	0.75	5.35	1.3	16.22
Gomphidae sp1	0.75	5.95	0	0
Caenis sp1	0	0	0.89	9.54
Asionurus sp2	0	0	1	9.53
Macrostemum sp1	0	0	0.54	3.36
Amphipsyche sp1	0	0	0.33	2.22
Chloroterpes sp1	0	0	1	8.14

Table 4.7: The percentage of contribution of all taxa with their average abundance between sampling periods (November-December 2016 and February-March 2017) of the Sae Daw Gyi multipurpose dam on Chaungmagyi River (71.06% dissimilarity in communities between sampling periods)

Taxon	November-December 2016		February-March 2017	
	Average. Abundance	**% Contribution**	**Average Abundance**	**% Contribution**
Platybaetis sp1	1.67	42.25	1.16	6.73
Baetis sp1	1.19	22.99	2.12	19.66
Asionurus sp1	0.79	11.02	1.53	10.2
Caenis sp1	0.38	3.06	0.73	2.9
Chloroterpes sp1	0	0	1.13	6.03
Gomphidae sp1	0.45	2.9	0	0
Cincticostella gosei	0	0	0.76	4.34
Pseudoneureclipsis sp1	0	0	0.71	3.43
Neoperla sp1	0	0	1.05	11.62
Ephoron	0	0	0.76	3.01
Asionurus sp2	0	0	1.4	15.71
Togoperla sp3	0	0	0.68	2.46
Togoperla sp1	0	0	0.59	2.41
Chironominae (L)	0	0	0.67	2.46

d) Chaungmagyi River (Sae Daw Gyi MultipurposeDam) – Morphospecies-level of Ephemeroptera, Plecoptera, Trichoptera, and Odonata, (EPTO)

MDS plot showed there was a distinct separation of the macroinvertebrate communities upstream and downstream the dam using only the EPTO taxa. The stress level was high at 0.17, and there was no overlap in ordination space (Figure 4.5.c). The Global R-value for the site comparison indicated that there was a significant difference ($p = 0.012$) between the communities upstream and downstream of the dam.

The sample time (season) for upstream and downstream the dam sites showed little overlap in multidimensional space (Figure 4.5.d) but generally indicated there was a difference between the sampling dates, which was confirmed with the Global R with $p = 0.012$.

SIMPER analysis indicated upstream of the Sae Daw Gyi dam six taxa contributed 90% of the community and downstream seven taxa were dominant (Table 4.8). The taxa common to both zones were *Platybaetis* sp1 (Average abundance of 1.19 upstream and 1.34 downstream), *Baetis* sp1 (Average abundance of 1.77 upstream and 1.20 downstream) and *Asionurus* sp1 (Average abundance of 0.75 upstream and 1.30 downstream). *Potamyia* sp1, *Neoperla* sp1 and Gomphidae sp1 were only recorded upstream and *Caenis* sp1, *Asionurus* sp2, *Chloroterpes* sp1 and *Macrostemum* sp1 were only recorded downstream. The dissimilarity of communities between upstream and downstream was 68.58%, supporting the conclusion the communities upstream and downstream were different.

Both the similarity results by SIMPER using all taxa and EPTO contributions between sampling periods were similar with five taxa accounting for over 90% of the community in November–December 2016 and 12 taxa in February–March 2017. Of these taxa the same four mayfly taxa were common to the two sampling periods as in the all taxa analysis, *Platybaetis* sp1 (Average abundance of 1.67 in 2016 and 1.16 in 2017), *Baetis* sp1 (Average abundance of 1.19 in 2016 and 2.12 in 2017), *Asionurus* sp1 (Average abundance of 0.79 in 2016 and 1.53 in 2017) and *Caenis* sp1 (Average abundance of 0.38 in 2016 and 0.73 in 2017) with 67.05% dissimilarity between dates. (i.e. sampling dates with different communities.) (Table 4.9).

Table 4.8: The percentage of contribution of EPTO taxa with their average abundance between sampling locations (upstream and downstream) of the Sae Daw Gyi multipurpose dam on Chaungmagyi River (68.58% dissimilarity in communities between upstream and downstream sites)

Taxon	Upstream		Downstream	
	Average. Abundance	% Contribution	Average. Abundance	% Contribution
Baetis sp1	1.77	30.1	1.2	12.78
Platybaetis sp1	1.68	25.16	1.34	30.28
Potamyia sp1	1.19	19.65	0	0
Neoperla sp1	0.75	7.07	0	0
Gomphidae sp1	0.75	6.43	0	0
Asionurus sp1	0.75	5.45	1.3	17.47
Caenis sp1	0	0	0.89	9.54
Asionurus sp2	0	0	1	9.37
Chloroterpes sp1	0	0	1	7.99
Macrostemum sp1	0	0	0.54	4.13

Table 4.9: The percentage of contribution of EPTO taxa with their average abundance between sampling periods (Nov-Dec 2016 and Feb-Mar 2017) of the Sae Daw Gyi multipurpose dam on Chaungmagyi River (67.05% dissimilarity in communities between sampling periods)

Taxon	November-December 2016		February-March 2017	
	Average. Abundance	% Contribution	Average Abundance	% Contribution
Platybaetis sp1	1.67	41.49	1.16	6.93
Baetis sp1	1.19	23.02	2.12	20.26
Asionurus sp1	0.79	11.73	1.53	10.55
Caenis sp1	0.38	2.95	0.73	3.01
Chloroterpes	0	0	1.13	6.19
Cincticostella gosei	0	0	0.76	4.54
Pseudoneureclipsis sp1	0	0	0.71	3.57
Gomphidae sp1	0.45	3.06	0	0
Neoperla sp1	0	0	1.05	11.98
Ephoron	0	0	0.76	3.07
Asionurus sp2	0	0	1.4	16.32
Togoperla sp3	0	0	0.68	2.52
Togoperla sp1	0	0	0.59	2.46

Ecological water quality Index

We determined the ecological water quality conditions at each sampling site in both rivers using the MABA rapid assessment method by [75]. Both rivers showed good water quality conditions in all upstream sites in both sampling period (> 6.9 Index value) (Figure 4.6). In the Chaungmagyi River, the first downstream site (CM-DS-I-1, CM-DS-II-1) just 6 km downstream of the dam, had index values of 5.1 and 6.9 respectively in 2016 whereas the second downstream site which was 8 km from the dam (CM-DS-I-2, CM-DS-II-2) had indices of 6.6 and 7.9 respectively in 2017. Similarly, in the Myitnge River during the first sampling occasion in 2016 the index was lowest,closer to the dam site (MT-DS-I-1, 5.0) than site (MT-DS-I-2, 6.9) some 40 km downstream of the dam. During the second sampling occasion in 2017, both downstream sampling sites in the Myitnge River showed similar poor water quality conditions (MT-DS-II-1, 4.8 and MT-DS-II-2, 4.7)..

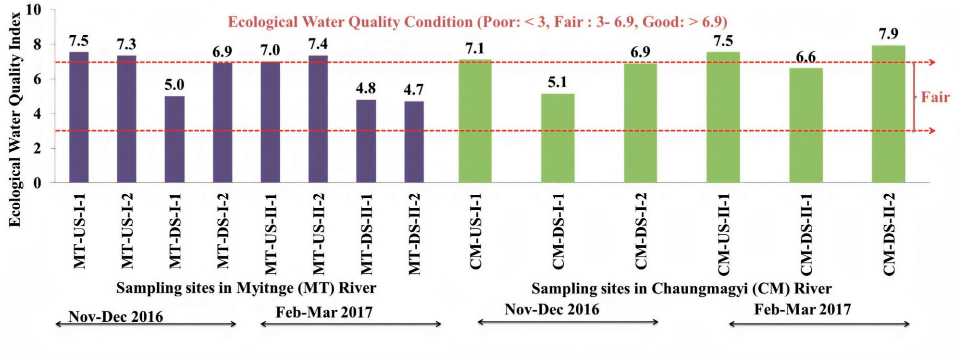


Figure 4.6: Calculated ecological river water quality index using rapid biomonitoring index method by Ko et al. (In preparation) in Myitnge (MT) and Chaungmagyi (CM) Rivers during two sampling periods using all collected taxa at each sample at each site; US-upstream, DS-downstream, I-first sampling period (Nov-Dec 2016), II-second sampling period (Feb-Mar 2017).

4.5. Discussion

4.5.1. Changes in hydrology

According to the data analysis of historical flows between pre- and post-impact periods by IHA, we found that the magnitude of monthly median flow changed in both rivers after the construction of the dams, but the degree of change was individually different based on the respective dam operation rules. Indeed, the difference in the magnitude of monthly median flow from pre- to post-impact periods is significant throughout the year in Chaungmagyi River, where water extraction for irrigation purposes is a priority (Figure 4.2.b). On the other hand, there was no significant alteration in flow regime over the year in the Myitnge River, where the water is used to run turbines to generate hydroelectricity (Figure 4.2.a). This is typical for the operation of hydropower reservoirs and for example was also found by Li et al. [115] in a study on the impact of hydropower dams in Mekong River. Li et al. [109] and Kuenzer et al. [123] showed that different reservoir operation rules caused increased flows during the dry season and decreased flows during the wet season downstream of the dams, with a varying degree of change based on a particular purpose.

Furthermore, there is uncertainty regarding the quality of hydrometeorological data in Myanmar [21, 131]. The latter study on Myitnge River reported that the annual runoff data compared to the annual precipitation do not fully match which also could have its effect on the given extreme conditions of duration, timing, and frequency. The overall loss of a seasonal flow signal that occurs in the Chaungmagyi River due to irrigation demands is consistent with rivers where the primary consumptive use is for irrigation. This pattern is now the norm in the Murray River, Australia [132].

4.5.2. Changes in the ecosystem

Changes in the hydrological regime can directly impact the diversity and composition of aquatic macroinvertebrates and fish, downstream of the dam [107, 55]. We found a lower number of species downstream than upstream in both rivers (Table 4.2). The greatest change in the hydrological regime was in the Chaungmagyi River with a reduced median flow in every month of the year with a loss of a seasonal pattern. This river, which has a high irrigation demand, is similar to other rivers where the greatest consumptive use is for irrigation. The River Murray in Australia has a reduction of flows from 11,883 GL/y under natural flows to 2,539 GL/y under current conditions [133] and the seasonal pattern is not only lost but in fact reversed [132]. These changes have altered the river's hydrological regime to one of drought years (61 years per 100 years compared with 5 years per 100 years under natural conditions) [133]. Recent studies by Paul et al. [134] and Le et al. [135] have shown that the macroinvertebrate fauna are impacted by the changes in hydrology and take over three decades to recover after a flood event [135].

Alterations in the magnitude of flows can cause unreliable habitat availability, water availability which can affect water temperature, and dissolved oxygen levels for aquatic communities [130]. The percentage dissimilarity in communities downstream of the dams was higher in the Myitnge River (89%) than in the Chaungmagyi River (73%). The dam on the Myitgne River is primarily used for hydroelectricity generation and although not substantially changing the monthly flows compared with pre-impact power generation is usual that flows vary daily depending on power demand resulting in high flows (hydro-peaking) followed by low flow. These conditions impact the river habitats by altering the wetting and drying of the littoral zone occupied by the benthic fauna [136] and impacting the macroinvertebrate communities [137] and may account for the higher dissimilarity in this river.

In addition to changes in flow regime, food availability may partly explain the change in species composition between upstream and downstream. Fine particulate organic material is usually stored in the reservoir behind dams thus reducing organic particulates flowing downstream [133]. The operation of the two dams studied release water from the epilimnion which is the main zone of algal production. It may be that phytoplankton and zooplankton are discharged downstream during releases providing food for filter feeders, which are dominant downstream of the dams. Bredebhand and Samways [121] found that filter feeders are in greatest abundance further downstream of dams, where there is plenty of fine particulate organic matter (FPOM). On the Myitnge River, collector-grazers were dominant upstream of the Yeywa dam compared to filter feeders downstream of the dam (Table 4.4 and 4.5). On the Chaungmagyi River (Table 4.6 and 4.8), collector-gatherers were dominant both upstream and downstream of Sae Daw Gyi dam. This difference may be due to the more stable water levels as irrigation water is released downstream of the Sae Daw Gyi dam compared with the hydro-peaking effects from power generation below the Yeywa dam.

In addition, the waste products of other anthropogenic activities, such as industry and agriculture, may have an impact on the macroinvertebrate communities along the river [43]. In this case study, there were agricultural activities upstream and downstream of both dams [138], which can contribute to the observed changes and can, with our dataset, not be completely separated from the effects of dams.

4.5.3. Physico-chemical water quality variables

The collected general physico-chemical water quality variables, such as electrical conductivity (150-500 μ S cm^{-1}), were within the normal range of freshwater aquatic life [139]. However, at the sites CM-US-I-1 and CM-US-I-2 on the Chaungmagyi River, turbidity exceeded this range. One reason for the high turbidity values (308, 498 NTU) at the upstream sites in Chaungmagyi River may be the inflow from the ruby mining wetlands. Along the Chaungmagyi River is a large ruby production zone [140]. During our field sampling, we found that the colour of the river was red in this area, and that local people sometimes call the river the "Red River" instead of the Chaungmagyi River. However, the turbidity did not seem to affect the macroinvertebrate composition in the investigated sites. We did not find any significant changes in the macroinvertebrate communities between the first sampling period with higher turbidity and the second sampling period with lower turbidity. Anderson et al. [141] also reported that most taxa, such as sensitive taxa (Ephemeroptera), are not affected by turbidity as high as 1,000 NTU.

Besides this, site CM-US-I-1 showed a pH value (pH: 5.5, Table 4.2) lower than the healthy range for fish and macroinvertebrate communities (pH: 6.5-9.0, according to Ward et al. [103]. However, we found a high number of sensitive insects (Ephemeroptera and Plecoptera), which considered considered groups unable to survive in a pH lower than 6.0 [103]. Bredenhand and Samways [121] in South Africa also found an abundance of mayflies and stoneflies upstream of a reservoir where the mean pH values were lower than 6.0, suggesting some species may be adapted to these natural acidic conditions.

The hypolimnetic releases of the dams can have a significant influence on the longitudinal pattern of water temperature in the downstream sites, within a range of distance from 10 to 100 km [142]. However, both of our study dams have epilimnetic water releases, which tend to have less of an effect on temperature changes. The length of egg development and consequent hatching species in tropical and subtropical streams can be affected by water temperature at lower than 15°C [2]. Thus, the timing of the life-cycle events of the macroinvertebrates is not likely to be affected by the current water temperature recorded in this study.

We only measured physico-chemical water quality at the time and location of the macroinvertebrate sampling. Hence we may have missed a pollution event which happened earlier and affected the fauna. However, the current spot samples of physico-chemical water quality variables did not show significant changes between the two sampling periods in both study rivers except the hight turbidity at site CM-US-1 on Chaungmagyi River (308 NTU to 108 NTU). An interview with local people during field sampling showed that the water quality of both rivers did not apparently change during the year. Generally, our physico-chemical water quality measurements showed the existing conditions of the sampling sites at the time of sampling. As the measurement of physico-chemical is an instantaneous measure, it does not necessarily reflect the values prior to the sampling or the fluctuations of each parameter. Only two samples were taken from each site and consequently it is not possible to show any correlation between aquatic communities and physic-chemical variables.

4.5.4. Macroinvertebrate communities

We observed a clear and significant difference in all taxa communities between the upstream and downstream sites on both the Myitnge and Chaungmagyi Rivers (Figure 4.4 and 4.5). Samples from the downstream sites rarely contained the most sensitive taxa (EPTO) and had fewer sensitive taxa such as Mollusca (*Corbicula*) and Diptera (Chironominae) from the Myitnge and Chaungmagyi Rivers, respectively (Table 4.4 and 4.6) compared to the upstream sites. These results are in line with a study on the effect of hydropower dams on macroinvertebrate communities by Vaikasas et al. [122].

4

We also analysed the communities using only the morphospecies level of EPTO, and the results were just as strong as they were for the comparison of all taxa between upstream and downstream sites. The stress values were lower on both rivers. We found sensitive taxa downstream of both study dams. However, the predators (Plecoptera and Odonata) were rare in all the downstream sampling sites of both rivers (Table 4.5 and 4.8), a finding which is not in keeping with the previous study of [143]. Mwedzi et al. [143] found rare predators less than 1 km downstream, but the number of predators did not change significantly between upstream and downstream sites further than 1 km downstream of the dam. Predator numbers are generally low as they are at the top of the macroinvertebrate food web [133].

The community differences of all taxa and EPTO between the sampling periods were not significant in the Myitnge River, unlike the Chaungmagyi River. There were different dominant families between the two sampling periods in the Chaungmagyi River. Five taxa were represented during November and December 2016, and 13 taxa were represented during February and March 2017, respectively (Table 4.7). This may be more due to the life cycles of the animals than water quality. The later sampling may have different numbers as a result of the timing of their reproduction and life cycles. This follows the findings of Mesa [144], who demonstrated a significant difference in communities and abundance between seasons (March and September) because of the life-history adaptations of taxa, such as small adult body size, rapid development time, and nearly-continuous reproduction.

Furthermore, the sampling sites located just upstream and downstream of the dams saw a reduction in species richness (Table 4.2). This is supported by previous studies in Nepal [43] and China [120], which show that restoring the organic matter in the reservoir and changes in flow speed can have an impact on macroinvertebrate communities just upstream and downstream of the dam.

4.5.5. Ecological water quality index (MABA method)

The estimated ecological water quality index, using all the collected taxa, is lowest at the sites just downstream the dam on both rivers (MT-DS-1 & CM-DS-1) in both sampling periods (Figure 4.6). Then, the water quality index values steadily increased for the sites further downstream of both rivers (MT-DS-2 & CM-DS-2), which suggests that our study rivers have the potential to recover naturally from the dam disturbance.

The biomonitoring method MABA [75], which uses family data, can also be used to detect the ecological water quality of Myanmar's rivers and the impact of dams. This preliminary biomonitoring method can also potentially be used by citizens, which can help with community empowerment in the sector of water resources development around the country. However, adequate training in the identification of different groups of taxa and in the field to understand the monitoring method are needed. Furthermore, adequate collaboration space for young researchers is an important issue in building up a participatory monitoring program in Myanmar.

4.6. Conclusion

Hydropower dams are critical water infrastructure for Myanmar's economy. Negatively, dams alter the natural flow regime downstream of the dam, in terms of magnitude, frequency, and duration. Aquatic macroinvertebrate communities can be used as an indicator to detect humans' influence, such as dams, on river ecosystems. We sampled both upstream and downstream of Yeywa and Sae Daw

Gyi dams on the Myitnge and Chaungmagyi Rivers, to see how macroinvertebrate communities changed downstream of the dams. We also studied the natural flow regime before and after the construction of the dams to see how the hydrology changed, which can have an impact on aquatic macroinvertebrate communities downstream. We found that macroinvertebrate communities at morphospecies level of all taxa and sensitive taxa (Ephemeroptera, Plecoptera, Trichoptera, and Odonata) are significantly different between the upstream and downstream of both study dams in term of species richness, abundance, and functional feeding groups. We also tested the preliminary Myanmar Aquatic Biomonitoring Assessment Index to detect the ecological water quality index of both the upstream and downstream sampling sites. We found that the biomonitoring index at the family level also showed the same pattern with the results of species-level identification analyses between upstream and downstream of both study dams. We conclude that the indexing method can be applied to detect human influences on river ecosystems, leaving a potential role for citizen monitoring in Myanmar's rivers. However, further research over a longer duration and a greater number of flowing waters including natural and semi-natural water bodies such as rivers, streams and human-made channels is recommended to relate the preliminary index method to hydrology and water quality in both.

5

Aquatic Macroinvertebrate Indicators in the Irrigation Channels and a River

Rivers and wetlands in Myanmar provide essential services to people in terms of transportation, agriculture, fisheries and a myriad of other ecosystem services, all of which are dependent on a healthy ecosystem. Irrigation channels are also an important part of the infrastructure for daily water use in Myanmar. The objective of this research is to describe the aquatic ecosystem of irrigation channels using aquatic macroinvertebrate communities. The research focused on the taxonomic composition of the aquatic macroinvertebrates of the Zawgyi River and the associated irrigation channels in central Myanmar, east of the city of Mandalay. Significant differences between the river and channels, and among individual channels, were shown using an analysis of similarity: Bray–Curtis similarity, a multivariate equivalent of the univariate statistical method of analysis of variance: ANOSIM and an analysis of similarity percentages: SIMPER by Plymouth Routines in Multivariate Ecological Research: PRIMER v6

This chapter is based on [145]: Ko, N. T., Suter, P., Conallin, J., Rutten, M., Bogaard, T. (2020). Aquatic macroinvertebrate indicators in the zawgyi irrigation channels and a river in the central dry zone of myanmar. Sustainability, 12(21), 8788.

software. The initial findings suggest that there is a clear separation between macroinvertebrate communities at the morpho-species level of identification between river and irrigation channels, while there is less separation between functional feeding groups (FFG) between them. The lower taxonomic level of discrimination at the family level using a water quality index showed no significant difference between river and channels. The preliminary field results indicate that a recently modified biomonitoring index method could be applied in Myanmar to assess the ecological water quality of the modified river, as well as human-made channels.

5.1. Introduction

A better understanding of aquatic biodiversity values in different water body types is vital to achieve sustainable freshwater ecosystems [146, 147]. However, there is limited research on the comparison of freshwater aquatic biodiversity values within different water bodies (e.g., rivers, streams, lakes, ponds, and ditches), especially regarding novel ecosystems such as human-contrived channels and ditches [148, 149, 146]. Traditional aquatic ecological research has focused exclusively on larger water bodies, larger rivers, streams and lakes [150]. Smaller water bodies, such as channels, ditches and ponds, have recently received growing interest due to their abundance, importance for freshwater biodiversity and global biogeochemical cycles [151, 152]. Recent studies have concentrated on natural smaller water bodies (e.g., streams and springs) based on aquatic communities and diversity [37, 153, 101]. Nonetheless, the aquatic biodiversity characteristics of semi-natural and artificial smaller water bodies (irrigation channels and ponds) remain understudied [154, 152].

In practice, artificial or human-made smaller water bodies, such as irrigation channels, are important components of farming infrastructure for human society and can also provide a habitat for aquatic flora and fauna communities, with many having distinct aquatic species of macroinvertebrates present [51]. In general, the principal purpose of human-made channels is agricultural, where they serve as conduits to deliver agricultural water and remove storm-water runoff [154]. Further, extensive irrigation channels replace the natural headwaters of regional watersheds [51] and serve as an interface between agriculture and aquatic ecosystems [155]. Alternatively, irrigation channels are significantly relevant to the optimization of productive agricultural areas globally [155], especially in Southeast Asia (SE Asia), which accounts for 60% of the world's irrigated area [156].

Myanmar is one of the most agriculturally dominated countries in SE Asia. People's income and the country's economy mainly depend on the availability of water: the agricultural sector employs more than 65% of the population [19]. Approximately one million hectares of the irrigated area traditionally receive water from the irrigation channels through weirs and dams established by about 200 irrigation projects [157]. Lazarus et al. [21] reported that there are around 180 irrigation reservoirs used for irrigation water supply. Irrigation channels are the most common waterways throughout urban and rural areas, with daily water use by the population reliant on them, but pollution sources are of concern in these systems.

The surface water in channels is susceptible to anthropogenic activities, including pollution from urban wastewater, stormwater runoff and the use of synthetic fertilizer and pesticides [158]. Polluted irrigation water causes negative impacts on food production, water quality [148], aquatic communities, faunal diversity and human health [149]. Irrigation channels may be a habitat that macroinvertebrates can occupy, but they are artificial and do not offer habitats that are as diverse as natural streams and therefore do not support biodiversity in an equivalent manner to streams. Similar to previous studies, the authors in [154, 150, 51] found that irrigation channels do not have the same aquatic taxonomic richness as streams, rivers, lakes and ponds due to the different environmental features associated with them. On the contrary, some studies have shown that irrigation channels in lowland fens and ancient wetlands sometimes support higher taxonomic richness than the larger downstream rivers [159, 147, 150, 154].

Macroinvertebrate communities have emerged as an appropriate representative of aquatic biodiversity communities to provide a time-integrated measurement of freshwater ecosystem characteristics [139]. Changes in an environmental gradient within water bodies can influence the variation of the richness of aquatic taxa and their abundance due to the availability of different food sources (e.g., organic matter, nutrient resources) [160]. There are five functional feeding groups [2]: shredders (which consume leaf debris–coarse particulate organic matter (CPOM)), collectors (which consume deposited fine-particulate organic matter (FPOM)), filterers (which consume suspended fine detritus and organic material), grazers (who consume algae) and predators (which consume other invertebrate prey). These different functional feeding groups can be used to detect the health of the function of the freshwater ecosystem [160].

To date, there is little knowledge about the aquatic biodiversity of natural water bodies in Myanmar. Recently, Ko et al. [75] reported on the development of the first Myanmar-based biomonitoring assessment tool to detect the ecological water quality index. This tool has been developed and tested using macroinvertebrate samples from the least impacted or minimally impacted sites of the Myitnge and Chaumagyi Rivers, east to northeast of Mandalay, Myanmar. In this region, large-scale irrigation works exist; however, to date, the aquatic ecosystem of these irrigation channels has not been assessed.

The objective of this work was to compare the aquatic ecosystems of irrigation channels with the river using macroinvertebrate communities. We describe the ecosystems of irrigation channels and associated rivers in terms of their taxa richness, abundance, functional feeding groups and different land uses. We performed sampling in irrigation channels within the vicinity of urban settlements and a rural area with intensive and extensive agriculture, as well as in a natural river (the Zawgyi River). We further applied the first Myanmar-based biomonitoring index [75] to determine the current status of ecological water quality in both the river and channels. With this approach, we investigated the suitability of the method for the impacted sites of the river, as well as for human-made irrigation channels.

5.2. Materials and Methods

5.2.1. Study area

We selected the Zawgyi Irrigation Network located around the Kyaukse township, 40 km south of Mandalay city in the central dry zone of Myanmar. Kyaukse is a town within the irrigation network of the Zawgyi River, with an estimated population of 257,907 in 2014 [161].

The Zawgyi River flows through the Shan Plateau of eastern Myanmar and then joins the Myitnge River. There is a dam (Zawgyi dam) $21°33'52.13''$ N, and $96°52'25.31''$ E upstream on the Zawgyi River in Shan state. At 100 km below the Zawgyi dam, there is a second dam, namely Myogyi dam (Figure. 5.1). The governmental Irrigation Department constructed four diversion weirs at 13 km, 24 km, 41 km and 41.5 km downstream of Myogyi dam, respectively. Six irrigation channels were built along this stretch of the river, and these four glacis weirs around the Kyaukse area are used to provide water for agricultural land and urban daily water use.

The size of the channels varies from a small ditch with a depth of 1 m and a width of 6 m to larger ditches with a depth of 1.8 m and a width of 31 m. The capacity of the ditches ranges from 2.8 m^3/s to 27.4 m^3/s, and their service area ranges from 16.82 km^2 to 104.78 km^2 based on the size and capacity of the channels. We selected both the Zawgyi River and its six irrigation channels to collect macroinvertebrates samples and in situ physico-chemical water quality parameters (Figure. 5.1).

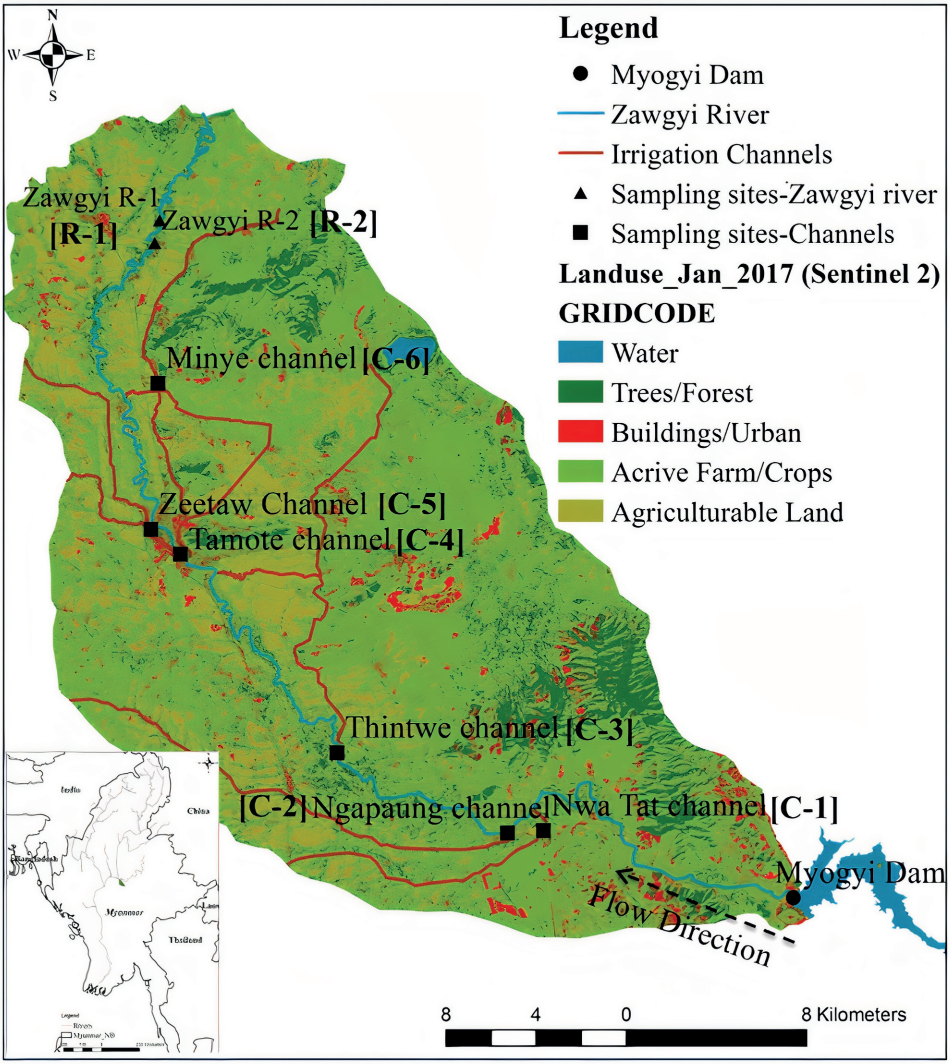


Figure 5.1: Location of sampling sites on the Zawgyi River and its irrigation channels and the dam on the Zawgyi River on a map showing different land uses, based on Sentinel 2 imagery; R: river; C: channel.

5.2.2. Physicochemical water quality variables

We collected five in situ physico-chemical parameters (pH, turbidity (Nephelometric Turbidity Units, NTU), surface water temperature (Temp) [°C], electrical conductivity (EC) ($\mu S\,cm^{-1}$) and water velocity ($m\,s^{-1}$) at all sampling sites in both the Zawgyi River and irrigation channels at the time of sampling. We used Simplex Health pH test strips with a range from 4.5 to 9.0, Ground Truth water clarity tubes, Greisinger, a GMH 3400 series meter and a Transparent Velocity Head Rod (TVHR) (http://www.groundtruth.co.za/our-products/).

5.2.3. Macroinvertebrates sampling

We collected macroinvertebrate samples from six irrigation channels (C-1, C-2, C-3, C-4, C-5 and C-6) and two sampling sites in the Zawgyi River (R-1 and R-2) during the period from November to December 2016 (Figure 5.1). All channel and river sites are impacted by human modifications and are located in an agricultural landscape. We repeated sampling in two sites of the Zawgyi River (R-II-1 and R-II-2) between February and March 2017, but we could not repeat sample collection in the irrigation channels as there was a high water level due to unexpected heavy rainfall. The sampling sites on the river lie at the downstream of the Myogyi dam, as well as downstream of rural and urban settlements before the Zawgyi River joins the Myitnge River.

Both sampling sites in the Zawgyi River have a rocky substrate with vegetation along the riverbank, while all sampling sites in the channels have an earthen or clay-based substrate without vegetation along the edge. Sites C-1, C-2 and C-3 were located in an area with agricultural farming (agricultural). Sites C-4 and C-5 were in the city centre of Kyaukse (urban). Sample site C-6 was outside of the city and located in a rural settlement (rural) (Figure.5.1).

We collected aquatic macroinvertebrate communities from the bank of each channel and the Zawgyi River using a sweep-sample technique with nylon nets (500 micron mesh) [37]. Three individual sweeps each—over a sampling length of 5 m parallel to the bank—were taken from each site. A total of 30 macroinvertebrate samples from the river and channels were collected in the period between December 2016 to March 2017. Specimens were preserved in 70% ethanol in the field. We identified all collected Arthropoda (insects and crustaceans) and Mollusca (gastropod snails and bivalves) as their family and species in the laboratory using keys from [56, 2]. Feeding traits for each taxon were determined based on the functional feeding groups (FFG) in Dudgeon [2] and Merritt and Cummins [162].

5.2.4. Ecological water quality Index

We applied the first Myanmar-based biomonitoring index developed by Ko et al. [75] to determine the current status of ecological water quality in both the river and channels based upon information from all macroinvertebrte taxa present in each site. The first Myanmar-based biomonitoring index method was developed by modifying the index of the Asia Foundation biomonitoring method, which was developed from the Mekong River basin. This revised standard scoring method represents the first index method in Myanmar and includes 48 taxonomic groups. The average score per taxon (ASPT) of this method ranges from 1 to 10 based on tolerant to intolerant water quality. We calculated the ecological water quality index of the river and channels with the following equation by Ko et al. [75]:

$$\text{Ecological Water Quality Index} = \frac{\text{Sum of ASPT}}{\text{Total number of taxa}} \tag{5.1}$$

Ko et al [75] defined three ecological water quality classes based on the calculated index: a value between 1 to 2.9 means a poor or a largely to seriously modified ecosystem by human activities with serious deviation from the natural ecosystem, a score between 3.0 and 6.9 means a fair or moderately modified ecosystem by human activities with little deviation from the natural ecosystem, and a score between 7.0 and 10.0 means a good or unmodified to little-modified condition by human activities.

5.2.5. Statistical analysis

Statistical analysis was performed using the statistical program PRIMER v6 [95]. We tested different statistical variables: for all present taxa, for only Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO) and for FFG based on abundance and species contributions, in order to compare the community difference between different water bodies, we computed the resemblance matrix by using Bray–Curtis similarity using a square root transformation, then applied non-metric multidimensional scaling (MDS) for visualization to all resemblance matrixes by using Bray–Curtis similarity with 999 random stars. An MDS plot shows the stress value, which represents the rank order correlation distance among the resemblance matrix. A stress value of less than 0.05 means a near-perfect representation of ordination space among samples [96].

If there was any significant difference between samples (variables), we used a one-way analysis of similarity (ANOSIM) to confirm clear separation based on a null hypothesis of no community/FFG/index differences between channels and between the river and irrigation channels. ANOSIM calculates a test statistic (Global R between 0 to 1) that provides a comparative measure of the degree of separation of pre-defined sampling groups and its probability of occurring by chance using 999 permutations [95]. The higher the Global R-value, the larger the differences between samples, but if all permuted statistics are higher than the Global R, then the null hypothesis can be rejected at 0.001 significance [95].

Additionally, we used an analysis of similarity percentages (SIMPER) to determine the percentage of (dis)similarity of macroinvertebrate communities among irrigation channels and between the river and irrigation channel sites and the contribution of individual taxa to the resulting dissimilarity. In SIMPER analysis, we used the feeding traits of the macroinvertebrates as a variable to examine the contribution of each feeding behavior between the two water bodies.

5.3. Results

5.3.1. Physicochemical water quality

Figure 5.2 shows the collected physico-chemical attributes of the irrigation channels and the Zawgyi River. The values of pH ranged from 7.25 to 8.0. The turbidity values of sites in the river were higher than the values in some sampling sites of the channel (C-1, C-2, C-3 and C-6) but similar to the value in C-4 and C-5. We obtained a higher EC in the river (range of 547–550 $\mu S\,cm^{-1}$) than in the channels (range of 329–473 $\mu S\,cm^{-1}$). The flow velocity at the time of sampling ranged from 0.12 $m\,s^{-1}$ to 0.92 $m\,s^{-1}$ in the channels and from 0.3 $m\,s^{-1}$ to 0.5 $m\,s^{-1}$ in the river.

Figure 5.2: Schematic diagram with distance from the main river to sampling sites on irrigation channels with the collected physico-chemical parameter between November and December 2016.

Table 5.1: Collected macroinvertebrates communities at order, family, and morpho-species-level of the Zawgyi River and its six irrigation channels (Remark: L = larva, A= adult, P=pupae, sp=specie), and their Average Score per Taxon (ASPT) of first Myanmar Index method by Ko et al. [75].

Order	Family	Species	FFG	ASPT	Irrigation Channels						Zawgyi River			
					C-1	C-2	C-3	C-4	C-5	C-6	R-1	R-2	R-II-1	R-II-2
Mesogastropoda	Bithynidae	Bithynidae sp. 1	Grazer	6	0	0	0	0	0	0	0	4	0	0
	Thiaridae	Thiaridae sp. 1	Grazer	6	16	0	11	11	0	22	0	7	3	5
Bivalvia	Corbiculidae	*Corbicula* sp. 1	Filterer	3	7	0	0	21	46	0	33	2	1	0
	Margaritiferidae	Margaritiferidae sp. 1	Filterer	3	0	0	0	1	0	0	0	1	0	0
Decapoda	Palaemonidae	*Macrobrachium* sp. 1	Predator	8	0	0	0	0	0	0	0	17	0	0
	Parathephusidae	Parathelphusidae sp. 1	Collector	3	0	1	0	1	0	0	2	0	1	0
Ephemeroptera	Baetidae	*Baetis* sp. 1	Collector	5	8	5	19	15	0	0	78	36	76	22
		Platybaetis sp. 1	Collector	5	0	0	0	0	0	0	17	3	65	0
	Heptagenidae	*Asionurus* sp. 1	Filterer	10	4	0	5	16	0	0	1	0	0	0
		Asionurus sp. 2	Filterer	10	0	0	0	2	0	0	0	0	0	0
	Caenidae	*Caenis* sp. 1	Collector	4	25	17	40	65	4	9	25	1	1689	2072
Odonata	Gomphidae	Gomphidae sp. 1	Predator	6	3	9	2	5	0	0	0	2	0	0
Hemiptera	Micronectidae	Micronectidae sp. 1	Predator	1	0	0	0	0	0	0	0	1	0	0
Trichoptera	Hydropsychidae	*Potamyia* sp. 1	Filterer	5	0	0	0	0	0	0	50	5	3	7
Coleoptera	Dytiscidae	Dytiscidae sp. 1	Predator	2	2	50	0	0	4	0	0	0	0	0
	Elmidae	Elmidae (L)	Predator	8	0	0	0	2	0	8	1	0	0	31
		Elimidae (A)	Predator	8	1	0	0	1	0	0	1	0	0	0
	Hydrophilidae	Hydrophilidae sp. 1	Collector	3	2	23	0	0	1	0	0	0	0	0
Diptera	Chironomidae	Tanypodinae sp. 1	Predator	3	0	0	0	3	4	0	0	0	45	85
		Chironomidae (P)		3	0	0	0	0	0	0	1	0	20	23
	Ceratopogonidae	Ceratopogonidae sp. 1	Predator	3	0	0	0	4	4	0	0	0	1	1
Neuroptera	Sisyridae	Sisyridae sp. 1	Predator	3	0	0	0	0	0	0	0	0	0	1
Total species richness					9	6	5	13	6	3	10	11	10	9
Total abundance					68	105	77	147	63	39	209	79	1904	2247

5.3.2. Qualitative comparisons of taxa richness, abundance, and taxa composition

Table 5.1 shows all collected aquatic invertebrates at the order, family and morpho-species-level taxonomies from all sampling sites of the river and channels, as well as their representative FFG and ASPT. A total of 22 aquatic invertebrate taxa from 18 families in 10 different orders were recorded from all samples in the river and channel sites (Table 5.1). The channels had lower diversity than the river sites, with 15 taxa from 13 families in six orders in the channels, while there were 19 taxa from 16 families in 10 orders in the river. Sample site R-II-2 on the Zawgyi River showed the highest abundance, while site C-6 showed the lowest abundance. The highest richness was 13 taxa in site C-4, and the lowest richness was three taxa in site C-6 (Table 5.1).

Aquatic insects dominated the majority of taxa at all sampling sites, with 11 taxa in channels and 13 taxa in the river. The most common insect order in both channels and the river was Ephemeroptera, with three families: Baetidae, Heptagenidae and Caenidae. Of these, Caenidae were most abundant, ranging from 4 to 65 individuals in the channels and from 1 to 2072 individuals in the river. Our sampling recorded three non-insect orders, with four and six taxa from the channels and the river, respectively. All four main functional feeding groups—collectors, filterers, grazers and predators—were present in both the river and channels.

5.3.3. Comparisons of Macroinvertebrate Communities at Morpho-Species Level between the River and Channels

Based on Bray–Curtis similarity using all aquatic taxa at the lowest taxonomic level (morpho-species), there was a separation between the two water body types. The MDS ordination plot showed a significant separation between the communities in the river and channels (stress = 0.17) (Figure 5.3.a). ANOSIM also indicated that there was no overlap between the macroinvertebrate assemblage between the river and channels (R statistic = 0.489), with a dissimilarity between these two water bodies of 80% (Table 5.2).

The percentage of average dissimilarity in the community decreased to 64% when only taxa (Ephemeroptera, Plecoptera, Trichoptera, Odonata and EPTO) at the morpho-species level were considered (Table 5.2), and the stress level of MDS ordination was also lower (stress = 0.12) (Figure 5.3.b). Table 5.2 shows the lists of results of SIMPER and ANOSIM for comparisons between the river and channels using different variables. The comparison of the river and channels using FFG showed less separation than the other two comparisons using all taxa and EPTO (Table 5.2).

Besides this, the difference in FFG composition between the river and channels based on different land uses (urban, rural, agricultural) showed that there was no significant difference between different land uses in the present study (Table 5.2). However, the comparison of macroinvertebrate communities based on FFG composition between the open river and channels in urban groups showed over 70% average dissimilarity.

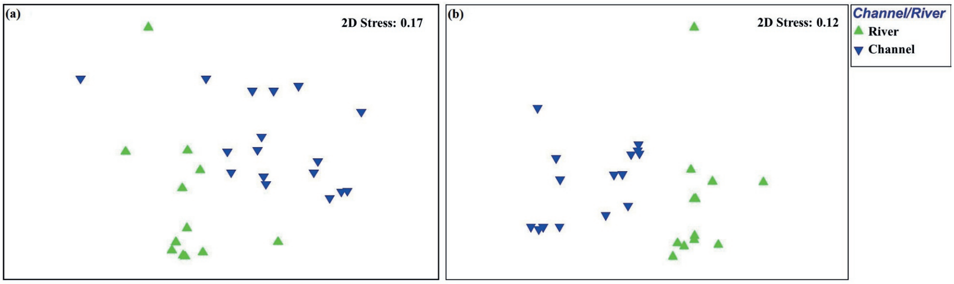


Figure 5.3: Dimensionless multidimensional scaling (MDS) ordination plot for the comparison of the communities of the Zawgyi River and six irrigation channels: (**a**) MDS plot using all taxa at the morpho-species level, (**b**) MDS plot using only Ephemeroptera, Plecoptera, Trichoptera and Odonata (EPTO) taxa at the morpho-species level.

Table 5.2: Results of an analysis of similarity percentages (SIMPER) (average dissimilarity) and one-way analysis of similarity (ANOSIM) (Global statistic R, significant level of statistic, P-value) for the comparison of macroinvertebrate communities based on all taxa at the morpho-species level, tolerant taxa (Ephemeroptera, Plecoptera, Trichoptera, Odonata, EPTO) at the morpho-species level and functional feeding groups (FFG) of morpho-species contributions between the Zawgyi River and six Irrigation Channels

Waterbodies	**Variable**	**(SIMPER) Average Dissimilarity [%]**	**ANOSIM R-Statistic**	***p*-Value**
River and Channels	All taxa	80	0.489	0.001
	EPTO	64	0.645	0.001
	FFG	61	0.303	0.003
River--Urban channels	FFG	58	0.136	0.110
River--Rural channel		73	0.531	0.004
River--Agricultural channels		58	0.262	0.012

Note: Urban channels are C-4 and C-5; the rural channel is C-6; agricultural channels are C-1, C-2, and C-3.

Figure 5.4 shows the bubble plots of the number of individuals of different FFG at each sampling site. In four FFG groups, collectors were high in abundance in all sampling sites of the river, except for site R-2, and were absent from C-5 and rare in C-4 and C-5 (Figure 5.4.a). Filterers were rare in sampling sites of the river (R-2, R-II-1, R-II-2) in comparison with the sites in channels C-1, C-2, C-4 and C-5 (Figure 5.4.b). We found a high abundance of filterers only in the river site (R-1) (Figure 5.4.b). Grazers had high abundance in site R-1 but were absent in sites C-4, C-5 and C-2 (Figure 5.4.c). The abundance of predators was highest in river sites and sites C-2 and C3, but these were rare or absent at all other sites (Figure 5.4.d).

Table 5.3 shows the average dissimilarity percentage and FFG with the highest contribution in percentage between the sites of the river and six channels. Collectors were the dominant FFG group to control all dissimilarity percentages. The highest average dissimilarity percentage was found between C-5 and sites R-1 and R-2, with over 70% in both sites of the river (Table 5.3).

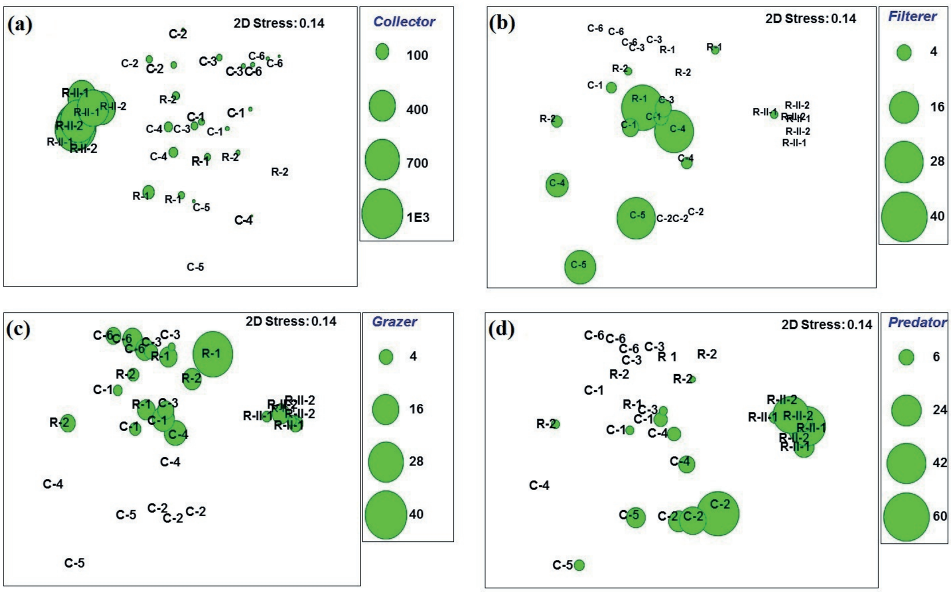


Figure 5.4: Bubble plot of present abundance by dimensionless MDS ordination based on four FFG (**a**): Collectors, (**b**): Filterers, (**c**) scraper grazers and (**d**) predators with their respective abundance numbers between the Zawgyi River (R) and irrigation channels (C) .

Table 5.3: Average dissimilarity percentages of each sampling site of the river and channels with the respective functional feeding group (FFG) of the highest species contribution and their contribution (%) using functional feeding groups (FFG) by an analysis of similarity percentages (SIMPER).

Channels	River	Average dissimilarity [%]	FFG of the highest species contribution	Contribution [%]
C-1	R-1	54	Collector	63
	R-2	52	Collector	68
C-2	R-1	70	Collector	54
	R-2	66	Collector	56
C-3	R-1	50	Collector	64
	R-2	54	Collector	69
C-4	R-1	57	Collector	56
	R-2	62	Collector	57
C-5	R-1	77	Collector	57
	R-2	77	Collector	52
C-6	R-1	60	Collector	71
	R-2	59	Collector	70

5.3.4. Comparison of Macroinvertebrate Communities at the Morpho-Species Level in the Irrigation Channels

The resemblance matrix of all macroinvertebrate assemblages at the morpho-species level among the six different channels obtained with Bray–Curtis similarity generated a clear separation among samples, which is displayed on the two-dimensional MDS ordination plot (stress = 0.13) (Figure 5.5.a). The MDS plot shows that there was no overlap between macroinvertebrate communities within the six channels. The Global R statistic was high (0.714), with a significantly low level of the sample statistic (p = 0.001), demonstrating that there was a good separation in the communities between different channels (Figure 5.5.b).

The similarity analysis using SIMPER provided the average percentage of (dis)similarity among the individual channels. Table 5.4 shows the results of SIMPER with the highest species contribution alongside the contribution percentages and FFG for each group for all taxa and individual taxa (EPTO). The highest average dissimilarity percentages were found in the groups of C-5 and C-6, at 91%, while the lowest average dissimilarity percentages were shown in the groups of C-1 and C-3, with 40%, when all taxa are considered. The highest taxa contribution of groups C-5 and C-6 were the filter-feeding bivalves Mollusca–*Corbicula*.

The collector mayfly Ephemeroptera–*Baetis* was the main contributor to the group with least dissimilarity (C-1 and C-3) (Table 5.4). However, when we counted only taxa (EPTO), the average dissimilarity percentages of communities between individual channels were lower than the percentages of communities of all

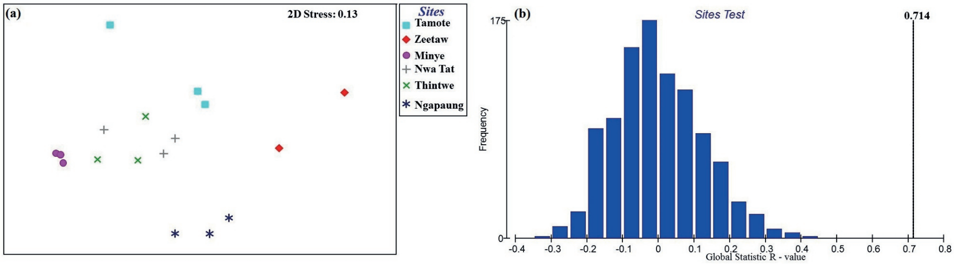


Figure 5.5: **a**): Dimensionless MDS ordination plot of morpho-species contributions among six channels based on the Bray–Curtis similarity matrix of square root transformation. (**b**): ANOSIM plot for morpho-species contribution similarity among six channels.

taxa (Table 5.4). The EPTO communities were not significantly different between individual channels (average dissimilarity percentages ranged from 4% to 63%).

Additionally, we considered channels in different land-use groups, such as urban channels, rural channels and agricultural channels, using SIMPER and ANOSIM analysis to see the average percentage of dissimilarity among different land-use groups. The highest average dissimilarity percentages were found between urban channels and rural channels, at 73%, which is the same result found from the comparison of individual channels (C-5 and C-6). Channels in the rural area and channels in the agricultural area showed similar communities (45% dissimilarity) (Table 5.5).

5.3.5. Ecological Water Quality Condition of the River and Channels

All sampling sites in both the river and irrigation channels showed fair ecological conditions, with an average ASPT index ranging from 3.0 to 6.2 among channels and from 4.14 to 4.86 at river sites (Figure 5.6.a).

The statistical analysis of the Bray–Curtis similarity and MDS of the calculated ecological water quality index between the river and channels showed a very low stress value (0.05), indicating that the ordination space between samples exhibited a near-perfect representation [96]. Although the magnitude of the calculated ecological water quality indices was different between different water bodies, there was an overlap between the rank order correlation distance among samples (Figure

Table 5.4: Average dissimilarity percentages among individual channels with their highest species contribution and percentage and functional feeding groups (FFG) (L: larvae, sp.: species) using the morpho-species contributions of all taxa and EPTO by an analysis of similarity percentages (SIMPER).

Channels		Average Dissimilarity [%]		Highest Species Contribution		Respective FFG		Contribution [%]	
		All Taxa	EPTO	All Taxa	EPTO	All Taxa	EPTO	All Taxa	EPTO
C-1	C-2	62	33	Dytiscidae	*Asionurus* sp. 1	Predator	Filterer	27	34
C-2	C-3	66	36	Dytiscidae	*Baetis* sp. 1	Predator	Collector	30	38
C-3	C-4	58	41	*Caenis* sp. 1	*Asionurus* sp. 1	Collector	Filterer	17	31
C-3	C-1	40	33	*Baetis* sp. 1	*Baetis* sp. 1	Collector	Collector	23	35
C-4	C-5	74	62	*Corbicula*	*Asionurus* sp. 1	Filterer	Filterer	22	35
C-4	C-2	76	48	Dytiscidae	*Asionurus* sp. 1	Predator	Filterer	21	36
C-4	C-1	58	33	*Caenis* sp. 1	*Baetis* sp. 1	Collector	Collector	16	25
C-5	C-6	91	4	*Corbicula*	*Caenis* sp. 1	Filterer	Collector	34	100
C-5	C-3	91	40	*Corbicula*	*Baetis* sp. 1	Filterer	Collector	30	48
C-5	C-2	81	37	*Corbicula*	*Gomphidae* sp. 1	Filterer	Predator	30	48
C-5	C-1	77	47	*Corbicula*	*Asionurus* sp. 1	Filterer	Filterer	25	32
C-6	C-4	74	63	Thiaridae	*Asionurus* sp. 1	Grazer	Filterer	16	35
C-6	C-3	50	43	*Baetis* sp. 1	*Baetis* sp. 1	Collector	Collector	26	46
C-6	C-2	79	40	Dytiscidae	*Gomphidae* sp. 1	Predator	Predator	29	45
C-6	C-1	54	50	Elmidae (L)	*Asionurus* sp. 1	Collector	Filterer	19	31

Table 5.5: Results of an analysis of similarity percentages (SIMPER) (average dissimilarity) and one-way analysis of similarity (ANOSIM) (Global statistic R, significant level of statistic, p-value) for the comparison of macroinvertebrate communities between channel groups with different land uses based on the functional feeding groups (FFG) of morpho-species contribution.

Water bodies	Variable	SIMPER Average Dissimilarity	ANOSIM	
		[%]	R-Statistic	p-Value
Urban channels–rural channel	FFG	74	0.938	0.018
Urban channels–agricultural channels		54	0.389	0.009
Rural channel–agricultural channels		45	0.221	0.011

Note: Urban channels are C-4 and C-5; the Rural channel is C-6; Agricultural channels are C-1, C-2, and C-3.

5

5.6.b). A one-way similarity ANOSIM with 999 permutations also confirmed that the variety of sites based on the indices was not significantly different between the river and channels.

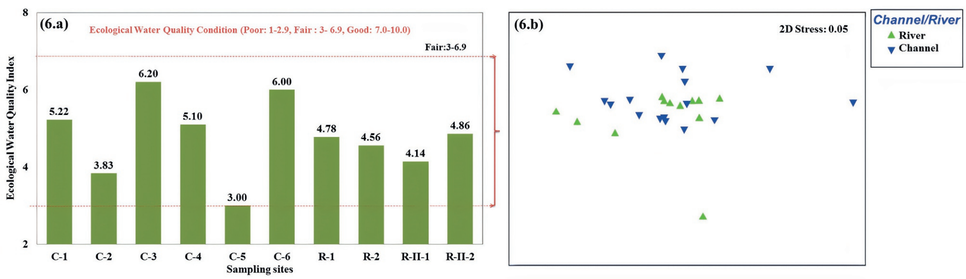


Figure 5.6: **a**) Calculated ecological water quality indices on the river and channels using the full list of identified families from three composite samples at each site; (**b**) dimensionless MDS ordination plot for the comparison of indices between the river and channels.

5

5.4. Discussion

5.4.1. Objectives

This study presents pioneering work on the aquatic ecosystems of irrigation channels in Myanmar. Our objective was to investigate the aquatic ecosystem of human-made irrigation channels based on macroinvertebrate communities and to test the differences of these communities to those of the natural river. A number of methods were used: the lowest taxonomic level (morpho-species data), EPTO taxa, FFG comparisons and a rapid biomonitoring method (family level taxonomy) in both river and irrigation channels.

5.4.2. Water Quality

In situ water quality values at all sites of both the river and channels were within acceptable irrigation water quality standards (pH 6.5-8.4, EC < 700 $\mu S\,cm^{-1}$; [163]) but not suitable for household use, as the suspended sediment concentration was quite high (>30 NTU) at the time of testing. The electrical conductivity in channels was also within the normal freshwater aquatic life criteria range (150–500 $\mu S\,cm^{-1}$), as discussed by [139]. EC levels in the river were a little higher than the normal range (546–550 $\mu S\,cm^{-1}$) . Small changes in EC level such as those found in our study (546–550 $\mu S\,cm^{-1}$) are not relevant to changes in the macroinvertebrate assemblage [164].

Kartikasar [158] noted that the spot sampling of physico-chemical water quality measurement does not fully capture water quality fluctuations. However, our collected physico-chemical water quality in the Zawgyi River did not show significant changes between the first sampling occasion and the second. Therefore, while not accurately representing the fluctuations that may occur during storms, our findings can be considered representative for baseflow water quality conditions in the dry season.

Additionally, during the field sampling period, we performed a participatory monitoring interview project in our study area [165]. We interviewed inhabitants from two villages near channel C-6 and children from two private high schools in Kyaukse city (near C-4 and C-5). All interviewees complained about pollution and diseases such as cholera but did not mention dramatic water quality changes over the seasons. Generally, the collected physico-chemical water quality variables showed that the water quality was within acceptable standards for irrigation water and freshwater aquatic life; however, it was not acceptable as drinking water without adequate treatment.

Notably , the most sensitive group, Plecoptera, which requires cold and unpolluted freshwater with a high dissolved oxygen level [2], was not recorded at any site in both water body types, suggesting that all sites were impacted by modified water quality. The lack of this family could be related to the nutrient composition of water associated with the direct discharge of household hazardous waste disposal into both river and channels. This corresponded to the situation observed during our field visit. Indeed, we found several hard rubbish waste disposal areas near the river bank and channels during our sampling collection, but we could not measure the nutrient or other pollutant composition of organic and inorganic materials in this current study.

5.4.3. Comparison of Macroinvertebrates Community between River and Channels

Although the comparison between the natural river and human-made irrigation channels highlighted significantly different taxonomic assemblages of all aquatic taxa (highest taxonomic level of identification; i.e., morpho-species level), the difference between these two water bodies decreased from 80% to 64% when we used only EPTO taxa, which includes the more sensitive groups. The comparison is based on a significantly reduced data set with only four species in the rivers and seven in the channels, with a high abundance of the tolerant mayfly *Caenis* and absence of *Asionurus* in the river.

5

FFG compositions still support differences between the river and channels, in that collectors and grazers were more present in rivers while filterers were found more often in channels. The higher diversity of collectors in the river is consistent with the study presented in [160], which found that collectors were most abundant in the downstream reach of a forest–agriculture–urban river where high human inputs into the watercourses occurred. The presence of grazers in the river shows that there were ideal conditions to produce algae and biofilm [139]. Filterers in the channels suggest that the substrate is mainly silty/sandy sediments, as the number of filterers has a positive correlation with the total dissolved solids within the water body [166] and a flowing current to provide natural organic matter.

Among the collected FFGs, there was a lack of shredders at all sampling sites at the time of sampling. Dudgeon [2] states that there are a lack of shredders or a relatively low proportion of shredders in tropical Asian streams. For example, shredders encompass not more than 8.8% of the communities in the streams in Hong Kong. The lack of shredders in our study could be related to the absence of leaf input for decomposed terrestrial leaf litter in the Zawgyi River and irrigation channels.

This difference in FFGs might be related to the different substrates between river and channels (rocky and earth, respectively), which could support different food sources, with aquatic macrophytes and algae in the river and sediments and detritus in the channels. The input of anthropogenic pressure and agricultural activities on water bodies also create changes in FFG variation [160].

Additionally, the different communities between the river and channels might reflect the different habitat availability and hydrological regimes. Irrigation channels are not streams but water courses that do not mimic the flow regimes of streams but rather ensure flows in constructed channels and thus do not create stream-like habitat diversity. The channels are subjected to dry or low water levels (ranging from 0.15 to 0.5 m) during the late-season of crop development, enabling fresh harvest or dry harvest based on the particular crop, whereas the river fluctuates less throughout the year, with a constant baseflow and with wet season fluctuations above this. For example, Kartikasari [158] reported that the dominant taxa (*Melanoides tuberculata*–Thiaridae) in irrigation channels show whether dry periods occur or not. This species of gastropod snail has an operculum, enabling it to seal its shell and withstand dry periods. We also found a high abundance of these Thiaridae snails in almost all channels, except C-2 and C-5; the Thiaridae snail was also found in the Zawgyi River, although only a few individuals were present.

5.4.4. Aquatic Ecosystem of Irrigation Channels

The macroinvertebrate communities in the irrigation channels were not homogenous. The highest dissimilarity was found in channels C-5 and C-6. This is logical in the case of the different anthropogenic activities within agricultural or urban areas, as discussed in [155].

This holds particularly for filterers, which feed mainly on detritus and fine organic matter in the water and are usually buried in the sediment bed of the waterbody [167] and were abundant in C-5. In the C-6 channel, grazers (Thiaridae) were highly abundant. Grazers feed on soft sediments, as at channel C-6 where they feed in the mud and are effectively grazing in the mud [168]. The difference in the physical structure of channels may affect the flow velocity, which relates to the water–sediment interface within the water column [51]. However, the most abundantly found taxa in all channels were the tolerant mayflies *Baetis*, *Asionurus* and *Caenis*. Therefore, EPTO taxa did not show significant differences among individual channels (Table 5.5).

5.4.5. Ecological Water Quality Index

All sampling sites showed fair ecological water quality conditions (Figure 5.6.a). Different assemblages of families gave different ecological water quality indices based on the ASPT and taxa richness at each site, but all sites still ranked as "fair". This result—the same fair condition—indicates that all the sampling sites are impacted by human disturbance in both water bodies (e.g., direct household waste disposal, organic pollutants) but show different physical and chemical characteristics (e.g., substrate, flow velocity, wetted width and hydrology). Although this new water index method for Myanmar did not show significant differences between sites—unlike the morpho-species, EPTO and FFG indices—it did show that human activities in the lower section of the Zawgyi River resulted in impaired water quality. Therefore, it becomes clear that the Myanmar based biomonitoring index, which is still under development [75], should be extended to improve its sensitivity.

5.4.6. Challenges and Citizen Science Potential

The lack of detailed knowledge about aquatic biodiversity in Myanmar makes our study challenging and hinders the extrapolation of our findings to other studies in the same region. Additionally, the limited availability of long-term instantaneous physico-chemical data for smaller water bodies in Myanmar is restrictive. Our research, then, aims to fill a critical knowledge gap, which is necessary to manage Myanmar's freshwater resources for sustainable development. No macroinvertebrate studies focusing on irrigation channels have been published in Myanmar. However, recently, Ko et al. [75] studied macroinvertebrate communities upstream of hydropower dams in the Myitnge and Chaungmagyi Rivers in the Eastern part of Myanmar. They found fair to good ecological water quality using three different international biomonitoring indexing methods (The South African Scoring System: miniSASS, Australian Waterwatch and Asia Foundation methods). However, our current study is also the first study of artificially constructed water courses in Myanmar. The Myanmar-based biomonitoring index method [75] showed that the sampling sites are all of low/fair ecological water quality, but we had no high-quality sites for comparison. However, at higher levels of taxonomic identification, our study showed the differences in communities among sampling sites, because we considered morpho-species and abundance together. The index method, a family-based method, is a reduction of data information, but this does not remove its value in water quality monitoring. Therefore, the preliminary, Myanmar-based biomonitoring index is a potential indicator for water resource research, particularly in the area of citizen science. However, when we apply the index method as a citizen science approach, there will always be difficulties in terms of data accuracy and reliability; however, there are gains from helping local communities to monitor their water quality using macroinvertebrates. During our field sampling period, we tested indexing methods in the field with Grade 6 and 8 students from a high school near channels C-4. Most of the students could detect water quality well when they used the index method with an order-based method (miniSASS: http://www.minisass.org/en/) rather then a family-based method (Asia Foundation, which formed the basis of the Myanmar-based biomonitoring index) during their field visit. Ko et al. [75] also recommended the use of a much-easier order-based method such as miniSASS, which is more suitable for non-professional citizen participation approaches. Such a citizen science approach could increase awareness of river health as well as influencing local water management decisions.

5.5. Conclusions

Irrigation channels are small, artificial water bodies that not only play an essential role in social-economic activities but also provide a habitat for aquatic fauna and flora in agricultural countries such as Myanmar. However, small water bodies are often overlooked in aquatic ecological studies compared to the larger natural and modified rivers. We sampled both river and irrigation channels to determine how the macroinvertebrate communities altered between the Zawgyi River and human-made irrigation channels. Our findings were that the diversity of macroinvertebrates was low in both water bodies, which we linked to the (household) pollution of these environments. Thus, in the absence of impacted streams, it is likely that irrigation channel communities will merely be similar to impacted stream communities; i.e., reduced biodiversity and the selection of more tolerant taxa. We also illustrated the use of macroinvertebrate communities to detect ecological water quality in different water bodies in Myanmar, which could have a potential role in a program of participatory monitoring by local people and management authorities.

Our study is a pioneering study with a limited dataset which aimed at the assessment of irrigation channel ecosystems in Myanmar using aquatic macroinvertebrate assemblages. Further aquatic ecology research in Myanmar on other natural and semi-natural water bodies is recommended. We also recommend that researchers should monitor and document irrigation water quality, with a focus on nutrient loads, in further studies. Molecular analyses using DNA could be used in the future to verify morphological identification and to separate closely related species, but this was considered to be beyond the scope of this ecological study as it aimed to support community-based monitoring by local people. We suggest that future research should focus on extending the spatial scale of macroinvetebrate sampling with a multi-year sampling period with increased replicates (five) at each site to fill the knowledge gap of the biodiversity of small water bodies in Myanmar.

6

Synthesis

6.1. Beginning of contributions

Rivers are important and finite water resources. Out of all the water available on the earth's surface, less than 3% is fresh water, and more than 97% of all water is saline water. River water makes up only 1.6% of the total available freshwater on earth [169]. Rivers provide considerable social and economic benefits to all life on earth and, therefore, river health monitoring deserves greater understanding.

However, around the world, the health of rivers has been steadily declining through direct and indirect natural and human-related activities [15, 5, 10, 14], especially in developing countries of South East Asia (SE Asia) [2]. River health can be identified either by the overall health of a river's ecosystem or by the benefits derived from rivers by humans [14]. Nevertheless, research on the monitoring of river health is limited in SE Asia.

In Myanmar, a low-income country in SE Asia, water resources play a central role in the economy. However, an awareness of river health monitoring is lacking. Inadequate funding and lack of education are most critical in the failure to implement sustainable river health measurements.

There are various low-cost approaches to monitoring the quality of river water. Remote sensing analyses of water quality with the use of space-based data sets has taken a prominent place in research. The monitoring of water quality using spaceborne instruments is becoming more popular globally due to free open-access resources. The assessment of river water quality using aquatic macroinvertebrate communities, biomonitoring, has received interest as an approach to monitor the ecological water quality of rivers due to it being scientifically reliable and low-cost, and its ease of application by both scientists and non-scientists [48, 40] [37, 51].

Therefore, we aimed to develop an approach to monitor the health of river ecosystems using remote-sensing satellite images and freshwater macroinvertebrate communities. To do so, this thesis addresses the following research questions:

1. How reliable are space-based data sets as a system for monitoring water quality,

2. Is it possible to develop a specific biomonitoring method for Myanmar based on recent biomonitoring assessment tools in SE Asia,

3. Can macroinvertebrate measurements be used as an indicator to study the potential impact of dams in Myanmar,

4. Can macroinvertebrate measurements be used to monitor water quality in human-made channel systems?

6.2. Main contributions

This dissertation comprises of the development of a modified rapid macroinvertebrate bioassessment method and applies it to describe the impact of humans on rivers and human-made irrigation channels. Moreover, this thesis looks into the potential of remote sensing for monitoring the quality of surface water in Myanmar's rivers (Chapter 2). Supplementary material A and Chapter 3 introduce the first identification keys to freshwater macroinvertebrate communities in Myanmar and the development of a modified biomonitoring method based on an existing method used in SE Asia. Chapters 4 and 5 discuss human impact on ecological water quality using freshwater macroinvertebrate communities.

Chapter 2 demonstrates how space data sets can be used to assess the water quality of rivers in Myanmar. We show that a remote sensing analysis using a space data-set can be successfully applied to detect the Suspended Sediment Concentration (SSC) and the water temperature of the Ayeyarwady River basin, in the central dry zone of Myanmar ***(Research Question 1)***. Remote sensing information can offer a spatial and temporal view of the surface water quality in regard to suspended solids, and water temperature for larger bodies of water such as the Ayeyarwady and Chindwin Rivers [61, 64]. With current remote sensing information it is not possible to detect other critical markers of water quality such as total nitrogen and dissolved phosphorus, due to weak optical characteristics and low signal-to-noise ratios [170]. Also, the current spatial resolution is not high enough to estimate the quality of shallow water or smaller water bodies and human-made channels [34].

We first developed illustrated keys to taxa in Myanmar based on taxa found in eight rivers in the northern region (Maykha, Malikha, Myitsone-Ayeyarwady, Yae Kyi), the northwest region (Myit Thar), and the central dry zone (Myitnge, Chuangmagyi, Zawgyi) and six irrigation channels of the Zawgyi River (supplementary material A in this thesis). The use of macroinvertebrate communities depends on the ability to identify invertebrates of family, species, or genus taxonomic rank, according to the particular purpose. We also present the habitats and functional feeding groups of each of the dominant taxa. However, we developed illustrated keys based on the available collected taxa from only eight rivers and six irrigation channels. Still, we believe that other new taxa will be found in different streams and rivers in Myanmar. Therefore, it is required to study all rivers and streams as much as possible when we make professional illustrated keys at a national scale. We used the initial illustrated keys to enable us to identify freshwater macroinvertebrates for the following studies in Chapter 3, 4 and 5.

Chapter 3 evaluates three rapid macroinvertebrate bioassessment methods (miniSASS, Australia Waterwatch, and The Asia Foundation) under Myanmar's taxonomic conditions. Currently, there are no standardized biomonitoring tools in Myanmar. We used macroinvertebrate samples from minimal impacted sites upstream of hydropower dams in two tributaries of the Ayeyarwady River (Myitnge and Chaungmagyi). We used our illustrated keys to identify macroinvertebrates at family and morpho–species levels and statistically analysed our results to determine the most appropriate index to use in Myanmar from the three pre-selected indices. Based on the results of the statistical analysis and the similarity of the Myanmar macroinvertebrates to the countries in close proximity, we selected The Asia Foundation index.

6

This result is understandable, given that the Asia Foundation Index was developed for SE Asia in particular in the biogeographically comparable Mekong River basin. We modified this rapid macroinvertebrate bioassessment method by adding four taxa, to improve the precision of the method for use in Myanmar. These four taxa were found in Myanmar, but they were not included in the Asia Foundation Index ***(Research Question 2)***.

Chapter 4 looks at the impact of hydropower dams on aquatic assemblages downstream in the Myitnge and Chaungmagyi Rivers. We explored the ecological water quality upstream and downstream of the barriers using the modified rapid macroinvertebrate bioassessment method. Although all essential taxa, such as the sensitive and tolerant communities (Ephemeroptera, Plecoptera, Trichoptera, and

Odonata, i.e.EPTO), were found in both upstream and downstream locations, the ecological water quality was better upstream than the downstream of the dams. We concluded that macroinvertebrates could be used as an indicator to study the potential impact of dams in Myanmar ***(Research Question 3)***.

Chapter 5 describes the taxonomic composition of the aquatic macroinvertebrates in terms of family and morpho–species levels, and Functional Feeding Groups (FFG) of the Zawgyi River (a tributary of Myitnge River) and the associated human-made irrigation channels in central Myanmar, east of Mandalay. According to the identification process and statistical analysis, the difference between the communities of the river and irrigation channels was significant at morpho–species level. In contrast, the FFG contributions between the river and irrigation channels were insignificant. The estimated ecological water quality determined using a modified rapid macroinvertebrate bioassessment method of the river and associated human-made irrigation channels were not significantly different ***(Research Question 4)***. The ecological water quality results show that both the natural river and human-made channels have a pollution problem, caused by human activities. Chapter 5 emphasizes the vital role of irrigation channels and their aquatic ecosystems.

6.3. Data availability in Data-Scarce Regions

There is a famous quote about data science by W. Edwards Deming (1900-1993), who said that "Without data, you are just another person with an opinion." Equally, rivers are constantly changing over time, partly due to human influence, and decisions on the management of water resources in the present and future rely on timely and accurate data [171]. Therefore, without a robust data set, projects to develop water resource strategies and infrastructure are a wasted investment in terms of a country's development [40].

However, it is difficult to observe data with a consistent regularity and evaluate the quality of data. In the case of Myanmar, researching and measuring river health is difficult due to the instantaneous hydrological and metrological data gap [19, 21]. Additionally, inadequate financial and technical knowledge and support, which is quite common in low-income countries like Myanmar, adds to the data-gap. Indeed, the data is not very reliable. For example, there is a minimal data set for the issue of concentration of suspended sediment in the Ayeyarwady River basin. For reliability, we presented data validation in Chapter 2. Suspended sediment is a crucial variable for river health assessment. Therefore, we looked into the use of remote sensing data in this thesis.

Furthermore, there is currently no surface water quality monitoring network in Myanmar. The first study on the water quality monitoring network of the Ayeyarwady and Chindwin Rivers was published in 2019 [25]. However, there is still no water quality monitoring network in the tributaries, such as the Myitnge, Chaungmagyi, and Zawgyi Rivers.

Therefore, water resource researchers use space-data sets to monitor surface water quality, flow velocity, river morphology, soil erosion, and changes in land use on a large spatial scale [61, 64, 73, 34, 172]. There are numerous publicly accessible and copyright-free space-data sets, like NASA (https://www.nasa.gov/).

Sensors aboard satellites enable measurements of the optical properties (i.e. reflectance) of water at various wavelengths reflected by the water surface which can be correlated to water quality parameters using remote sensing techniques [34]. Thus, remote sensing techniques make it possible to measure the large spatial scale of water quality estimations in remote and inaccessible areas in water resources data scare regions [61, 64]. With advances in the technology of space data sets, the use of remote sensing techniques have become useful tools since the 1970s and continue to be widely used in water quality monitoring around the world [170].

However, the correlations between what can be directly detected from a satellite data-set versus a variety of water quality issues are limited, such as toxins, bacteria, pathogens, nutrients, biochemical and chemical oxygen demand [34, 35]. Despite this limitation, the use of remote sensing information appears to have great potential in monitoring and identification of water quality issues guiding allocation of limited in-situ sampling resources [35], as in developing countries like Myanmar.

Nevertheless, accessing the issue of resources is still a challenge in developing countries because high-resolution satellite data-sets are not easily accessible without the support of organizations and the capacity of adequate internet connections [61]. Currently, Myanmar's information technologies and communication sectors are improving, and adequate internet connections will be provided in the near future. An international collaboration network to ensure researchers of water resource technology support for analysing and interpreting large space data-set using remote sensing applications is still necessary.

Furthermore, the use of remote sensing to analyse the quality of water is problematic in a data-scarce country like Myanmar, as in-situ or ground observation data is needed to validate the space data-set. Illustrated by our research, available secondary suspended sediment concentration data is very limited in Myanmar, and when we performed a remote sensing analysis of the concentration of suspended sediment in the Ayeyarwady and Chindwin Rivers in the central dry zone of Myanmar, we had to carry out a field observation to obtain in-situ data. Based on our experiences of this field observation, field sampling for large rivers is quite expensive and time-consuming in terms of labour and travel. Consequently, it is challenging to build a broad and wide-ranging in-situ data-set for the whole Ayeyarwady River basin, which has a catchment area of 412,500 km^2.

A new approach to low-cost water quality monitoring is to use citizen volunteers to collect data of a large spatial coverage and aids to overcome the problem of data scarcity. A recent water quality monitoring study used mobile technology of non-expert and/or local volunteers in the Ayeyarwady and Chindwin Rivers. Weekly baseline water quality data, collected for three years by non-expert volunteers using test strips and sensors at seven locations, were presented [25]. The collected sensor-based EC and transparency by transparency tube results were consistent with the measurements of laboratory-based experiments.

We compared their transparency data with our SSC at the station of Mandalay (Ayeyarwady River) and Monywa (Chindwin River), where we collected water samples for SSC [mg/L] from January to March, 2017 (Chapter 2). We found the order of magnitude was reasonable ranged between transparency data by Thatoe Nwe Win et al [25] and our field sampling results of SSC (Figure 6.1).

Thus, this new transparency data can be useful in the remote sensing analysis of an SSC study. However, the transparency data points are still needed to set up more sampling points. For example, the distance between sampling points is quite far. There is only one sampling point in one Landsat image; Mandalay in Landsat (133Path/45Roll) and Monywa in Landsat (134Path/45Roll). In a remote sensing analysis, it is difficult to develop the regression line with only one in-situ data point. At least 20 or more in-situ data points are needed to establish a precise relationship between in-situ data and the reflectance of satellites images. In Chapter 2, we used 20 in-situ data points in a remote sensing analysis of suspended sediment concentration.

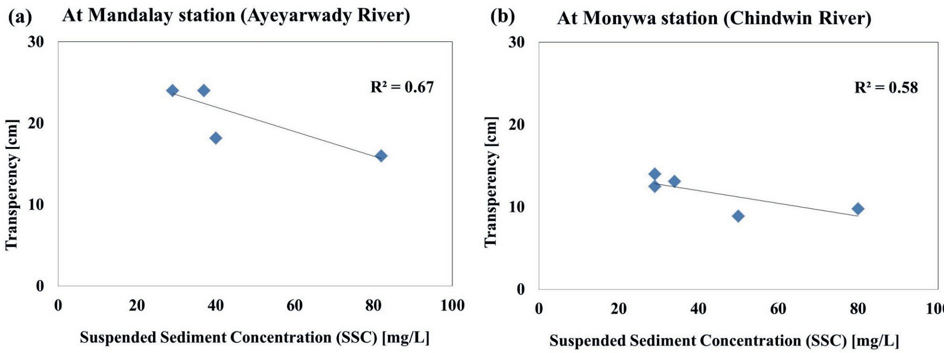


Figure 6.1: The comparison of field SSC (our results) with the transparency [cm] from the results by [25] (a): on Ayeyarwady River and (b): on Chindwin River

A low-cost water quality monitoring network using test-strips and sensor meters by mobile technology is one of the more positive efforts to improve and fill the data gap in Myanmar. However, as far as reliability is concerned, the accuracy of the results of test-strip could still be doubted [25]. Sensor meters, or single or multi-parameter photometers, can improve data uncertainties. However, it is more challenging to provide a sensor meter than a mobile phone application with a test-strip to each volunteer, as financial and technical issues are a hurdle for a broad range of monitoring programs in Myanmar.

Therefore, biological water quality monitoring techniques, using aquatic macroinvertebrate communities, have gained widespread use in both developed and developing countries, such as the United States, Europe, and South Africa. The use of macroinvertebrates to monitor water quality does not require expensive equipment, and it only needs a simple net. However, the awareness of biomonitoring using aquatic macroinvertebrate communities is limited in Myanmar.

Subsequently, there is no standard identification key to identify/distinguish different taxonomic levels. We developed the first illustrated keys using the identification keys of the Mekong River and its tributaries as a reference point [56]. We collected macroinvertebrate samples from 16 sampling sites for two sampling periods on eight rivers, and from six sampling sites for one sampling period on six human-made irrigation channels to develop an identification key for Myanmar's taxa. Thus, our current illustrated key cannot represent a national identification key for Myanmar, but is a base from which such a key can be developed.

Likewise, there is no standard biomonitoring index method in Myanmar. Therefore, we developed a modified biomonitoring index method to use in Myanmar. Then, we tested this index method in the study of human influences on river water quality, such as for instance the influence of dams and irrigation channels. We aimed to find a low-cost monitoring technique to improve the monitoring of river health in Myanmar. However, it should not be viewed that it can replace traditional water quality measuring/ research methods such as the ones using physical and chemical variables. Each different indicator identifies a different aspect of river health. Indeed, the biomonitoring associated with physical and chemical variables is vital to detect an environmental impact on the river health, and as a result effective management strategies can be formulated to address the different aspects of river health [2].

Water resources are essential for the development of a country like Myanmar. Nevertheless, unreliable hydrological and meteorological data can jeopardize the development and continuity of sustainable water resources. Currently, governmental and non-governmental organizations, researchers, academic staff, and students, are trying to solve water-related data-gap challenges. Therefore, Myanmar welcomes international collaboration projects to strengthen national strategies and policies in order to advance the development of sustainable water resources.

To date, there is an ongoing project supported by the World Bank to build the Hydro-Informatics Centre (HIC), a research-based non-profit consultancy firm which aims to support scientific researchers, students, and other institutions or clients in Myanmar (https://www.airbm.org/nwrc/).

The centre initially aims to help build Myanmar's infrastructure (personal communication) to create a national database. The initiative is crucial to build the basic fundamental requirements for data collection, analysis, evaluation, storage, and data sharing to the public. Collaboration spaces for young researchers, or researchers who need to use data, must be provided in the HIC to sustain a national data centre after the current World Bank project period. The HIC will thus provide substantial hydrological and metrological data for further research in Myanmar. Also, strategies for collaboration with international/national universities, and with industrial partners for funding, for capacity building and technology, are recommended to sustain a national data centre.

6.4. Challenges during field observation

Two years of field sampling observations were taken for this dissertation.

Firstly, we collected water samples of the Ayeyarwady and Chindwin rivers to monitor river sediment in the central dry zone of Myanmar. The Ayeyarwady River is the longest river in Myanmar (2210 km), and the Chindwin River is the largest tributary of the Ayeyarwady River (900 km). Thus, it is difficult to collect large range of water samples along both rivers. We agree with [73] that more in-situ data can provide a more precise regression line in remote sensing analyses. However, we could only collect water samples from 20 points on the Ayeyarwady River, within 100 km in one day, due to limited equipment and time. The assistance of non-expert volunteers, such as fishermen and boatmen, would help to increase the number of water samples.

The study of [173] is one example of the use of fisherman in water resources research on large tropical river basins, namely, the lower Mekong River basin going through Cambodia, Laos, Thailand, and Vietnam. They used 350 volunteer fishermen to identify fish migration routes and spawning habits in order to cover an area of 2500 km through four countries. We learned from this that it would be challenging to conduct research on a whole river basin without local knowledge and local volunteers. Therefore, if we train fishermen to use the sampling method, in the local language, it will not be a difficult task for them to collect samples of water across the river, as they are used to working on the river every day.

Building trust between scientists and fisherman, conveying awareness of the importance of a sustainable river and its environment, and a payment for the sample collection would hopefully motivate local volunteers. Indeed, the incentives to involve the citizens are highly dynamic in terms of time, cultural awareness, social responsibility and, in particular, whether citizens are willing to contribute to the project or not [174].

Secondly, we sampled aquatic macroinvertebrates in eight rivers in the northern region (Maykha, Malikha, Myitsone-Ayeyarwady, Yae Kyi), the northwest region (Myit Thar), and the central dry zone (Myitnge, Chuangmagyi, Zawgyi) in Myanmar. Also, we collected macroinvertebrate samples in six irrigation channels of the Zawgyi River. We collected twice a year, once at the beginning of the low-water season and, again, at the end of the low-water season, for all sampling sites, which is in line with [175]. Our sampling frequency is appropriate for our analysis because of the lifespan of aquatic macroinvertebrates, ranging from weeks to years depending on particular species [46, 47, 2].

Typically, spring and autumn are the best seasons for macroinvertebrate sampling, when the flow is stable and steady, allowing access to the rivers and habitats used by macroinvertebrates [176, 37]. Myanmar has a tropical monsoon climate, with a summer, a rainy, and a winter season. In the summer season (March-May), the water level is low in all water bodies and the temperature is high during the day and the night. In the rainy season (June-October) the water level is highest, and in the winter (November-February) the water level and flow are lowest. We used relatively low flow criteria as a visual expertise assessment when we selected the sampling sites and time. Sampling can be formulated according to the environmental conditions before sampling. For example, the sample should not be collected if there was a flood before sampling, and not for at least three or four weeks after [175]. Therefore, we propose the low-water seasons of summer and winter for further macroinvertebrate sampling in Myanmar's rivers and streams.

Based on our experience of field sampling in Myanmar, we learned that collaborative work with local people and local stakeholders from governmental and non-governmental organizations is vital. Local governmental organizations, such as the Irrigation Department, the Energy Hydropower Department and the army based at respective study areas, supported the collection of in-situ data for our study area, like flow discharge, mapping of irrigation water distribution, information about dams, weirs, and channels, as well as valuable information about the safety in locations. In Myanmar, safety is not guaranteed and access to certain areas was limited, such as the upstream sampling sites on the Myitnge and Chaungmagyi rivers in the east of the country, and sampling sites on the Myakha, Malikha, Myitsone-Ayeyarwady, and Yae Kyi Chaung rivers in the northern part of the country. We were protected by the local government military for safety purposes during field sampling.

Local people have a good knowledge of the rivers, as they often depend on them for their livelihoods. For example, we quickly found suitable sampling sites with the help of local people. Otherwise, it would have taken a lot of time to find appropriate sampling sites along the river. Besides, transportation is another issue with field sampling in Myanmar, as all our sampling sites were not accessible by public transport. The sampling sites on the Myitnge, Chaungmagyi, and Zawgyi rivers were only accessible by foot, meaning local knowledge was beneficial in helping us get to the sampling sites easily.

Moreover, non-governmental organizations (Fauna Flora International, FFI) volunteered to collect macroinvertebrate samples with us in the northern part of the country (Maykha and Malikha River). This cooperative work experience in the field can foster the opportunity to establish partnerships with universities and local non-governmental organizations to do citizen science in the future. The advantage of cooperating with local citizens who have experience in regional biology, is that they learn to understand the monitoring method and the sampling system.

Public relations and communication skills are most important, and we took advantage of being academic staff at the university to establish a communication network with both local people and stakeholders who were interested in contributing to the water quality monitoring campaign. Being a Myanmar researcher made it easier to establish a relationship with the local people as opposed to an international researcher, knowing the language and understanding the local culture and traditions. Based on our experience, collaborative research between national and international researchers can be more productive and protective in the exchange of local knowledge and modern technologies.

6.5. The potential use of Citizen Science Campaign

Generally, the score-based biomonitoring program was developed as a community monitoring approach in the field to monitor river water quality by local people or high school students (www.minisass.org, http://asiafoundation.org/, http://www.waterwatch.org.au/). However, it is difficult to accurately identify taxa in the field if you do not have much experience. With citizen monitoring, it cannot be expected of the community to identify species or genus taxonomic levels. However, they may well be able to identify with reasonable confidence the family level. But without a microscope we could lose track of the number of families counted in the field, even those aquatic macroinvertebrate families that can be seen with the naked eye. For example, the Prosopistomatidae can be wrongly identified due to their smooth and hemispherical body, and the fact that they are a rare and relatively small family of mayfly [2].

Besides, each taxon has a different ecological range of tolerance to environmental conditions. For example, the families of Ephemeroptera (Mayflies) are sensitive to water quality, but the sensitivity level of the families are not the same. For instance, families of Mayflies (e.g., Heptagenidae, Leptophlebiidae, Ephemerellidae) are more sensitive to water quality (sensitive score value - 10) than the Baetidae family (sensitive score value - 5) (Table 4.3, Chapter 4).

Nevertheless, the trade-off between the number of families or groups of taxa required for accurate monitoring and the difficulties in using local people to identify taxa must be taken into consideration when we develop a professional biomonitoring index on a national scale. Adapting the indexing method to local contexts and a training in the lab and in the field are recommended to provide participants with the appropriate cognitive skills. For example, after a month-long lab training, the ability to identify taxa should improve considerably, thus making it easier to identify taxa in the field with the naked eye. Training in the lab with a microscope is time consuming but beneficial work.

Thus, training in the field and in the lab are the best way to acquire knowledge and skills regarding field monitoring, and to motivate people to participate in the monitoring project. During the two-year sampling period of this thesis, we gave a knowledge-sharing seminars on ecological water quality monitoring using macroinvertebrate communities and conducted training in the field on how to monitor water quality at three technological universities (Myit Thar River, Ayeyarwady River: Myitsone and Zawgyi), the Department of Fisheries (Ayeyarwady River: Myitsone), two high schools (irrigation channels), and two villages (Zawgyi River). We recruited many participants in our seminar and training. Most people were fascinated by water quality monitoring and very eager to participate in the field and gain new knowledge.

One group of bachelor students and teaching staff from Technological University (Kalay), near Myit Thar River, is still working on water quality monitoring [177, 178]. They use a sensor meter, a multi-parameter photometer, a turbidity tube and the miniSASS biomonitoring Index to monitor the water quality in Myit Thar River and UBoke creek near Kalay city. The physiochemical parameters, such as turbidity, temperature and electric conductivity, the concentration of nitrate, nitrite, phosphate, chlorine, alkaline, iron, and pH, and the biological parameter (i.e. present macroinvertebrates groups) are measured at three locations at each watercourse twice a month on the same date in the summer and once in the rainy season. Based on the monitoring work, the miniSASS appeared to be much easier to use for non-expert teachers and students as it uses only order level (12 taxa groups) as compared to our modified Index proposed in Chapter 3 (48 taxa groups).

During our field training, we found that younger people, like university, high school students, and inexperienced teaching staff, responded more positively to our training than older people. This is consistent with the study of van Hamel [165], who interviewed people about a water quality monitoring project in Myanmar. Based on the answers of 405 interviewers from Mandalay (Myanmar's second largest city), Yangon (Myanmar's largest city), high schools and universities, the younger generation is more interested in participating because of the importance of science, data access and a feeling of civic duty, whereas, people from (sub)urban areas showed a sense of responsibility to participate, because they understood the positive impact of a better water quality on their life [165].

Thus, the younger generation is more aware and cooperative to contribute to monitoring in the field, as they are willing to confront new challenges in their life. The response to our training shows that young researchers will be an essential human resource in supporting water resources development projects in the future, if enough collaboration space to participate is available [171].

Both young and old people equally ranked data access as necessary in the data-scarce country of Myanmar [165]. The need for data is an important motivation for people to participate in water quality monitoring in Myanmar, which agrees with the findings of a review of citizen science in developed countries [179]. However, the protocol to motivate people to participate in projects in developed countries is different from that in developing countries. In developing countries, any kind of payment can be part of the daily income of citizen volunteers, whereas monetary payments are highly unusual in developed countries, where volunteering is a part-time activity [174]. The interviews conducted showed that the least cited reason for participating in Myanmar was the receiving of profit [165], but is probably due to the fact that it was a short-term study in a limited area. In order to recruit citizen volunteers for long-term water quality monitoring projects, to include a reward would be a great motivation. To summarise, recruitment, training, ability to use collected data, evaluating the process, and transparency are essential motivations to involve volunteers in projects in both developed and developing countries.

6.6. Perspectives for further study

In this thesis, we monitored the health of river ecosystems using remote sensing satellite images and freshwater macroinvertebrate communities. Our initial motivation was to encourage the use of aquatic macroinvertebrate communities to monitor river health in Myanmar. As a result of this study we would like to draw attention to several potential avenues for further research.

Firstly, we demonstrated the use of remote sensing information to monitor river sediment and surface water temperature in the Ayeyarwady and Chindwin Rivers before their confluence near Mandalay city. Using space datasets is a useful and practical approach, but an extensive range of in-situ data is needed for validation. According to our findings, presented in Chapter 2, the Chindwin River has a higher sediment concentration than the Ayeyarwady River, concurring with previous studies stating that approximately half of the sediment load in the lower Ayeyarwady River basin originates from the Chindwin River [74, 33]. Based on our knowledge, this high amount of sediment is possibly due to geological factors, catchment size and/or mining upstream the Chindwin River (near Homalin

Township). Empirical data is needed and it would be interesting to have more in-situ data points after/behind the confluence and upstream of the Chindwin River, before the mining area and after mining area, to see where a considerable amount of the sediment comes from and how much is deposited into the lower Ayeyarwady River. Therefore, we propose further research to be done in the upstream and after the confluence of both rivers.

Secondly, we focused on the use of aquatic macroinvertebrate communities, acting as reliable and low-cost indicators of river health in Myanmar. Due to the lack of any kind of standard identification keys in Myanmar, we introduced general information on aquatic macroinvertebrate families and species. We provided the first illustrated keys to identify taxa found in eight rivers and six human-made irrigation channels in Myanmar, based on the reference identification keys of the Mekong River basin [56]. The identification key is premature and needs to be supported by a more significant number of samples. This is important because without it our results have limited verification.

Our current identification keys need to be modified at a national scale based on all available taxa information around the country as we currently have a preliminary key to several taxa, designed to assist citizen science monitoring. We found Odonata of four families under two suborders, but the study in Nepal found 17 different families in three suborders [102]. We can expect to find new families in other rivers around the country. For example, identification keys on the Mekong River basin include 13 orders of aquatic and semiaquatic insects with 122 families. In the current study, we found ten orders of aquatic insects with 49 different families. Therefore, taxonomic research on other rivers and streams around the country is recommended to develop a professional identification key for freshwater macroinvertebrates in Myanmar.

Likewise, our current modified indexing method needs to be tested in other natural and semi-natural water bodies around the country, to check its utility and reliability in detecting the quality of river water. We developed an index based only on three sampling sites on the Myitnge and Chaungmagyi rivers in Myanmar, and we tested it in three rivers and six human-made irrigation channels in the current study. Therefore, the modified indexing method should be adapted by adding or eliminating taxa based on the taxonomic information of all rivers and streams in

Myanmar. Furthermore, as already mentioned in section 6.5 that the number of taxa groups for the index method is an important issue in the trade-off between scientific reliability and difficulties in using non-expert persons, when we develop a national biomonitoring index as a citizen science tool in the future.

After we developed identification keys and the modified indexing method, we successfully demonstrated the use of freshwater macroinvertebrates to study the impact of humans on rivers (Chapter 4) and human-made irrigation channels (Chapter 5). However, we still need to consider the use of freshwater macroinvertebrates for other issues, such as the impact of gold mining on the ecological water quality, which we have not yet tested.

During the process of field sampling, we found several gold mines along the Maykha and Maliha rivers in the northern part of Myanmar. Previous research has already stated the impact of gold mining on the quality of groundwater, due to the use of heavy metals such as cyanide, amalgam, and arsenic during the mining process near Mandalay in the centre of the country. However, in Myanmar, research on the impact of improper mining activities on the quality of surface water is still limited [23]. Therefore, it would be interesting to study the impact of gold mining on the quality of river water in the northern part of the country, which can provide valuable information to improve regional development.

Moreover, the northern region is one of the least developed regions in the country, particularly along the border, due to political and environmental issues. Access to most of the border regions of the country is limited due to inadequate public transportation, which can have an effect on the level of education, and economic and social development. Up to date we do not have any involvement of citizen science in the northern territories. A response to involve the project in the border regions of the country would be different as compared with the reaction from main cities, where participatory monitoring interviews by van Hamel [165] showed that the difference in response to participation by citizens in the cities of Mandalay and the area around Yangon was not significant. Therefore, it is necessary to do a participatory interview in the northern part of the country and the border of the country, if we want to establish a national plan for a citizen science project.

To conclude, we established a precedent for studying the use of macroinvertebrate communities to monitor river health in Myanmar. However, we still have much work to do in the future. In this study, I aspired to be useful and to help my people in my country. Therefore, I left my comfort zone of education to take on this challenge and gain new knowledge. I aimed to provide a reliable, low-cost method of scientific research to support, in part, the ongoing development of my country. However, although this research is vital in filling the knowledge gap regarding the biomonitoring approach to monitoring river health in Myanmar, there is still much more research that needs to be done. I still need to learn more regarding freshwater ecology and biology in water management.

References

[1] R. H. Norris and M. C. Thoms, "What is river health?" *Freshwater biology*, vol. 41, no. 2, pp. 197–209, 1999.

[2] D. Dudgeon, *Tropical Asian streams: zoobenthos, ecology and conservation*. Hong Kong University Press, 1999, vol. 1.

[3] S. Bunn, E. Abal, M. Smith, S. Choy, C. Fellows, B. Harch, M. Kennard, and F. Sheldon, "Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation," *Freshwater Biology*, vol. 55, pp. 223–240, 2010.

[4] J. R. Karr, "Defining and measuring river health," *Freshwater biology*, vol. 41, no. 2, pp. 221–234, 1999.

[5] D. J. Ollis, H. F. Dallas, K. J. Esler, and C. Boucher, "Bioassessment of the ecological integrity of river ecosystems using aquatic macroinvertebrates: an overview with a focus on south africa," *African Journal of Aquatic Science*, vol. 31, no. 2, pp. 205–227, 2006.

[6] R. Speed, C. Gippel, N. Bond, S. Bunn, X. Qu, Y. Zhang, W. Liu, and X. Jiang, "Assessing river health and environmental flow requirements in chinese rivers," *International Water Centre, Brisbane 63p*, 2012.

[7] A. J. Boulton, "An overview of river health assessment: philosophies, practice, problems and prognosis," *Freshwater Biology*, vol. 41, no. 2, pp. 469–479, 1999.

[8] C. Liu and X. Liu, "Healthy river and its indication, criteria and standards," *Journal of Geographical Sciences*, vol. 19, no. 1, pp. 3–11, 2009.

[9] P. G. Fairweather, "State of environment indicators of 'river health': exploring the metaphor," *Freshwater Biology*, vol. 41, no. 2, pp. 211–220, 1999.

[10] I. Maddock, "The importance of physical habitat assessment for evaluating river health," *Freshwater biology*, vol. 41, no. 2, pp. 373–391, 1999.

[11] C. J. Vörösmarty, P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. R. Liermann *et al.*, "Global threats to human water security and river biodiversity," *Nature*, vol. 467, no. 7315, p. 555, 2010.

[12] B. Davies and M. Wishart, "River conservation in the countries of the southern african development community," *Global perspectives on river conservation: science, policy and practice. John Wiley & Sons Ltd., London*, pp. 179–04, 2000.

[13] Y. Che, K. Yang, E. Wu, Z. Shang, and W. Xiang, "Assessing the health of an urban stream: a case study of suzhou creek in shanghai, china," *Environmental monitoring and assessment*, vol. 184, no. 12, pp. 7425–7438, 2012.

[14] G. Pan, Y. Xu, Z. Yu, S. Song, and Y. Zhang, "Analysis of river health variation under the background of urbanization based on entropy weight and matter-element model: A case study in huzhou city in the yangtze river delta, china," *Environmental research*, vol. 139, pp. 31–35, 2015.

[15] D. J. Allen, *The status and distribution of freshwater biodiversity in the Eastern Himalaya*. IUCN, 2010.

[16] A. C. Hughes, "Understanding the drivers of s outheast a sian biodiversity loss," *Ecosphere*, vol. 8, no. 1, p. e01624, 2017.

[17] D. Dudgeon, "Endangered ecosystems: a review of the conservation status of tropical asian rivers," *Hydrobiologia*, vol. 248, no. 3, pp. 167–191, 1992.

[18] ——, "The ecology of tropical asian rivers and streams in relation to biodiversity conservation," *Annual review of Ecology and Systematics*, vol. 31, no. 1, pp. 239–263, 2000.

[19] L. Taft and M. Evers, "A review of current and possible future human-water dynamics in myanmar's river basins," *Hydrology and Earth System Sciences*, vol. 20, no. 12, p. 4913, 2016.

[20] IFC and G. Myanmar, "Strategic environmental assessment of the hydropower sector in myanmar," 2018.

[21] K. M. Lazarus, P. Cardinale, M. Corbett, N. S. Lin, and T. K. H. Noeske, "Strategic environmental assessment of the hydropower sector in myanmar : Baseline assessment report : Introduction (english)."

[22] J. Bowles, "Ayeyarwaddy, the river endangered," 2013.

[23] T. H. Oo and T. Hata, "Approach to assessment of soil and water contamination by mining activities in mandalay region, myanmar," *INTERNATIONAL JOURNAL OF GEOMATE*, vol. 16, no. 57, pp. 130–136, 2019.

[24] S. Thiha, "Flood predictions in myanmar using distributed hydrological models."

[25] T. Thatoe Nwe Win, T. Bogaard, and N. van de Giesen, "A low-cost water quality monitoring system for the ayeyarwady river in myanmar using a participatory approach," *Water*, vol. 11, no. 10, p. 1984, 2019.

[26] S. M. Baban, "Detecting water quality parameters in the norfolk broads, uk, using landsat imagery," *International Journal of Remote Sensing*, vol. 14, no. 7, pp. 1247–1267, 1993.

[27] C. G. Fichot, B. D. Downing, B. A. Bergamaschi, L. Windham-Myers, M. Marvin-DiPasquale, D. R. Thompson, and M. M. Gierach, "High-resolution remote sensing of water quality in the san francisco bay–delta estuary," *Environmental science & technology*, vol. 50, no. 2, pp. 573–583, 2015.

[28] S. Munyika, V. Kongo, and R. Kimwaga, "River health assessment using macroinvertebrates and water quality parameters: A case of the orange river in namibia," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 76, pp. 140–148, 2014.

[29] G. C. Snow, "Determining the health of river-dominated estuaries using microalgal biomass and community composition," *South African journal of botany*, vol. 107, pp. 21–30, 2016.

[30] X. Deng, Y. Xu, L. Han, Z. Yu, M. Yang, and G. Pan, "Assessment of river health based on an improved entropy-based fuzzy matter-element model in the taihu plain, china," *Ecological Indicators*, vol. 57, pp. 85–95, 2015.

[31] J.-J. Wang, X. X. Lu, S. C. Liew, and Y. Zhou, "Remote sensing of suspended sediment concentrations of large rivers using multi-temporal modis images: an example in the middle and lower yangtze river, china," *International Journal of Remote Sensing*, vol. 31, no. 4, pp. 1103–1111, 2010.

[32] C. E. Torgersen, R. N. Faux, B. A. McIntosh, N. J. Poage, and D. J. Norton, "Airborne thermal remote sensing for water temperature assessment in rivers and streams," *Remote Sensing of Environment*, vol. 76, no. 3, pp. 386–398, 2001.

[33] R. A. J. Robinson, M. Bird, N. W. Oo, T. Hoey, M. M. Aye, D. Higgitt, A. Swe, T. Tun, and S. L. Win, "The irrawaddy river sediment flux to the indian ocean: the original nineteenth-century data revisited," *The Journal of Geology*, vol. 115, no. 6, pp. 629–640, 2007.

[34] F. Hellweger, P. Schlosser, U. Lall, and J. Weissel, "Use of satellite imagery for water quality studies in new york harbor," *Estuarine, Coastal and Shelf Science*, vol. 61, no. 3, pp. 437–448, 2004.

[35] G. Zheng and P. M. DiGiacomo, "Uncertainties and applications of satellite-derived coastal water quality products," *Progress in oceanography*, vol. 159, pp. 45–72, 2017.

[36] V. J. Santucci Jr, S. R. Gephard, and S. M. Pescitelli, "Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the fox river, illinois," *North American Journal of Fisheries Management*, vol. 25, no. 3, pp. 975–992, 2005.

[37] D. F. Buss, D. M. Carlisle, T.-S. Chon, J. Culp, J. S. Harding, H. E. Keizer-Vlek, W. A. Robinson, S. Strachan, C. Thirion, and R. M. Hughes, "Stream biomonitoring using macroinvertebrates around the globe: a comparison of large-scale programs," *Environmental monitoring and assessment*, vol. 187, no. 1, p. 4132, 2015.

[38] V. H. Resh and D. M. Rosenberg, *Freshwater biomonitoring and benthic macroinvertebrates*. Chapman & Hall New York, NY, USA:, 1993, no. 504.4 FRE.

[39] C. W. Dickens and P. Graham, "The south african scoring system (sass) version 5 rapid bioassessment method for rivers," *African Journal of Aquatic Science*, vol. 27, no. 1, pp. 1–10, 2002.

[40] S. Mustow, "Biological monitoring of rivers in thailand: use and adaptation of the bmwp score," *Hydrobiologia*, vol. 479, no. 1-3, pp. 191–229, 2002.

[41] T. H. Hoang, K. Lock, K. C. Dang, N. De Pauw, and P. Goethals, "Spatial and temporal patterns of macroinvertebrate communities in the du river basin in northern vietnam," *Journal of Freshwater Ecology*, vol. 25, no. 4, pp. 637–647, 2010.

[42] A.-S. S. ABDO, C. S. MD RAWI, A. H. Ahmad, and M. ROSMAHANIE MADRUS, "Biodiversity of stream insects in the m alaysian p eninsula: spatial patterns and environmental constraints," *Ecological Entomology*, vol. 38, no. 3, pp. 238–249, 2013.

[43] C. M. Sharma, S. Sharma, R. Borgstrom, and I. Bryceson, "Impacts of a small dam on macroinvertebrates: A case study in the tinau river, nepal," *Aquatic Ecosystem Health & Management*, vol. 8, no. 3, pp. 267–275, 2005.

[44] C. Dickens, A. Cox, R. M. Johnston, S. Davison, D. Henderson, P. Meynell, and V. Shinde, "Monitoring the health of the greater mekong's rivers," 2018.

[45] T. E. Eriksen, I. Nesheim, N. Friberg, T. T. Aung, and Z. W. Myint, "Characterization of the bago sub-basin pilot implementing the eu water framework directive," *NIVA-rapport*, 2017.

[46] W. D. Williams, *Australian freshwater life: the invertebrates of Australian inland waters*. Macmillan Education AU, 1980.

[47] B. C. CHESSMAN, "Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat-specific sampling, family level identification and a biotic index," *Australian Journal of Ecology*, vol. 20, no. 1, pp. 122–129, 1995.

[48] P. M. Graham, C. W. Dickens, and R. J. Taylor, "minisass—a novel technique for community participation in river health monitoring and management," *African Journal of Aquatic Science*, vol. 29, no. 1, pp. 25–35, 2004.

[49] D. L. Strayer, N. F. Caraco, J. J. Cole, S. Findlay, and M. L. Pace, "Transformation of freshwater ecosystems by bivalves: a case study of zebra mussels in the hudson river," *BioScience*, vol. 49, no. 1, pp. 19–27, 1999.

[50] A. Visser, L. Beevers, and S. Patidar, "Macro-invertebrate community response to multi-annual hydrological indicators," *River research and applications*, vol. 33, no. 5, pp. 707–717, 2017.

[51] A. W. Leslie and W. O. Lamp, "Taxonomic and functional group composition of macroinvertebrate assemblages in agricultural drainage ditches," *Hydrobiologia*, vol. 787, no. 1, pp. 99–110, 2017.

[52] C. H. Hocutt, "Assessment of a stressed macroinvertebrate community 1," *JAWRA Journal of the American Water Resources Association*, vol. 11, no. 4, pp. 820–835, 1975.

[53] C. J. Benetti, A. Pérez-Bilbao, and J. Garrido, "Macroinvertebrates as indicators of water quality in running waters: 10 years of research in rivers with different degrees of anthropogenic impacts," *Ecological Water Quality-Water Treatment and Reuse, Voudouris (Ed.)., InTech, China*, pp. 95–122, 2012.

[54] D. Castro, R. Hughes, and M. Callisto, "Influence of peak flow changes on the macroinvertebrate drift downstream of a brazilian hydroelectric dam," *Brazilian Journal of Biology*, vol. 73, no. 4, pp. 775–782, 2013.

[55] J. M. Serrana, S. Yaegashi, S. Kondoh, B. Li, C. T. Robinson, and K. Watanabe, "Ecological influence of sediment bypass tunnels on macroinvertebrates in dam-fragmented rivers by dna metabarcoding," *Scientific reports*, vol. 8, no. 1, p. 10185, 2018.

[56] S. Narumon and B. Boonsoong, "Identification of freshwater invertebrates of the mekong river and tributaries," *Faculty of Science, Appllied Taxonomic Research Center Khon Kean University, Khon Kean, Thailand*, 2004.

[57] N. Thanda Ko and M. Rutten, "Remote sensing analysis of temperature and suspended sediment concentration in ayeyarwady river in myanmar," in *EGU General Assembly Conference Abstracts*, vol. 19, 2017, p. 5261.

[58] J. D. Milliman and J. P. Syvitski, "Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers," *The journal of Geology*, vol. 100, no. 5, pp. 525–544, 1992.

[59] T. Furuichi, Z. Win, and R. Wasson, "Discharge and suspended sediment transport in the ayeyarwady river, myanmar: centennial and decadal

changes," *Hydrological Processes: An International Journal*, vol. 23, no. 11, pp. 1631–1641, 2009.

[60] W. Osterkamp, "Geoindicators for river and river-valley monitoring in the humid tropics," *Environmental Geology*, vol. 42, no. 7, pp. 725–735, 2002.

[61] T. M. Pavelsky and L. C. Smith, "Remote sensing of suspended sediment concentration, flow velocity, and lake recharge in the peace-athabasca delta, canada," *Water Resources Research*, vol. 45, no. 11, 2009.

[62] R. E. Villar, J.-M. Martinez, M. Le Texier, J.-L. Guyot, P. Fraizy, P. R. Meneses, and E. de Oliveira, "A study of sediment transport in the madeira river, brazil, using modis remote-sensing images," *Journal of South American Earth Sciences*, vol. 44, pp. 45–54, 2013.

[63] B. C. Ko, H. H. Kim, and J. Y. Nam, "Classification of potential water bodies using landsat 8 oli and a combination of two boosted random forest classifiers," *Sensors*, vol. 15, no. 6, pp. 13 763–13 777, 2015.

[64] C. Giardino, M. Pepe, P. A. Brivio, P. Ghezzi, and E. Zilioli, "Detecting chlorophyll, secchi disk depth and surface temperature in a sub-alpine lake using landsat imagery," *Science of the Total Environment*, vol. 268, no. 1-3, pp. 19–29, 2001.

[65] M. S. Latif, "Land surface temperature retrival of landsat-8 data using split window algorithm-a case study of ranchi district," *International Journal of Engineering Development and Research*, vol. 2, no. 4, pp. 2840–3849, 2014.

[66] R. Allen, M. Tasumi, and R. Trezza, "Metrict: Mapping evapotranspiration at high resolution," *Applications manual for landsat satellite imagery. Version*, vol. 2, no. 3, 2012.

[67] Y. Liu, M. A. Islam, and J. Gao, "Quantification of shallow water quality parameters by means of remote sensing," *Progress in physical geography*, vol. 27, no. 1, pp. 24–43, 2003.

[68] A. M. Bhatti, D. Rundquist, J. Schalles, L. Ramirez, and S. Nasu, "A comparison between above-water surface and subsurface spectral reflectances collected over inland waters," *Geocarto International*, vol. 24, no. 2, pp. 133–141, 2009.

[69] D. Doxaran, R. N. Cherukuru, and S. Lavender, "Estimation of surface reflection effects on upwelling radiance field measurements in turbid waters," *Journal of Optics A: Pure and Applied Optics*, vol. 6, no. 7, p. 690, 2004.

[70] M. Oxford, "Remote sensing of suspended sediments in surface waters," *Photogrammetric Engineering and Remote Sensing*, vol. 42, no. 12, pp. 1539–1545, 1976.

[71] R. L. Miller and B. A. McKee, "Using modis terra 250 m imagery to map concentrations of total suspended matter in coastal waters," *Remote sensing of Environment*, vol. 93, no. 1-2, pp. 259–266, 2004.

[72] P. Curran and E. Novo, "The relationship between suspended sediment concentration and remotely sensed spectral radiance: a review," *Journal of Coastal Research*, pp. 351–368, 1988.

[73] Z. Suif, A. Fleifle, C. Yoshimura, and O. Saavedra, "Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the mekong river basin," *Science of the Total Environment*, vol. 568, pp. 933–945, 2016.

[74] L. D. Stamp, "The irrawaddy river," *The Geographical Journal*, vol. 95, no. 5, pp. 329–352, 1940.

[75] N. T. Ko, P. Suter, J. Conallin, M. Rutten, and T. Bogaard, "The urgent need for river health biomonitoring tools for large tropical rivers in developing countries: Preliminary development of a river health monitoring tool for myanmar rivers," *Water*, vol. 12, no. 5, p. 1408, 2020.

[76] H. T. T. Hoang, T. T. Duong, K. T. Nguyen, Q. T. P. Le, M. T. N. Luu, D. A. Trinh, A. H. Le, C. T. Ho, K. D. Dang, J. Némery *et al.*, "Impact of anthropogenic activities on water quality and plankton communities in the day river (red river delta, vietnam)," *Environmental Monitoring and Assessment*, vol. 190, no. 2, p. 67, 2018.

[77] C. Nilsson and B. M. Renöfält, "Linking flow regime and water quality in rivers: a challenge to adaptive catchment management," *Ecology and Society*, vol. 13, no. 2, 2008.

[78] C. E. Hughes, "Are there many different routes to becoming a global biodiversity hotspot?" *Proceedings of the National Academy of Sciences*, vol. 114, no. 17, pp. 4275–4277, 2017.

[79] B. Boonsoong, N. Sangpradub, and M. T. Barbour, "Development of rapid bioassessment approaches using benthic macroinvertebrates for thai streams," *Environmental Monitoring and Assessment*, vol. 155, no. 1-4, pp. 129–147, 2009.

[80] R. B. Oliveira, R. Mugnai, C. M. Castro, and D. F. Baptista, "Determining subsampling effort for the development of a rapid bioassessment protocol using benthic macroinvertebrates in streams of southeastern brazil," *Environmental Monitoring and Assessment*, vol. 175, no. 1-4, pp. 75–85, 2011.

[81] D. F. Buss and A. S. Vitorino, "Rapid bioassessment protocols using benthic macroinvertebrates in brazil: evaluation of taxonomic sufficiency," *Journal of the North American Benthological Society*, vol. 29, no. 2, pp. 562–571, 2010.

[82] P. Armitage, D. Moss, J. Wright, and M. Furse, "The performance of a new biological water quality score system based on macroinvertebrates over a wide range of unpolluted running-water sites," *Water research*, vol. 17, no. 3, pp. 333–347, 1983.

[83] C. W. Dickens and P. M. Graham, "The south african scoring system (sass) version 5 rapid bioassessment method for rivers," *African Journal of Aquatic Science*, vol. 27, no. 1, pp. 1–10, 2002. [Online]. Available: https://doi.org/10.2989/16085914.2002.9626569

[84] D. F. Buss and F. F. Salles, "Using baetidae species as biological indicators of environmental degradation in a brazilian river basin," *Environmental Monitoring and Assessment*, vol. 130, no. 1-3, p. 365, 2007.

[85] I. A. WRIGHT, B. C. CHESSMAN, P. G. FAIRWEATHER, and L. J. BENSON, "Measuring the impact of sewage effluent on the macroinvertebrate community of an upland stream: the effect of different levels of taxonomic resolution and quantification," *Australian Journal of Ecology*, vol. 20, no. 1, pp. 142–149, 1995.

[86] D. J. Ollis, "Rapid bioassessment of the ecological integrity of the lourens, palmiet and hout bay rivers (south western cape, south africa) using aquatic macroinvertebrates," Ph.D. dissertation, Stellenbosch: Stellenbosch University, 2005.

[87] E. D. Stein, J. S. Brown, and R. D. Mazor, "Transferability of bioassessment indices among water body types and ecoregions: A california experiment in wetland assessment," *Ecological indicators*, vol. 81, pp. 65–73, 2017.

[88] M. Watson and H. Dallas, "Bioassessment in ephemeral rivers: constraints and challenges in applying macroinvertebrate sampling protocols," *African journal of Aquatic science*, vol. 38, no. 1, pp. 35–51, 2013.

[89] N. Nixon and M. Mustafa, "Asia foundation supports water quality monitoring project in mongolia," https://asiafoundation.org/2009/07/08/asia-foundation-supports-water-quality-monitoring-project-in-mongolia/, 2009.

[90] H.-I. C. (HIC), "Ayeyarwady soba 2017: Synthesis report state of the basin assessment (volume 1)."

[91] S. Choÿ and P. Thompsons, "River bioassessment and monitoring using benthic macroinvertebrate community structure: the monitoring river heath initiative," *Downstream effects of Landuse.(Department of Natural Resources, Brisbane)*, pp. 53–55, 1996.

[92] (DMH) Department of Meteorology and Hydrology, Myanmar, Yangon.

[93] F. M. Chutter, *Research on the rapid biological assessment of water quality impacts in streams and rivers: Final Report to the Water Research Commission*. WRC, 1998.

[94] B. C. Chessman, "New sensitivity grades for australian river macroinvertebrates," *Marine and Freshwater Research*, vol. 54, no. 2, pp. 95–103, 2003.

[95] K. Clarke and R. Gorley, "Primer v6: user manual/tutorial, primer e: Plymouth," *Plymouth Marine Laboratory, Plymouth, UK*, 2006.

[96] K. R. Clarke, "Non-parametric multivariate analyses of changes in community structure," *Australian journal of Ecology*, vol. 18, no. 1, pp. 117–143, 1993.

[97] T. Soldán and D. Braasch, "Two new species of the genus prosopistoma (ephemeroptera, prosopistomatidae) from vietnam," *Acta Entomologica Bohemoslovaca*, vol. 81, pp. 370–376, 1984.

[98] P. J. Suter, "The taxonomy and ecology of the ephemeroptera (mayflies) of south australia," Ph.D. dissertation, University of Adelaide, Department of Zoology, 1980.

[99] J. L. Carter, V. H. Resh, and M. J. Hannaford, "Macroinvertebrates as biotic indicators of environmental quality," in *Methods in stream ecology*. Elsevier, 2017, pp. 293–318.

[100] B. C. Chessman and M. J. Royal, "Bioassessment without reference sites: use of environmental filters to predict natural assemblages of river macroinvertebrates," *Journal of the North American Benthological Society*, vol. 23, no. 3, pp. 599–615, 2004.

[101] T. Prommi and P. Thamsenanupap, "Diversity and structure of trichoptera communities and water quality variables in streams, northern thailand," *International Journal of Environmental and Ecological Engineering*, vol. 9, no. 9, pp. 1065–1072, 2015.

[102] H. Nesemann, R. D. T. Shah, and D. N. Shah, "Key to the larval stages of common odonata of hindu kush himalaya, with short notes on habitats and ecology," *Journal of threatened Taxa*, pp. 2045–2060, 2011.

[103] J. V. Ward *et al.*, *Aquatic insect ecology. 1. Ecology and habitat.* John Wiley & Sons, Inc., 1992.

[104] W. Z. A.B.H Dim, M Rutten and O. Hoes, "Estimation of hydropoweer potential in myanmar," *Global Journal of Engineering and Technology Review*, vol. 2, no. 4, pp. 78–85, 2017. [Online]. Available: http://www.gjetr.org/pdf/vol-2.4/GCOET-00467.pdf.

[105] N. T. Ko, P. Suter, J. Conallin, M. Rutten, and T. Bogaard, "Aquatic macroinvertebrate community changes downstream of the hydropower generating dams in myanmar-potential negative impacts from increased power generation dams impact on aquatic macroinvertebrate community," *Frontiers in Water*, vol. 2, p. 57, 2020.

[106] B. D. Richter and G. A. Thomas, "Restoring environmental flows by modifying dam operations," *Ecology and society*, vol. 12, no. 1, 2007.

[107] S. E. Bunn and A. H. Arthington, "Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity," *Environmental management*, vol. 30, no. 4, pp. 492–507, 2002.

[108] Q. Chen, Q. Yang, and Y. Lin, "Development and application of a hybrid model to analyze spatial distribution of macroinvertebrates under flow regulation in the lijiang river," *Ecological Informatics*, vol. 6, no. 6, pp. 407–413, 2011.

[109] K. Li, C. Zhu, L. Wu, and L. Huang, "Problems caused by the three gorges dam construction in the yangtze river basin: a review," *Environmental Reviews*, vol. 21, no. 3, pp. 127–135, 2013.

[110] J. C. White, D. M. Hannah, A. House, S. J. Beatson, A. Martin, and P. J. Wood, "Macroinvertebrate responses to flow and stream temperature variability across regulated and non-regulated rivers," *Ecohydrology*, vol. 10, no. 1, p. e1773, 2017.

[111] C. Donnelly, N. Nalder, N. Paroschy, and M. Philips, "Issues and controversies associated with dam removals," *Canadian Dam Association Bulletin*, vol. 13, no. 1, pp. 7–18, 2002.

[112] N. Ishiyama, M. Ryo, T. Kataoka, S. Nagayama, M. Sueyoshi, A. Terui, T. Mori, T. Akasaka, and F. Nakamura, "Predicting the ecological impacts of large-dam removals on a river network based on habitat-network structure and flow regimes," *Conservation Biology*, vol. 32, no. 6, pp. 1403–1413, 2018.

[113] P. J. Dugan, C. Barlow, A. A. Agostinho, E. Baran, G. F. Cada, D. Chen, I. G. Cowx, J. W. Ferguson, T. Jutagate, M. Mallen-Cooper *et al.*, "Fish migration, dams, and loss of ecosystem services in the mekong basin," *Ambio*, vol. 39, no. 4, pp. 344–348, 2010.

[114] Q. Chen, X. Zhang, Y. Chen, Q. Li, L. Qiu, and M. Liu, "Downstream effects of a hydropeaking dam on ecohydrological conditions at subdaily to monthly time scales," *Ecological engineering*, vol. 77, pp. 40–50, 2015.

[115] D. Li, D. Long, J. Zhao, H. Lu, and Y. Hong, "Observed changes in flow regimes in the mekong river basin," *Journal of Hydrology*, vol. 551, pp. 217–232, 2017.

[116] J. B. Wallace and J. R. Webster, "The role of macroinvertebrates in stream ecosystem function," *Annual review of entomology*, vol. 41, no. 1, pp. 115–139, 1996.

[117] Q. A. Hussain, A. K. Pandit *et al.*, "Macroinvertebrates in streams: A review of some ecological factors," *International Journal of Fisheries and Aquaculture*, vol. 4, no. 7, pp. 114–123, 2012.

[118] F. R. Hauer and V. H. Resh, “Macroinvertebrates,” in *Methods in Stream Ecology, Volume 1*. Elsevier, 2017, pp. 297–319.

[119] R. M. V. Cortes, M. T. Ferreira, S. V. Oliveira, and F. Godinho, “Contrasting impact of small dams on the macroinvertebrates of two iberian mountain rivers,” *Hydrobiologia*, vol. 389, no. 1-3, p. 51, 1998.

[120] F. Xiaocheng, T. Tao, J. Wanxiang, L. Fengqing, W. Naicheng, Z. Shuchan, and C. Qinghua, “Impacts of small hydropower plants on macroinvertebrate communities,” *Acta Ecologica Sinica*, vol. 28, no. 1, pp. 45–52, 2008.

[121] E. Bredenhand and M. J. Samways, “Impact of a dam on benthic macroinvertebrates in a small river in a biodiversity hotspot: Cape floristic region, south africa,” *Journal of Insect Conservation*, vol. 13, no. 3, pp. 297–307, 2009.

[122] S. Vaikasas, K. Palaima, and V. Pliūraitė, “Influence of hydropower dams on the state of macroinvertebrates assemblages in the virvyte river, lithuania,” *Journal of Environmental Engineering and Landscape Management*, vol. 21, no. 4, pp. 305–315, 2013.

[123] C. Kuenzer, I. Campbell, M. Roch, P. Leinenkugel, V. Q. Tuan, and S. Dech, “Understanding the impact of hydropower developments in the context of upstream–downstream relations in the mekong river basin,” *Sustainability science*, vol. 8, no. 4, pp. 565–584, 2013.

[124] Department of Hydropower, Yeywa Dam, Yeywa Dam, 2017.

[125] Department of Irrigation, Mandalay, Mandalay, 2017.

[126] B. Richter, J. Baumgartner, R. Wigington, and D. Braun, “How much water does a river need?” *Freshwater biology*, vol. 37, no. 1, pp. 231–249, 1997.

[127] N. Conservancy, *IHA Software Version 7.1 User’s Manual, The Nature Conservancy*, 2009.

[128] F. O. Masese and P. Raburu, “Improving the performance of the ept index to accommodate multiple stressors in afrotropical streams,” *African Journal of Aquatic Science*, vol. 42, no. 3, pp. 219–233, 2017.

[129] R. W. Merritt, K. W. Cummins, M. B. Berg, J. A. Novak, M. J. Higgins, K. J. Wessell, and J. L. Lessard, “Development and application of

a macroinvertebrate functional-group approach in the bioassessment of remnant river oxbows in southwest florida," *Journal of the North American Benthological Society*, vol. 21, no. 2, pp. 290–310, 2002.

[130] S. Swanson, "Indicators of hydrologic alteration," *Resource Notes*, vol. 58, 2002.

[131] J. Eulderink, "Silenced rivers: Modelling and assessing the impacts of large-scale hydropower projects on the ecohydrology of the myitnge and myittha rivers in myanmar," Master thesis, 2019.

[132] M. Thoms, A. Close, T. Hillman, G. Jones, J. Koehn, J. A. G. Roberts, P. J. Suter *et al.*, "Report of the river murray scientific panel on environmental flows. river murray-dartmouth to wellington and the lower darling river," 2000.

[133] A. J. Boulton and M. A. Brock, "Australian freshwater ecology processes and management. 1999," *Glen Osmond SA: Gleneagles Publishing*.

[134] W. L. Paul, R. A. Cook, P. J. Suter, K. R. Clarke, M. E. Shackleton, P. J. McInerney, and J. H. Hawking, "Long-term monitoring of macroinvertebrate communities over 2,300 km of the murray river reveals ecological signs of salinity mitigation against a backdrop of climate variability," *Water Resources Research*, vol. 54, no. 9, pp. 7004–7028, 2018.

[135] C. T. Le, W. L. Paul, B. Gawne, and P. J. Suter, "Quantitative flow-ecology relationships using distributed lag nonlinear models: Large floods in the murray river could have delayed effects on aquatic macroinvertebrates lasting more than three decades," *Water Resources Research*, vol. 56, no. 8, p. e2019WR025896, 2020.

[136] B. D. Richter, J. V. Baumgartner, J. Powell, and D. P. Braun, "A method for assessing hydrologic alteration within ecosystems," *Conservation biology*, vol. 10, no. 4, pp. 1163–1174, 1996.

[137] J. Gore, "Hydrological change," *The rivers handbook: Hydrological and ecological principles*, vol. 2, pp. 33–54, 1994.

[138] FAO, "Overview agricultural atlas of the union of myanmar," 2009. [Online]. Available: http://dwms.fao.org/atlases/myanmar/atlas_en.htm

[139] J. Bacey and F. Spurlock, "Biological assessment of urban and agricultural streams in the california central valley," *Environmental monitoring and Assessment*, vol. 130, no. 1-3, pp. 483–493, 2007.

[140] R. Hughes, "Burma ruby • pigeon's blood • mogok stone tract," http://www.ruby-sapphire.com/pigeons-blood-mogok.htm, 2013.

[141] B. S. Anderson, B. M. Phillips, J. W. Hunt, V. Connor, N. Richard, and R. S. Tjeerdema, "Identifying primary stressors impacting macroinvertebrates in the salinas river (california, usa): Relative effects of pesticides and suspended particles," *Environmental Pollution*, vol. 141, no. 3, pp. 402–408, 2006.

[142] M. Kędra and Ł. Wiejaczka, "Climatic and dam-induced impacts on river water temperature: assessment and management implications," *Science of the Total Environment*, vol. 626, pp. 1474–1483, 2018.

[143] T. Mwedzi, T. Bere, N. Siziba, T. Mangadze, and C. Bangira, "Longitudinal macroinvertebrate assemblages in contrasting discontinuities: the effects of damming in tropical streams," *African Journal of Ecology*, vol. 54, no. 2, pp. 183–194, 2016.

[144] L. M. Mesa, "Interannual and seasonal variability of macroinvertebrates in monsoonal climate streams," *Brazilian Archives of Biology and Technology*, vol. 55, no. 3, pp. 403–410, 2012.

[145] N. T. Ko, P. Suter, J. Conallin, M. Rutten, and T. Bogaard, "Aquatic macroinvertebrate indicators in the zawgyi irrigation channels and a river in the central dry zone of myanmar," *Sustainability*, vol. 12, no. 21, p. 8788, 2020.

[146] A. Mabidi, M. S. Bird, and R. Perissinotto, "Distribution and diversity of aquatic macroinvertebrate assemblages in a semi-arid region earmarked for shale gas exploration (eastern cape karoo, south africa)," *PloS one*, vol. 12, no. 6, p. e0178559, 2017.

[147] P. Williams, M. Whitfield, J. Biggs, S. Bray, G. Fox, P. Nicolet, and D. Sear, "Comparative biodiversity of rivers, streams, ditches and ponds in an agricultural landscape in southern england," *Biological conservation*, vol. 115, no. 2, pp. 329–341, 2004.

[148] B. Davies, J. Biggs, P. Williams, J. Lee, and S. Thompson, "A comparison of the catchment sizes of rivers, streams, ponds, ditches and lakes: implications for protecting aquatic biodiversity in an agricultural landscape," in *Pond Conservation in Europe*. Springer, 2007, pp. 7–17.

[149] T. N. Simon and J. Travis, "The contribution of man-made ditches to the regional stream biodiversity of the new river watershed in the florida panhandle," *Hydrobiologia*, vol. 661, no. 1, pp. 163–177, 2011.

[150] B. Davies, J. Biggs, P. Williams, M. Whitfield, P. Nicolet, D. Sear, S. Bray, and S. Maund, "Comparative biodiversity of aquatic habitats in the european agricultural landscape," *Agriculture, Ecosystems & Environment*, vol. 125, no. 1-4, pp. 1–8, 2008.

[151] J. Biggs, S. Von Fumetti, and M. Kelly-Quinn, "The importance of small waterbodies for biodiversity and ecosystem services: implications for policy makers," *Hydrobiologia*, vol. 793, no. 1, pp. 3–39, 2017.

[152] K. T. Martinsen, M. R. Andersen, and K. Sand-Jensen, "Water temperature dynamics and the prevalence of daytime stratification in small temperate shallow lakes," *Hydrobiologia*, vol. 826, no. 1, pp. 247–262, 2019.

[153] C. F. Rabení, K. E. Doisy, and L. D. Zweig, "Stream invertebrate community functional responses to deposited sediment," *Aquatic Sciences*, vol. 67, no. 4, pp. 395–402, 2005.

[154] M. J. Hill, R. P. Chadd, N. Morris, J. Swaine, and P. J. Wood, "Aquatic macroinvertebrate biodiversity associated with artificial agricultural drainage ditches," *Hydrobiologia*, vol. 776, no. 1, pp. 249–260, 2016.

[155] A. W. Leslie, R. F. Smith, D. E. Ruppert, K. Bejleri, J. M. Mcgrath, B. A. Needelman, and W. O. Lamp, "Environmental factors structuring benthic macroinvertebrate communities of agricultural ditches in maryland," *Environmental Entomology*, vol. 41, no. 4, pp. 802–812, 2012.

[156] R. Barker, *Evolution of irrigation in South and Southeast Asia*. Iwmi, 2004, vol. 5.

[157] K. Frenken *et al.*, "Irrigation in southern and eastern asia in figures: Aquastat survey-2011." *Water Reports*, no. 37, 2012.

[158] D. Kartikasari, "Application of water quality and ecology indices of benthic macroinvertebrate to evaluate water quality of tertiary irrigation in malang district," *Journal of Tropical Life Science*, vol. 3, no. 3, pp. 193–201, 2013.

[159] P. D. Armitage, K. Szoszkiewicz, J. H. Blackburn, and I. Nesbitt, "Ditch communities: a major contributor to floodplain biodiversity," *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 13, no. 2, pp. 165–185, 2003.

[160] L. Fu, Y. Jiang, J. Ding, Q. Liu, Q.-Z. Peng, and M.-Y. Kang, "Impacts of land use and environmental factors on macroinvertebrate functional feeding groups in the dongjiang river basin, southeast china," *Journal of Freshwater Ecology*, vol. 31, no. 1, pp. 21–35, 2016.

[161] D. of Population Myanmar, "The 2014 myanmar population and housing census. the union report," 2015.

[162] R. W. Merritt and K. W. Cummins, *An introduction to the aquatic insects of North America*. Kendall Hunt, 1996.

[163] R. S. Ayers, D. W. Westcot *et al.*, *Water quality for agriculture*. Food and Agriculture Organization of the United Nations Rome, 1985, vol. 29.

[164] B. J. Kefford, "The relationship between electrical conductivity and selected macroinvertebrate communities in four river systems of south-west victoria, australia," *International Journal of Salt Lake Research*, vol. 7, no. 2, pp. 153–170, 1998.

[165] A. van Hamel, "Participatory monitoring myanmar: A research on the motivation of people in myanmar to participate in participatory monitoring by making use of q methodology," 2018.

[166] R. E. Uwadiae, "Macroinvertebrates functional feeding groups as indices of biological assessment in a tropical aquatic ecosystem: implications for ecosystem functions," 2010.

[167] C. C. Hakenkamp and M. A. Palmer, "Introduced bivalves in freshwater ecosystems: the impact of corbicula on organic matter dynamics in a sandy stream," *Oecologia*, vol. 119, no. 3, pp. 445–451, 1999.

[168] J. Gooderham and E. Tsyrlin, *The waterbug book: a guide to the freshwater macroinvertebrates of temperate Australia*. CSIRO publishing, 2002.

[169] H. Qadri and R. A. Bhat, "The concerns for global sustainability of freshwater ecosystems," in *Fresh Water Pollution Dynamics and Remediation*. Springer, 2020, pp. 1–13.

[170] M. H. Gholizadeh, A. M. Melesse, and L. Reddi, "A comprehensive review on water quality parameters estimation using remote sensing techniques," *Sensors*, vol. 16, no. 8, p. 1298, 2016.

[171] J. C. Davids, N. van de Giesen, and M. Rutten, "Continuity vs. the crowd—tradeoffs between continuous and intermittent citizen hydrology streamflow observations," *Environmental management*, vol. 60, no. 1, pp. 12–29, 2017.

[172] J. C. Davids, M. M. Rutten, R. D. T. Shah, D. N. Shah, N. Devkota, P. Izeboud, A. Pandey, and N. Van De Giesen, "Quantifying the connections—linkages between land-use and water in the kathmandu valley, nepal," *Environmental monitoring and assessment*, vol. 190, no. 5, p. 304, 2018.

[173] A. Poulsen, "Integration of fishers' knowledge into research on a large tropical river basin, the mekong river in southeast asia'," *Fisheries Center Research Reports*, vol. 11, no. 1, pp. 198–207, 2003.

[174] W. Buytaert, Z. Zulkafli, S. Grainger, L. Acosta, T. C. Alemie, J. Bastiaensen, B. De Bièvre, J. Bhusal, J. Clark, A. Dewulf *et al.*, "Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development," *Frontiers in Earth Science*, vol. 2, p. 26, 2014.

[175] J. Stark, I. Boothroyd, J. Harding, J. Maxted, and M. Scarsbrook, "Protocols for sampling macroinvertebrates in wadeable streams," 2001.

[176] S. P. Davies and L. Tsomides, *Methods for biological sampling and analysis of Maine's rivers and streams*. Citeseer, 2002.

[177] A. B. H. Dim, N. T. Win, and V. N. Maw, "Monitoring and analysis of the water quality of urban stream (uboke creek) in kalay township." First International Conference on Science and Technology for Sustainable Development 2019 (ICSTSD 2019), 2019.

[178] P. W. Thu, K. M. Kyaw, and A. B. H. Dim, "Monitoring and analysis of the water quality of myitthar river." First International Conference on Science and Technology for Sustainable Development 2019 (ICSTSD 2019), 2019.

[179] M. Rutten, E. Minkman, and M. van der Sanden, "How to get and keep citizens involved in mobile crowd sensing for water management? a review of key success factors and motivational aspects," *Wiley Interdisciplinary Reviews: Water*, vol. 4, no. 4, p. e1218, 2017.

[180] D. Hering, C. K. Feld, O. Moog, and T. Ofenböck, "Cook book for the development of a multimetric index for biological condition of aquatic ecosystems: experiences from the european aqem and star projects and related initiatives," in *The ecological status of European rivers: Evaluation and intercalibration of assessment methods*. Springer, 2006, pp. 311–324.

[181] A. A. Rosenberg and K. L. McLeod, "Implementing ecosystem-based approaches to management for the conservation of ecosystem services," *Marine Ecology Progress Series*, vol. 300, pp. 270–274, 2005.

[182] M. T. Barbour, J. Gerritsen, B. D. Snyder, J. B. Stribling *et al.*, *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish*. US Environmental Protection Agency, Office of Water Washington, DC, 1999, vol. 339.

[183] J. C. Morse, Y. J. Bae, G. Munkhjargal, N. Sangpradub, K. Tanida, T. S. Vshivkova, B. Wang, L. Yang, and C. M. Yule, "Freshwater biomonitoring with macroinvertebrates in east asia," *Frontiers in Ecology and the Environment*, vol. 5, no. 1, pp. 33–42, 2007.

[184] M. R. Commission, *Identification of freshwater invertebrates of the Mekong River and its tributaries*. Mekong River Commission, 2006.

[185] N. S. B. Boonsoong, "Indentification of feshwater invertebrates of the mekong river and its tributaries," *Mekong River commission, Vientiane, Lao*, 2006.

[186] R. Madden, *Being ethnographic: A guide to the theory and practice of ethnography*. Sage, 2017.

[187] R. Merritt, K. Cummins, and M. Berg, "An introduction to the aquatic insects of north america," 2008.

[188] A. E. Bogan, "Freshwater bivalve extinctions (mollusca: Unionoida): a search for causes," *American Zoologist*, vol. 33, no. 6, pp. 599–609, 1993.

[189] W. Nakahara, "The neurorthinae, a new subfamily of the sisyridae (neuroptera)," *Mushi*, vol. 32, no. 2, pp. 19–32, 1958.

Acknowledgements

For this long journey of PhD achievement, I have had the generous support from wonderful people.

Here, I would first thank to Prof. Nick van de Giesen for offering me the opportunity of doing Ph.D in Water Management Department at Delft University of Technology.

I would like to offer my special thanks to my Promotor, Dr. Thom Bogaard for giving me the opportunity of doing research under his supervision started from my second year of Ph.D. I would thank for his guidance, constructive comments, warm encouragement and persistent help on my Ph.D research. It was a real pleasure to work with him.

I would like to express gratitude to Dr. Martine Rutten for her insightful comments and suggestions which were influential in my research. And, it was almost six years ago that I had treasured support from Martine to begin this Ph.D. study with the support of the Netherlands Fellowship Programme. Thanks to Netherlands Fellowship Programe (Nuffic) for providing me with the financial means to complete this dissertation.

Additionally, I would like to express my deepest appreciation to Prof. Dr. Phil Suter who trained me well in the laboratory for the identification work which I did not have a background before. Phil also shared with me his immense knowledge and plentiful experience to encourage my research, especially to make preliminary identification key for aquatic macroinvertebrates from Myanmar's Rivers. His guidance and kind support made a strong foundation upon which I could do a pioneer study with confidence.

Advice, comments and support given by Dr. John Conallin have been a great help during Ph.D study. John offered great support and help in my field sampling for data collection. And, thanks for hosting me well like a family when I was in Australia. I appreciate his continuous support on my research and my daily life.

Mom...she gave me a beautiful life. I am always proud of being the daughter of a great mom. Everything that I got in my life is because of my mom's love and encouragement. Mom, I am deeply grateful for everything. I believe that she would be proud of me if she would see my great achievement which was one of her wishes for me. I would like to apologize that I could not make this dissertation in time before she leave.

My dear hubby is always a great partner in my life. He always give me a hand to support me. My field sampling journeys went well because of his help, otherwise, I would not get a wonderful data collection. Moreover, I was able to adapt well in both study and life during a long stay in the Netherlands because of his love, kindness, tremendous understanding, and encouragement in the past five years.

I am grateful to Mariette van Tilburg who gave me a lot of valuable review on my research writing. And, I would like to express my sincere gratitude to Veronique van der Varst for managing travelling, housing, insuring, and all essential administration works during my Ph.D. study. They made my life more convenience in the Netherlands.

My appreciation also goes out to my numerous friends and colleagues for offering support and a cherished time spent together all through my study.

A

Supplement

Aquatic Macroinvertebrates from Myanmar rivers and irrigation channels with illustrate keys to identify taxa

Introduction

Freshwater is a finite resource which contains a fascinating and remarkably varied array of small animals called freshwater benthic macroinvertebrates, offering goods and services of fundamental importance for the development of human societies [28]. To deal with the greater demands from burgeoning populations, the river development projects such as a dam, reservoirs are being undertaken for power generation, flood control and irrigation, which tend to increase the magnitude and extent of anthropogenic pressures on river ecosystem [121]. Understanding the taxonomic composition and diversity of benthic macroinvertebrates in rivers and streams has long been an important parameter to access the ecological status of a water body [180] as each of macroinvertebrates has its preferred environment associated with various types of river and stream substrates [101].

Assessment methods using macroinvertebrates have become more accepted internationally. [40] pointed out that most methods were developed for use in Europe and North America, such as in the European Union Water Framework Directive 2000, RIVPACS 2005 in the United Kingdom, the Australian River Assessment System 2005, and programs in Canada [181] and the United States [182, 183]. However, these biomonitoring methods have now been used globally. [183] concluded that the use of macroinvertebrates for monitoring water quality recently started to emerge in several Asian countries, such as Thailand and Malaysia, as follow.

[40] developed a score based system by modifying the Biological Monitoring Working Party (BMWP) system, which was developed for the British Department of the Environment in 1976, for Thailand (BMWPTHAI) by eliminating 15 taxa not found in Thailand and inserting 11 taxa which were present in Thailand. The ecological condition of Loei River and adjacent catchment in North-Eastern Thailand have been determined using benthic macroinvertebrates communities (at the Family level of Diptera, Ephemeroptera, Plecoptera, Trichoptera, and Coleoptera) from 20 sampling sites with multi-metric and multi-variate approached [79]. And, the regulation of diversity and composition of Ephemeroptera, Plecoptera, and Trichoptera (EPT) in the forested headwater streams of Malaysian Peninsula have been studied based on the key environmental and spatial factors controlling the EPT taxonomic composition [42].

However, the use of biomonitoring depends on the ability to identify invertebrates at a family, genus or species level, which is practical both in the field as well as in the laboratory. [102] created a key to identify to the family level of Odonata larvae of the Hindu Kush Himalaya in Nepal. They presented a total of 17 sub-families of three of the most common families in the suborders Zygoptera, Anisoptera, and Anisozygoptera based on collections from 2005 to 2009 from various parts of Nepal and the Northern part of India. The key was illustrated with colorful illustrations, thus enabling identification in the field and in the laboratory. Identification to species level are still rudimentary or non-existent for tropical Asian countries.

There are few exceptions such as The Mekong River Commission which developed a key to species level of freshwater invertebrates of the Mekong River and its tributaries in Cambodia, Lao PDR, Thailand, and Vietnam by modifying the keys of North American, British and Asian benthic macroinvertebrates [184]. Dudgeon (1999) [2] developed the identify key to species level for zoobenthic invertebrates of tropical Asian streams with a body length greater than or equal to 0.5mm. However, most of the species had not been recorded in Myanmar streams. He concentrated on functional feeding traits, hydrochemistry characteristics and floodplain ecology of tropical Asian running waters. Still, the alteration and loss of distribution and abundance of macroinvertebrates are not of particular concern yet in tropical Asian streams rather than attention on certain species such as river dolphins and mahseer fish species [2]. No systematic study of aquatic macroinvertebrates from streams in Myanmar have been undertaken and impacts of developments are largely unknown.

There is thus a need to undertake introductory research which deals with the general information of macroinvertebrate groups. This study aims to provide illustrated keys to taxa found in Myanmar streams in this study and to provide information on the ecology such as the habitats occupied and functional feeding groups of each of the major taxa. The keys are preliminary but will aid in the identification of the freshwater aquatic invertebrates of Myanmar in the future. However, the current study used the identification keys for freshwater invertebrates of the Mekong river and its tributaries by [184] and the tropical Asian streams by [2] and were used to identify collected taxa. Identification keys to the taxa of

Myanmar streams are presented but it is recognised that other taxa will be found with increased sampling in additional streams in Myanmar but these keys give a first attempt to enable the identification of the macroinvertebrates. This is the first such study in Myanmar rivers and irrigation channels in areas impacted by human activity.

Study area

Eight rivers, namely Maykha, Malikha, Ayeyarwady (Myintsone), Yae Kyi Chaung, Myit Thar, Chaungmagyi, Myitnge, and Zawgyi Rivers and six irrigation channels network of Zawgyi River were selected from the Ayeyarwady river basin in Myanmar for this study.

Maykha and Malikha Rivers are located at the Northern part of Myanmar, and have their origin from the Himalayan glaciers of eastern Myanmar and they meet together at about 43 km north of Myitkyina city to become the Ayeyarwady River. Yae Kyi Chaung is one of the tributaries of Ayeyarwady River and is located after the confluence of Maykha and Maylikha Rivers. Myintthar River is one of the tributaries of Chindwin River which is the biggest tributary of Ayeyarwady River. The detail of Chaungmagyi and Myitnge Rivers were already explained in Chapter 3 and 4. The Zawgyi River and its six irrigation channels were already explained in Chapter 5. The location of all study rivers and irrigation network are shown in Figure A.1.

Methods

The classification of aquatic macroinvertebrates follow the systematic hierarchy based on the resemblances between groups ranging from the highest level: an animal kingdom to the lowest level: individual [46]. The hierarchical levels are divided into five major taxonomic levels by the International Code of Zoological Nomenclature (ICZN) [185], are as follows:

PHYLUM

Order

Family

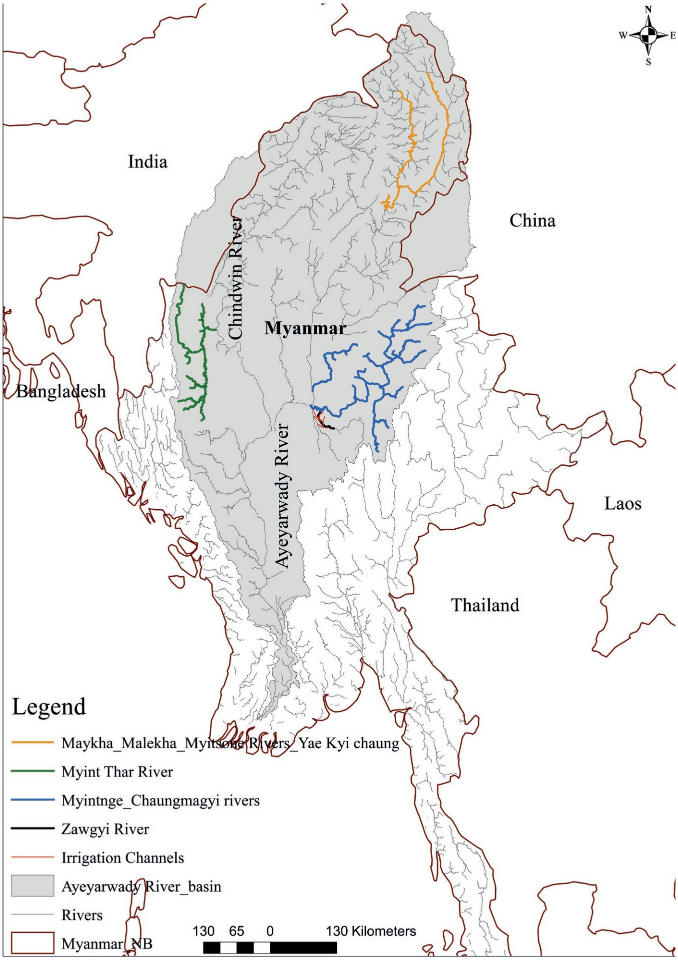


Figure A.1: The locations of all eight study rivers and irrigation network on the Ayeyarwady River basin in Myanmar

Genus

Species

There are two categories of freshwater invertebrates; 1) lower invertebrates which include Porifera, Cnidaria, Turbellaria, Nemertea, Nematoda, Nematomorpha, Ectoprocta, Polychaeta, Hirudinea and Branchiobdellida, and 2) higher invertebrates which includes Mollusca, Crustacea, Chelicerata, and aquatic insects [2]. This study mainly focused on the higher invertebrates; especially morpho-species which look morphologically different or genera with particular interest in all taxa or EPT and O (Odonata), with the body length greater than equal 0.5 mm which can be seen with the naked eye and which can be retained by a nylon net (500 μm 1000 μm mesh). Microscopic forms such as Zooplankton are not included here.

In this study, macroinvertebrates samples from 99 macroinvertebrates samples from eight rivers and six irrigation channels have been identified using the identification keys by [184] and [2]. This study constructed identification keys to taxa that were collected in Myanmar rivers and irrigation channels by modifying the keys from [184, 2, 46], and [186]. Ecological data were from personal observations and [2]. Functional feeding groups (FFG) from [2] and [187] were applied to classified FFG of collected macroinvertebrates taxa. Photographs were taken using a Nikon Digital Sight DS-fil digital camera or a DinoEye AM423 1.3MP microscope eyepiece camera with calibrated digital measuring software and images were assembled using Helicon Focus v5.2.9 (www.heliconsoft.com/helicomfocus).

Results

A total number of 2 Phyla, 58 family, 92 Genera with a total abundance of 9796 individual were collected from eight rivers and six irrigation channels in Myanmar. The total number of each major group are shown in Table A.1, A.2 and A.3.

Table A.1: Collected macroinvertebrates communities at order, family, and morpho-species from eight rivers and six human made channels (Remark: L = larva, A= adult, P=pupae, sp=specie)

Order	Family	Species	Rivers								Human-made channels
			Myitnge	Chaungmagyi	Malikha	Maykha	Myitsone	Yae Kyi Chaung	Myitthar	Zawgyi	Irrigation Channels
Ephemeroptera	Baetidae	*Platybaetis* sp 1	72	266	0	0	2	0	0	85	0
		Baetis sp 1	822	325	0	8	8	68	17	212	47
		Procloeon sp 1	6	0	0	0	0	0	1	0	0
	Prosopistomatidae	*Prosopistoma* sp 1	4	0	0	0	0	0	1	0	0
	Ephemeridae	*Ephemera* sp 1	3	0	0	0	0	0	0	0	0
	Heptagenidae	*Asionurus* sp 1	952	172	0	0	0	156	1	1	25
		Asionurus sp 2	0	89	0	0	0	0	0	0	2
	Caenidae	*Caenis* sp 1	112	37	0	0	0	5	22	3787	160
	Neoephemeridae	*Potamanthellus edmundsi*	0	0	0	0	0	0	2	0	0
	Leptophlebiidae	*Chloroterpes* sp 1	25	95	0	0	0	160	0	0	0
		Chloroterpidae sp	2	0	0	0	0	0	0	0	0
	Potamanthidae	Potamanthindus sp 1	0	1	0	0	0	0	0	0	0
	Polymitarcyidae	*Ephoron*	0	31	0	0	0	0	0	0	0
	Isonychiidae	*Isonychia*	0	1	0	0	0	0	0	0	0
	Ephemerellidae	*Torleya*	0	4	0	0	0	0	0	0	0
		Cincticostella gosei sp 1	0	15	0	0	0	0	0	0	0
Plecoptera	Perlidae	*Neoperla* sp 1	12	21	0	0	0	0	0	0	0
		Neoperla sp 2	5	9	0	0	0	13	0	0	0
		Neoperla sp 3	0	1	0	0	0	0	0	0	0
		Etrocorema sp 1	2	5	0	0	0	0	0	0	0
		Etrocorema sp 2	9	6	0	0	0	0	0	0	0
		Etrocorema sp 3	2	0	0	0	0	0	0	0	0
		Togoperla sp 1	0	12	0	0	0	0	0	0	0
		Togoperla sp 2	0	1	0	0	0	0	0	0	0
		Togoperla sp 3	0	23	0	0	0	0	0	0	0
Trichoptera	Hydropsychidae	*Potamyia* sp1	107	42	0	0	0	0	0	65	0
		Oestropsyche sp 1	1	0	0	0	0	0	0	0	0
		Macrostemum sp 1	76	41	0	0	0	0	0	0	0
		Amphipsyche sp 1	6	4	0	0	0	0	0	0	0
		Parpsyche sp 1	0	1	0	0	0	0	0	0	0
		Oxyethira			0	0	0	2	0	0	0
		Trichomacronema sp 1	0	46	0	0	0	0	0	0	0
	Helicopsychidae	*Helicopsyche* sp 1	1	0	0	0	0	0	0	0	0
	Odontoceridae	*Marilia* sp 1	22	9	0	0	0	0	0	0	0
	Dipseudopsidae	*Pseudoneureclipsis* sp 1	4	12	0	0	0	0	0	0	0
	Molannidae	*Molanna* sp 1	7	0	0	0	0	0	0	0	0
	Leptoceridae	*Triplectides* sp 1	1	0	1	0	0	1	0	0	0
		Oecetis sp 1	0	2	0	0	0	0	0	0	0
		Triplectides	1	0	0	0	0	0	0	0	0
	Stenopsychidae	*Stenopsyche* sp 1	0	5	0	0	0	43	0	0	0
		Stenopsyche sp 2	0	2	0	0	0	0	0	0	0
	Hydroptilidae	*Hydroptila*	0	6	0	0	0	0	0	0	0
	Ecnomidae	*Ecnomus*	0	4	0	0	0	2	0	0	0

Table A.2: Collected macroinvertebrates communities at order, family, and morpho-species from eight rivers and six human made channels (Remark: L = larva, A= adult, P=pupae, sp=specie) (continued)

Order	Family	Species	Rivers								Human-made channels
			Myitnge	Chaungmagyi	Malikha	Maykha	Myitsone	Yae Kyi Chaung	Myitthar	Zawgyi	Irrigation Channels
Odonata	Gomphidae	Gomphidae sp 1	65	8	0	0	0	1	5	2	19
		Gomphidae sp 2									
	Cordulidae	Corduliidae sp 1	1	1	0	0	0	0	0	0	0
	Megapodagrionidae	Megapodagrionidae sp 1	3	2	0	0	0	2	0	0	0
	Protoneuridae	Protoneuridae sp 1	1	0	0	0	0	0	0	0	0
	Euphaeidae	Euphaeidae sp 1	0	1	0	0	0	0	0	0	0
Megaloptera	Corydalidae	Corydalidae	6	8	0	0	0	0	0	0	0
Diptera	Ephydridae	Ephydridae	6	0	0	0	1	0	0	0	0
	Chironomidae	Orthocladinae	77	3	0	0	0	0	0	0	0
		Tanypodinae	1	0	0	1	0	12	0	130	7
		Chironominae (L)	2	24	0	0	0	0	2	0	0
		Chironomidae (P)	0	2	0	0	0	8	0	44	0
	Ceratopogonidae	Ceratopogonidae	3	0	0	0	0	0	0	2	8
	Tipulidae (L)	Tipulidae (L)	75	1	0	0	0	0	0	0	0
	Tipulidae (P)	Tipulidae (P)	17	0	0	0	0	0	1	0	0
	Tipulidae-Limoninae	Tipulidae-Limoninae	0	4	0	0	0	0	0	0	0
	Tipulidae	Tipulidae-Antocha	0	1	0	0	0	0	0	0	0
	Diptera (P)	Diptera (P)	10	0	0	0	0	0	0	0	0
	Athericidae	Athericidae sp 1	0	1	0	0	0	0	0	0	0
Coleoptera	Dytiscidae	Dytiscidae			0	0	0	0	0	0	56
	Noteridae	Noteridae sp 1	1	0	0	0	0	0	0	0	0
	Gyrinidae	Gyrinidae sp 1	1	0	0	0	0	0	0	0	0
	Hydrophilidae	Hydrophilidae			0	0	0	1	1	0	26
	Elmidae (L)	Elmidae (L) sp 1	0	1	0	0	0	1	0	32	10
		Elmidae (L) sp 2	0	0	0	1	0	0	0	0	0
		Elmidae (L) sp 3	32	1	1	0	0	0	1	0	0
		Elmidae (L) sp 4							1		
		Elimidae (A)	1	0	0	0	0	0	0	1	2
	Psephenidae	Psephenidae	1	0	0	0	0	2	0	0	0
	Scirtidae	Scirtidae sp						1			
	Carabidae	Carabidae			1	0	0	0	0	0	0
	Staphylinidae	Staphylinidae			2	1	0	0	0	0	0
Lepidoptera	Crambidae	Crambidae-Eoephyla	2	1	0	0	0	1	0	0	0
Hemiptera	Naucoridae	Naucoridae	2	3	0	0	0	4	0	0	0
	Aphelocheirus	Aphelocheirus sp 1	13	1	0	0	0	25	1	0	0
	Gelastocoridae	Gelastocoridae-Nerthra			0	0	2	0	0	0	0
	Micronectidae	Micronectidae	2	5	29	3	0	102	20	1	0
	Hebridae	Hebridae sp			0	0	1	0	0	0	0
Veneroida	Corbiculidae	Corbicula	53	0	0	0	0	0	0	36	74
Mesogastropoda	Thiaridae	Thiaridae	64	0	0	0	0	0	0	15	60
	Thiaridae-Melanoides	Thiaridae-Melanoides	19	0	0	0	0	0	0	0	0
	Bithyniidae	Bithyniidae sp	17	0	0	0	0	0	5	4	0
		Wattebledia			0	0	0	0	0	0	0
	Hydrobiidae	Hydrobiidae-Lacunopsis			0	0	0	0	4	0	0
	Viviparidae	Viviparidae	2	0	0	0	0	0	0	0	0

Table A.3: Collected macroinvertebrates communities at order, family, and morpho-species from eight rivers and six human made channels (Remark: L = larva, A= adult, P=pupae, sp=specie) (continued)

Order	Family	Species	Rivers								Human-made channels
			Myitnge	Chaungmagyi	Malikha	Maykha	Myitsone	Yae Kyi Chaung	Myitthar	Zawgyi	Irrigation Channels
Basematophora	Planorbidae	Planorbidae	1	0	0	0	0	0	0	0	0
Decapoda	Palaemonidae	Macrobrachium	12	0	0	0	0	0	1	17	0
	Margaritiferidae	Magaritiferidae			0	0	0	0	0	1	1
	Potamoidea	Parathelphusidae			0	0	0	0	0	3	2
Neuroptera	Sisyridae	Sisyridae			0	0	0	0	0	1	0
		Total abundance	2744	1356	34	14	14	610	86	4439	499
		Number of sites	4	3	1	1	1	1	3	2	6
		Nymber of occasion	2	2	1	1	1	1	1	2	1

Keys to Major Freshwater Invertebrates Groups

The following key to Phyla, Classes and Orders of Major freshwater invertebrates was created with the modification of the key from above references by eliminating some major groups not found in Myanmar. Therefore, if an animal does not fit in the major groups key presented here, then the identification key of [184] is recommended to be used. Key to Phyla, Classes and Orders of Major Groups in Myanmar

1 Body completely or largely enclosed by a calcareous shell which may be either coiled or spherical or bi-valved; unsegmented soft body with a ventral muscular foot..**Phylum MOLLUSCA**......2

1′ Segmented body not enclosed in a calcareous shell..................................3

2(1) Single shell unit.....................................**Class GASTROPODA** (page 173)

2′ Double shell unit...**Class BIVALVES** (page 176)

3(2) Body with obvious joined legs, a segmented body (i.e. head, thorax and abdomen)...**Phylum ARTHROPODA**........4

3′ Body without obvious joined legs, with some jointed appendages ....
....**Class INSECTA** (pupae or dipteran larvae)

4(3) Body with three pair of joined legs and one pair of antenna.................
....**Class INSECTA**(page 180)

4′ Body with more than four pairs of jointed legs and two pair of antennae
....**Subphylum CRUSTACEA**(page 178)

Phylum Mollusca

The phylum Mollusca is a large and important phylum with around 100,000 species already described [46]. Typically, the majority of species are marine with the total of five classes: Polyplacophora, Monoplacophora, Gastropoda, Bivalvia, and Cephalopoda but only two occur in freshwater, the Gastropoda and Bivalvia (also called Pelecypoda) [185].

Key to Mollusca of Myanmar

1 Body enclosed in a single shell ....**GASTROPODA**.........2

1′ Body enclosed in two shells or valves..............................**BIVALVES**.........7

2(1) Shell tall or globular with spire, shell, not flattened, operculum concentric or spiral,...**PROSOBRANCHIA**.........3

2′ Shell flat-coiled without a distinct elongate spire, without a concentric or spiral operculum .... **PULMNATA, PLANORBIDAE**

3(2) Shell with spire bi-coloured with alternating red and cream concentric circles ....**NEOGASTROPODA, BUCCIDAE**

3′ Shell with spire uniform coloured ....**MESOGASTROPODA**.........4

4(3) Shell smaller than 20mm...5

4′ Shell larger than 20 mm...6

5(4) Shell conical with large aperture that almost equal length of spire, spire with vertical striations ....**BITHYNIIDAE Wattebledia**

5′ Shell tall, elongate with small round aperture, diameter much shorter than spire ....**HYDROBIIDAE .... Hubendickia**

6(4) Opening elongated, shell with spiralled or concentric circles of slightly raised ridges ....**THIARIDAE** (2 morphospecies, sp 1 small approx. 20mm in length, sp 2 much larger than 20mm in length).

6′ Circular opening, shell globose, larger than 40 mm spire with strong ridges...... ....**VIVIPARIDAE**

7(1) Shell large, laterally compressed and elongated length > 45 mm and may be up to 180 mm long ....**MARGARITIFERIDAE**

7′ Shell with concentric raised ridges and not elongated, length > 10 mm and < 35mm long: shell solid, yellow-brown to dark olive-green or black............ ....**CORBICULIDAE**

Class Gastropoda

Gastropoda have a single shell either with a flattened spiral or the spire is elongate, helical unlike Bivalves which have a pair of hinged shells enclosing the body. The Gastropoda have been divided into two subclasses, the Prosobranchia called operculate snails and the Pulmonata called non-operculate snails.

Family Bithynidae

Operculum present, opening to shell rounded, shell spiral with vertical striations.

(a) (b)

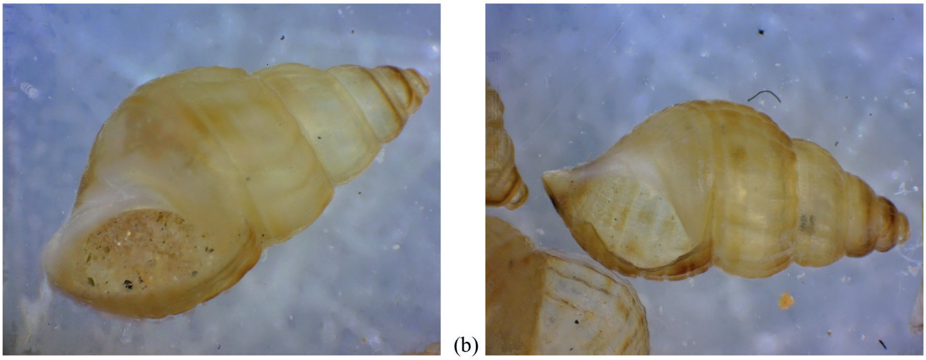


Figure A.2: (a):Bithynidae rounded opening, (b): Bithynidae vertical striations

Family Hydrobiidae Hubendickia

The size of shell are smaller than 20 mm. Operculum spiral without ridges present, opening are not constricted and basal whorl are not expanded.

Figure A.3: Hydrobiidae shell, strong spire with vertical striations.

Family Thiaridae

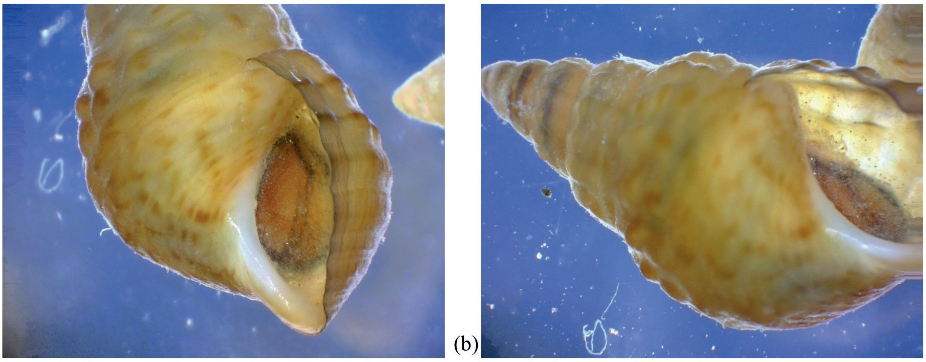
The size of the shell are larger than 20 mm. Shell with operculum; opening elongate; shell with spiraled or concentric circle of slightly raised ridges.

Family Viviparidae

Large shell >40mm, large circular opening, operculum present, spire with strong ridges.

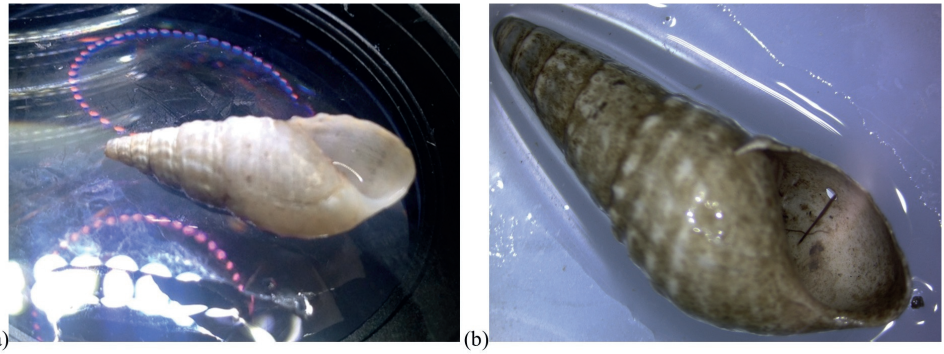
Family Buccidae

Shell with bands of colour and concentric ridges, siphonate opening.



(a) (b)

Figure A.4: (a):Thiaridae operculum and opening, (b):Thiaridae shell



(a) (b)

Figure A.5: Thiaridae sp 2 –very large shell > 20mm

Figure A.6: Viviparidae shell > 40mm

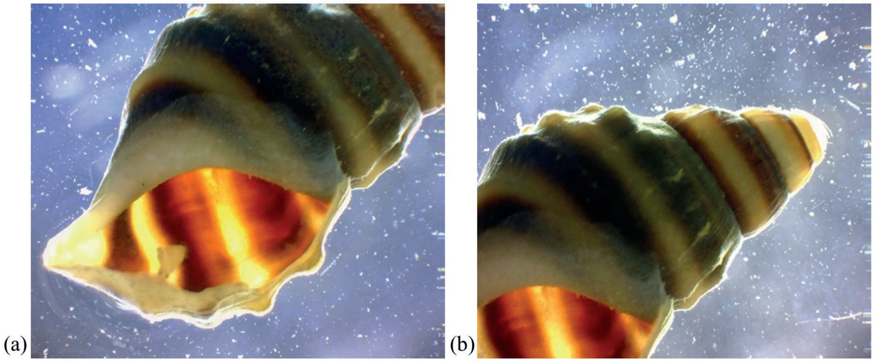


Figure A.7: (a):Buccidae siphonate opening, (b): Buccidae spire

Family Planorbidae

Shell planiform or flattened with open umbilicus, completely spire or circular flat. Normally, light or dark horn colour with the diameter of 2.5 to 3.5 mm. They usually live in ponds and lakes but also live in freshwater rivers.

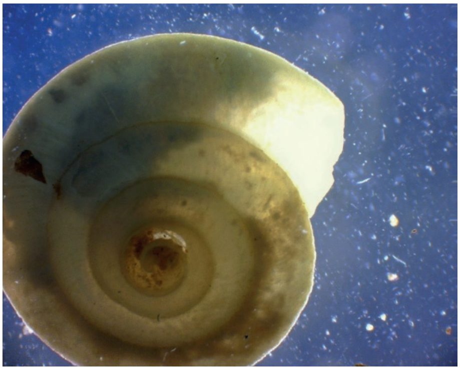


Figure A.8: Planorbidae spire flat

Class Bivalvia (Pelecypoda)

All forms of Bivalvia are known as freshwater mussels, freshwater cockles or orb mussels, pea-mussels which have two shell valves hinged together dorsally that can be closed over the soft inter central body mass. Freshwater bivalves occur in deep water, and frequently occur in shallow water [46] but they cannot withstand being exposed on rocky bottoms, or on the bottom of heavy loads of silt [188]. Bivalves feed on phytoplankton, bacteria and other small organic matter by filtering the water. The filtration rate varies with size, different species, and also the water temperature, size and concentration of sediment, and flow regime [49]. Bivalvia usually include relative large shell length often greater than 150 mm and relative small shell length smaller than 35 mm.

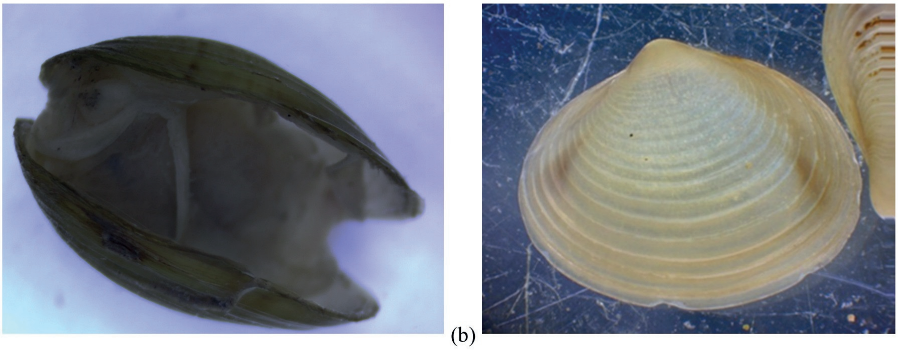
Family Margaritiferidae

Shell usually smaller than 180 mm long. Elongate shell and lacking umbo at the anterior end.

Figure A.9: Margaritiferidae shell

Family Corbiculidae

Shell coloured yellowish brown to dark olive-green or black, purple or violet coloured inner surface.



(a) (b)

Figure A.10: Corbiculidae

Phylum Arthropoda

Phylum Arthopoda is the most diverse phylum of macroinvertebrates in this study as 75 percentage of all well-known animal are included in this phylum. They are the main food sources for fishes and other large invertebrates communities. They can occupy all different types of habitats in streams and wetlands. Phylum Arthropoda included three subphyla (Chelicerata (Spiders), Crustacea, and Uniramia (insects)) of which only the Crustacea and Uniramia were collected in this study.

1 Three or less pairs of jointed legs, with one pair of antennae ....
....**Subphylum UNIRAMIA; Class INSECTA**

1′ Three or more pairs of joined legs, with two pair of antennae ....
....**Subphylum CRUSTACEA**

Subphylum Crustacea

Freshwater Crustacea include three orders: Decapoda, Isopoda and Amphipoda. The Decapoda is the most common occurring in tropical freshwater streams and include shrimps, crabs and crayfishes (Dudgeon, 1999b). Decapoda have five pairs of walking legs and the first legs and often second and third legs, are chelate. The body is enclosed with a carapace and the eyes are on stalks. In this study, only the families of the Decapoda have been discussed as the other orders were not collected.. The Decapoda are divided into two groups: Caridea and Brachyura.
Key to Order Decapoda of Myanmar

1 Laterally elongated carapace, with well-developed abdomen and swimming appendages (pleopods) beneath the abdomen (shrimps, prawns and crayfish) ....**Infraorder CARIDEA**............ 2

1′ Flattened carapace, reduced abdomen and swimming appendages not developed (crabs)...............................**Infraorder BRACHYURA**.........3

2(1) First two pairs of thoracic legs slender and similar, second pair of chelate limbs usually longer than the first, without terminal hair tufts of long seta, small to large size ....**Family PALAEMONIDAE, *Macrobrachium***

2′ First two pairs of thoracic legs broad and dissimilar, first and second chelae approximately the same size, with terminal hair tufts of seta, small size (< 35 mm)...**Family ATYIDAE**, ***Caridina***

3(2) Lateral margin of the carapace reaching front with one or more teeth, frontal medial triangle distinct, exopod of the third maxilliped with long flagellum ....**Family PARATHELPHUSIDAE**

3′ Lateral margin of the carapace reaching front with one tooth, frontal median triangle indistinct, exopod of the third maxilliped with flagellum vestigial or without flagellum.......................................**Family GECARCINUCIDAE**

Order Decapoda-Caridea

Family Palaemonidae Palaemonidae generally are called prawns and have elongated bodies with distinct head, thorax and abdomen. The head and thorax normally have been covered by a carapace. Two pairs of antennae and a pair of stalked eyes are situated on the head. They have at least five pairs of legs so called pereopods, the first three pairs of legs may have chela to feed on detritus or to hold prey. There are at least five swimming appendages on the abdominal segments called pleopods which are where the females hold eggs and developing young.

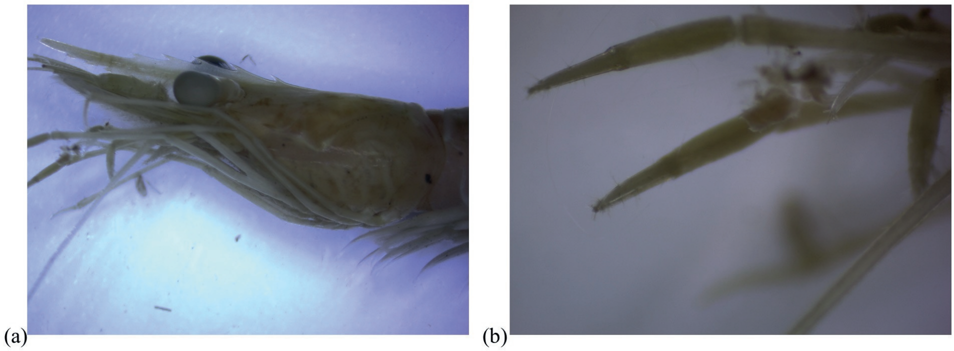


Figure A.11: Macrobrachium head and chelate.

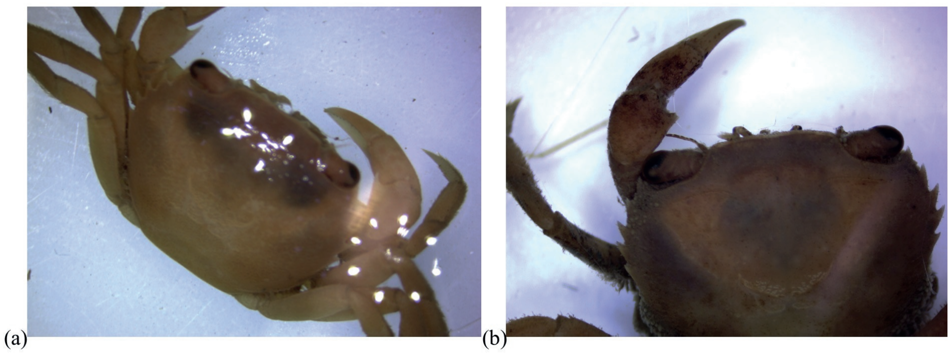


Figure A.12: (a):Parathelphusidae habitus, (b): Parathelphusidae Anterolateral margin with 3 teeth

Subphylum Uniramia

Class Insect

Of all insect orders, 13 have representatives that spend part of their life submerged in or associated with water [46]. Four orders, the Ephemeroptera, Plecoptera, Trichoptera and Odonata are aquatic in the juvenile stages but have terrestrial flying adults. The other nine orders, the Collembola, Hemiptera, Coleoptera, Neuroptera, Megaloptera, Mecoptera, Diptera, Hymenoptera and Lepidoptera are either aquatic or semiaquatic having aquatic juveniles and terrestrial adults or aquatic adults [46]. [2] stated that Ephemeroptera, Plecoptera, Trichoptera, Odonata Coleoptera and Diptera have highest diversity among these 13 orders.

All aquatic form of insect are mainly divided into two groups according to their life cycle except Collembola, they are Exopterygota and Endopterygota [184]. Collembola are significantly differ from other insects that they do not have wings and they are placed in the Apterygota (without wings) and are semiaquatic insects [184]. The Pterygota (with wings) or winged orders grow by moulting.and are systematically divided into two Divisions, the Exopterygota and the Endopterygota. All orders of Exopterygota have a hemimetabolous life cycle, in which immatures typically resembles the adult, have externally developing wing pads, and both nymphs, larvae and adults have compound eyes [2]. All adult of the Exopterygota develop from nymphs or larvae stage without passing a pupal stage, unlike the Endopterygota that develop with complete metamorphism which has a larva, a pupal stage and there is significant morphological difference between the adult and larva [46]. Endopterygota is also known as Holometabola as their wing pads develop internally. The systematic hierarchical structure of the aquatic insects is given in Table 3.1.

Insects bodies are composed of three parts: the head, three segments of the thorax (prothorax, mesothorax and metathorax), and eight - 11 segments of the abdomen (Figure A.13). Normally, they have a single pair of antenna on the head, and one or two pair of wings on the mesothorax or metathorax segments of the thorax, and no pleopods on the abdomen [46].

The aquatic insects breath underwater using either atmospheric oxygen or dissolved oxygen through gills, trachea and spiracles along the thorax and abdomen. There are two respiratory systems in the insects, aeropneustic and

Table A.4: The systematic hierarchical structure of the aquatic insects

Phylum	Sub-phylum	Class	Subclass	Infraclass	Division	Order
Arthropoda	Uniramia	Insecta	Apterygota			Collembola
			Pterygota	Palaeoptera	Exopterygota	Ephemeroptera
						Odonata
				Neoptera	Exopterygota	Plecoptera
						Hemiptera
						Orthoptera
					Endopterygota	Neuroptera
						Megaloptera
						Trichoptera
						Lepidoptera
						Coleoptera
						Diptera
						Hymenoptera

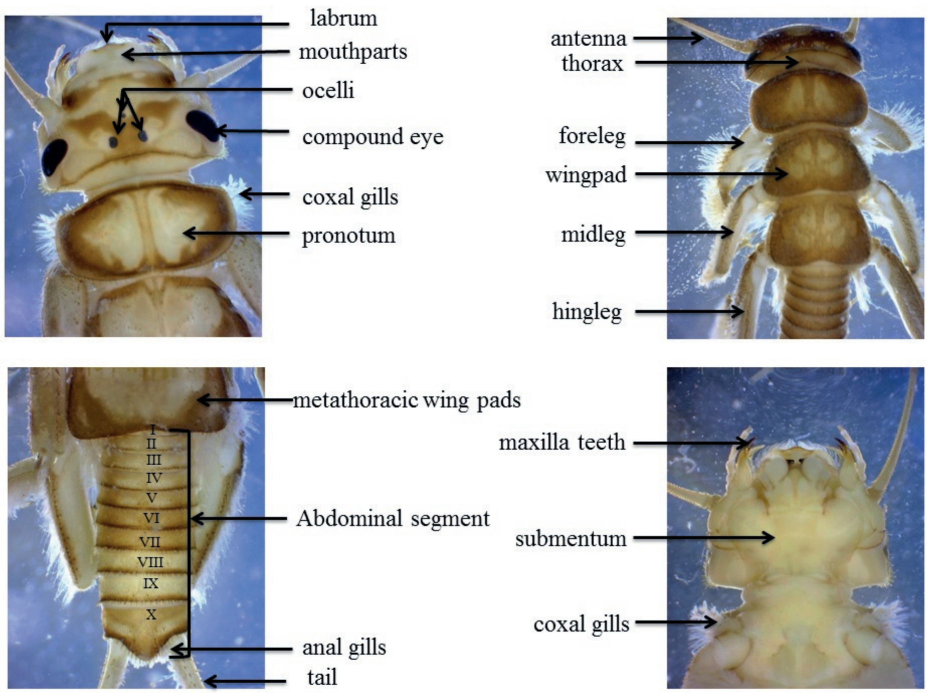


Figure A.13: Dorsal view and ventral view of Pelcoptera, Neoperla

hydropneustic. Typically, aeropneustic insects use atmospheric oxygen by way of respiration siphon or spiracles. These aeropneustic insects such as certain bugs and beetles come to the water surface at interval to fill up oxygen to survive underwater for hours or even days.

Most of the aquatic insects larvae are hydropneustic and absorb dissolved oxygen through a thin cuticle, either lamellate projections or filamentous bunches or tufts or gills. Those insects with cutaneous respiration favour well-aerated water. They have thin-walled bodies with.gills or outgrowths which vary in different orders of insects. Ephemeroptera, Plecoptera, Trichoptera and Lepidoptera breath through gills, Megaloptera breath by filamentous tufts, and Zygoptera (damselflies) have lamellae projections to absorb dissolved oxygen [2].

Key to Insect Order of subclass Pterygota recorded in Myanmar streams.

1 Wings present with forewings hard usually covering membranous hind wings (adults), insects able to fly 2

1′ Without well developed wings and insects unable to fly (nymphs and larvae)..3

2(1) Forewings hard and sclerotized, each symmetrical meeting in the centre of the body, mouthparts with biting mandibles .... **Order COLEOPTERA (Beetles) (page.229)**

2′ Forewings leathery, folded asymmetrically on the back, mouthparts with piercing conical rostrum (Fig.A.49) or triangular rostrum (Fig.A.51) ....**Order HEMIPTERA (page.208)**

3(1) With 3 pairs of segmented legs 4

3′ With stumpy prolegs only .... **Order DIPTERA (page. 237)**

4(3) Larvae live within a case 5

4′ Larvae free living without a case 6

5(4) Legs long, case of sand grains, sticks or leaves, silk ....**Order TRICHOPTERA (page. 213)**

5′ Legs short and stumpy, case of coarse vegetation ....**Order LEPIDOPTERA (page. 227)**

6(4) Wing pads present on mesothorax and metathorax 7

6′ Wing pads absent...10

7(6) Abdominal 'tails' absent, mouth cover by mask-like labium (Dragonflies) (Fig.A.32) ....**Order ODONATA (page.198)**

7′ Abdomen with 2 or 3 'tails', mouth not covered by labium 8

8(7) Three 'tails' are flattened or saccoid gills with hinged labium (Damselflies) ....**Order ODONATA (page. 198)**

8′ Tails filamentous and segmented 9

9(8) Three caudal filaments or cerci (tails), (rarely two) middle filament may be absent or reduced.......................**Order EPHEMEROPTERA (page.183)**

9′ Usually two caudal filaments or cerci (tails) ....**Order PLECOPTERA (page.203)**

10(6) Mouthparts with short and curved mandibles 11

10′ Mouthparts with straight mandibles which are longer than head ....**Order NEUROPTERA (page 245)**

11(10) Abdomen with 7-8 pairs of fleshy projections ....**Order MEGALOPTERA (page 245)**

11′ Abdomen with up to 10 fleshy projections 12

12(11) Last abdominal segment with large hooked anal prolegs .... **Order TRICHOPTERA (page. 213)**

12′ Last abdominal segment without large hooked anal prolegs larvae) ....**Order COLEOPTERA (page. 229)**

ORDER EPHEMEROPTERA (MAYFLIES)

Characters: Three caudal filaments or cerci (tails), which are distinctly segmented. Middle filament may be absent or reduced. Gills usually along margins of the abdomen from segment 1–7 or 1–5. Head may be hypognathous or prognathous.

Key to Mayflies of Myanmar

1 Body smooth and hemispherical; thorax and abdomen covered by a dorsal shield or carapace; legs also covered by carapace ....**PROSOPISTOMATIDAE; *Prosopistoma***

1′ Body not as above, legs obvious 2

2(1) Head prognathous, distinctly forward directed and body flat (dorso- ventrally flattened), usually with crawling legs; terminal filaments lacking swim hairs but a circle of spine setae at apex of each segment 3

2′ Head hypognathous, distinctly pointing downwards, body cylindrical with terminal filaments with long fine swim hairs on margins. Body streamlined for swimming 13

3(2) Head with mandibular tusks; legs modified for digging (broad) or for filter feeding (with long hair tufts) 4

3′ Head lacking mandibular tusks; legs not broad or modified for digging.......6

4(3) Head with frontal projections; legs robust or flattened or forelegs slender with long filtering hairs 5

4′ Head lacking frontal projection; legs all long and slender; gills extend laterally; mandibular tusks lacking long setae ....**POTAMANTHIDAE**

5(4) Head with a bifid frontal projection and smooth mandibular tusks; abdominal gills on segment 2-7 double and fringed, first gill asymmetrical; legs robust or flattened for digging............................... **EPHEMERIDAE;*Ephemera***

5′ Head lacking bifid projection; mandibular tusks robust and covered with tubercles; curved inwards; gills large and leaf shaped (lanceolate); $1^{-}st$ gill single; forelegs with long filtering setae................ ....**POLYMITARCIDAE;*Ephoron***

6(3) Second abdominal segment with an operculate gill (gill cover) which may cover more posterior gills 7

6′ Gills present on segments 1-7 or 3–7 and not covered by a gill cover; metathorax (wing pads) when developed extend over abdominal segments; first gill usually similar to other gills, but may be smaller 8

7(6) Second gill (gill cover) covers other gills; gill cover with a triangular section dorsally and each cover overlaps; metathorax in mature animals does not extend over abdomen; 1st gill a single filament.................................. ....**CAENIDAE; *Caenis***

7′ Second gill (gill cover) lacking triangular dorsal ridges dorsally; gill covers do not overlap; first abdominal segment without a gill..............................
....**Neophemeridae; *Potamanthellus***

8(6) Head with a flat plate–like extension which covers all mouthparts; abdominal gills 1–6 with an outer plate–like lamella and an internal tuft of filaments; 7th gill long at least 3 times longer than wide...............
....**HEPTAGENIIDAE; *Asionurus***...............9

8′ Head lacking plate–like cover, labrum and mouthparts obvious when viewed dorsally; gills paired 10

9(8) Colour pattern on abdomen uniform except for distinct markings on segments 7 and 8; thorax mainly light brown with 2 light lateral spots and head with 2 posterior placed light spots ....***Asionurus* sp 1**

9′ Colour pattern on abdomen with light markings on segments 1, 4 and 8–9; thorax mainly light with dark patches; head with 2 light spots and an laterally enlarged light posterior strip near the back of the head........***Asionurus*** sp 2

10(8) Gills paired on abdominal segments 1–7 and with inner and outer lamellae with three finger–like projections (trachea); abdominal segments without paired dorsal spines ....**LEPTOPHLEBIIDAE** 11

10′ Gills absent on abdominal segments 1 and 2; gills generally plate like lacking terminal tracheal filaments; abdominal segments with paired dorsal spines ....**EPHEMERELLIDAE** 12

11(10) Maxillary and labial palpi long, elongate and extend beyond side of head, clearly seen from above .... ***Choroterpides***

11′ Maxillary and labial palpi not obviously extended beyond side of head ....
....***Choroterpes***

12(10) Gill on abdominal segment 3 enlarges somewhat operculate ....
....***Torleya***

12′ Gills on abdominal segment 3 not enarged and similar to all other gills..***Cincticostella gosei***

13(2) Forelegs with tufts of long filtering setae on femora and tibiae; gills with an lamella single with clear trachea; coxal gills (ventral at base of legs) present ....**ISONYCHIDAE; *Isonychia***

13′ Forelegs without filtering setae; coxal gills absent 14

14(13) At least some gills with paired plate–lamellae 15

14′ Gills not paired (single) 16

15(14) Gills on segment 1-6 double and large almost circular, gill 7 single ....**BAETIDAE; *Cloeon***

15′ Gills on segments 1-5 double and small lanceolate shaped; lamellae of gills asymmetrical with one larger than other; gills 6 and 7 single ....**BAETIDAE; *Procloeon***

16(14) Legs fringed with long hairs; terminal filament (middle tail) reduced and less than half length of cerci .... **BAETIDAE; *Platybaetis***

16′ Legs not fringed with long hairs, but sparse, short, blunt setae present on edges of legs; all tails similar in size........................... **BAETIDAE; *Baetis***

Family Prosopistomatidae–Prosopistoma

Body smooth and hemispherical with thorax and much of the abdomen including the gills covered by a thoracic shield or carapace. Species of Prosopistoma can be distinguished by the dorsal colour pattern.The species present is near Prosopistoma funanense.

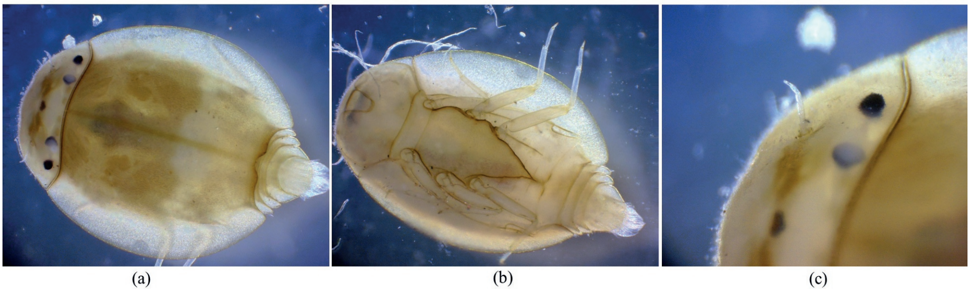


Figure A.14: (a):*Prosopistoma* dorsal, (b): *Prosopistoma* ventral, (c):*Prosopistoma* antenna

Family Ephemeridae–Ephemera

Head with mandibular tusks, best seen by looking ventrally on head, gills on abdominal segments 2–7 double with fringed margin and angled backwards and dorsally above abdomen, legs (especially tibia) robust or flattened for digging. smooth and slender curving outwards with inner edges convex. Head with well-developed frontal processes and bifid, abdominal gill on abdominal segment 1 asymmetrical with a larger outer lobe. Cerci with swimming hair fringe.

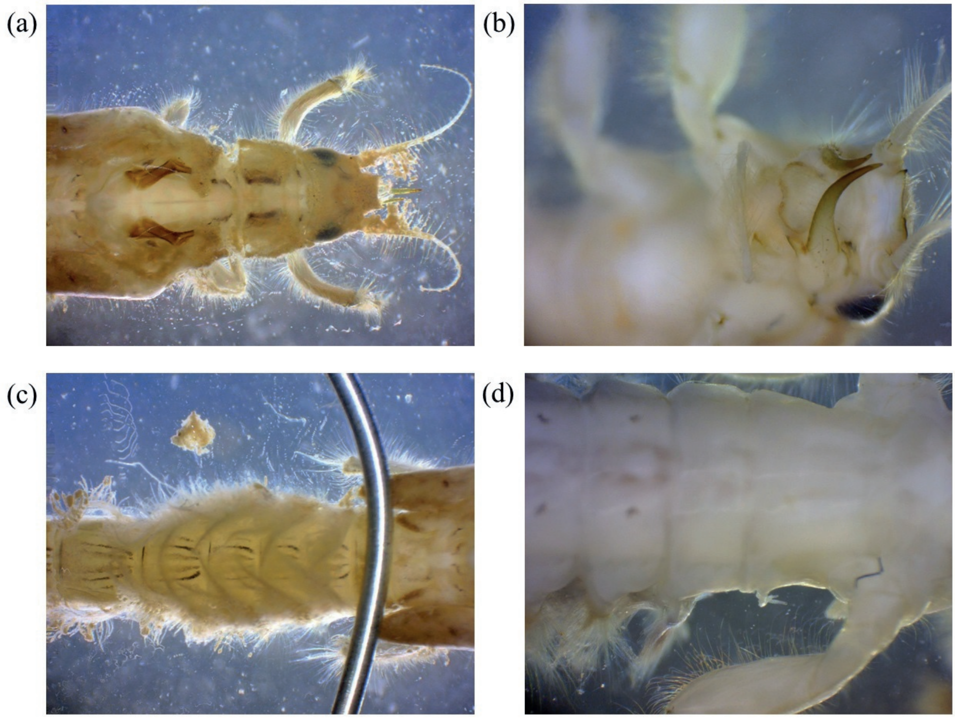


Figure A.15: (a):*Ephemera* head and thorax, (b): *Ephemera* ventral tusks, (c):*Ephemera* abdominal pattern, gills, (d)*Ephemera*1st gill

Family Ephemerellidae - Torleya

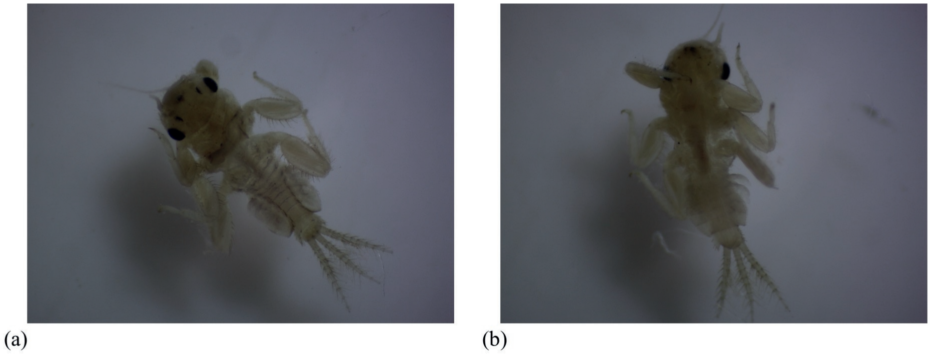
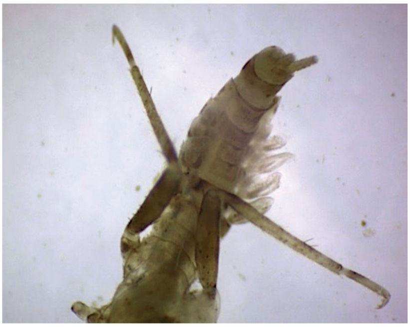
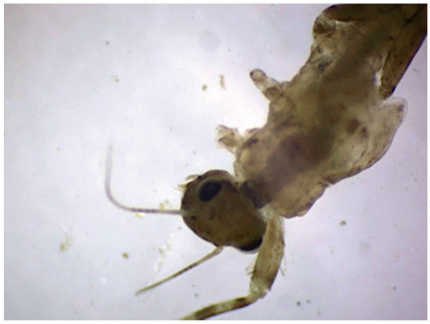


Figure A.16: (a):*Torleya* head and thorax, (b): *Torleya* gill

Family Ephemerellidae – Cincticostella gosei



(a)



(b)

Figure A.17: (a):*C.gosei* gill on abdomen, (b): *C.gosei*Head and antenna

Family Polymitarcyidae–Ephoron

Head with mandibular tusks, clearly seen from dorsal view of head, gills on abdominal segments 2–7 double with fringed margin and angled backwards and dorsally above abdomen, legs (especially tibia) robust or flattened for digging. Mandibular tusks slender with distinct tubercles on dorsal surface, curved inwards with inner edges concave. Abdominal gill on abdominal segment 1 single. Cerci with swimming hair fringe.

Family Isonychidae–Isonychia

Head lacking mandibular tusks, gills on segment 2 similar to other gills, forelegs with conspicuous rows of long filtering setae along the inner margins of femora and tibiae. Body steamlined and coxal gills present at base of legs. Cerci with swimming hair fringe.

Family Heptageniidae–Asionurus

Head prognathous, flat plate-like with eyes dorsally placed, mouthparts covered by front of head when viewed dorsally, body dorso-ventrally flattened. Mandibles without tusks, gills similar on abdomen, not forming a gill cover. Cerci with three filaments, abdominal gills 1 with distinct lamellae and a tuft of filaments. Abdominal segments 2–8 lacking large postero-lateral spines, gill lamellae lacking apical projection but gill 7 with a pointed tip and 3 times longer than broad, and lacking tracheal tuft. Cerci lack swimming hair fringe. Wing pads clearly developed extending over abdomen. The two species recognized (sp1 and sp2). The species differ by the colour pattern on head, thorax and abdomen.

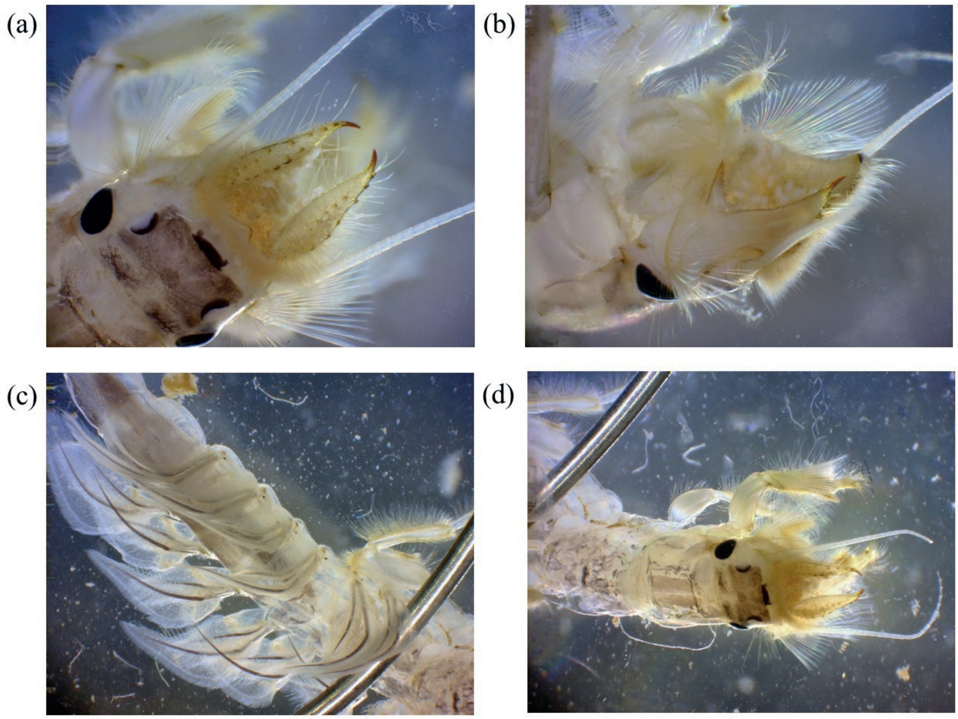


Figure A.18: (a):*Ephoron* tusks,(b):*Ephoron* head (c): *Ephoron*gills, (d):*Ephoron* thorax,

Family Caenidae–Caenis

Head prognathous, lacking ocular tubercles and lacking mandibular tusks, gills on segment 2 operculate (large and plate like–gill covers) and covering all other gills and overlap each other at the midline and has a triangular dorsal ridge. Gill cover without stout spines but "long" hairs are present. Fore tibiae without two transverse rows of filtering setae. Cerci lack swimming hair fringe. Rear edge of metathorax (wingpads) not clearly developed, but rounded with small central notch not extending over abdomen.

Family Neophemeridae–Potamanthellus

Head prognathous, lacking ocular tubercles and lacking mandibular tusks, gills on segment 2 operculate (large and plate like–gill covers) and almost covering all other gills, do not overlap each other at the midline and lacking a triangular dorsal ridge. Fore tibiae without two transverse rows of filtering setae. Cerci lack swimming hair fringe. Rear edge of metathorax (wingpads) not clearly developed, but rounded

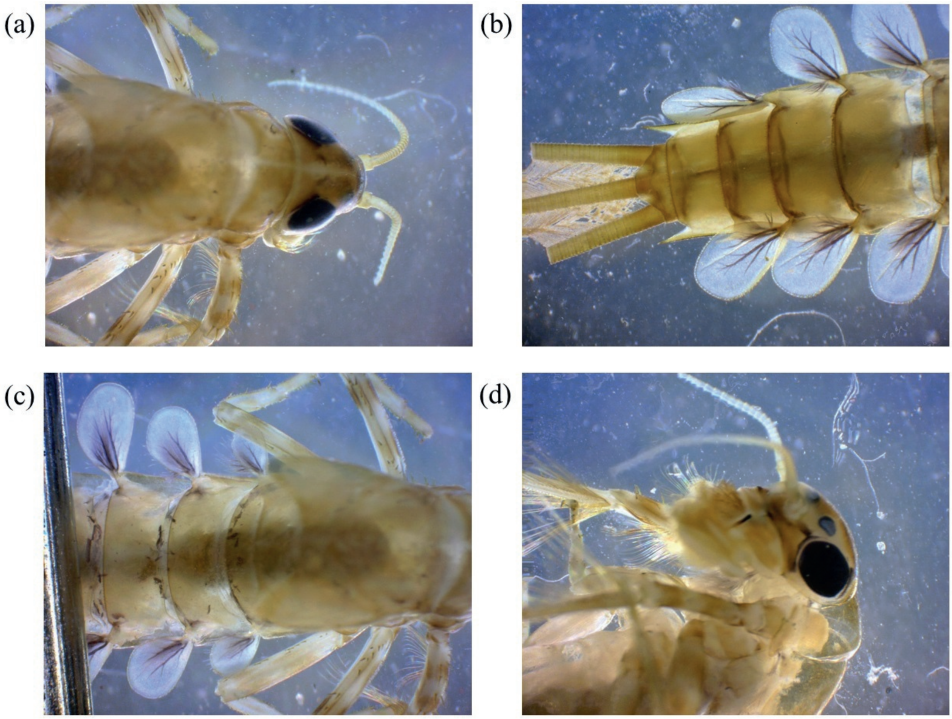


Figure A.19: (a):*Isonychia* head and thorax,(b):*Isonychia* cerci and gills (c): *Isonychia*Gills 1–3, (d):*Isonychia* lateral head

with small central notch not extending over abdomen.

Family Leptophlebiidae–Choroterpes (Choroterpes)

Head rectangular, prognathous, mouthparts can be seen when viewed dorsally, head not plate-like, lacking ocular tubercles and lacking mandibular tusks, gills on segment 1–7 similar and lacking a gill cover, and are dorsal on abdomen. Terminal filament (middle tail) well developed all cerci lack swimming hair fringe. Wing pads clearly developed extending over abdomen.

Family Baetidae–Baetis

Head prognathous, gills with single lamellae which are plate-like on abdominal segments 1–7. Body cylindrical in cross-section. Lack mandibular tusks. Terminal filament well developed, all gills single, tarsal claws with teeth. Ventral surface of thorax without thread-like thoracic gills, tibiae lack a transverse row of setae, but have few sparse blunt setae on edges of segment. Abdominal segments with

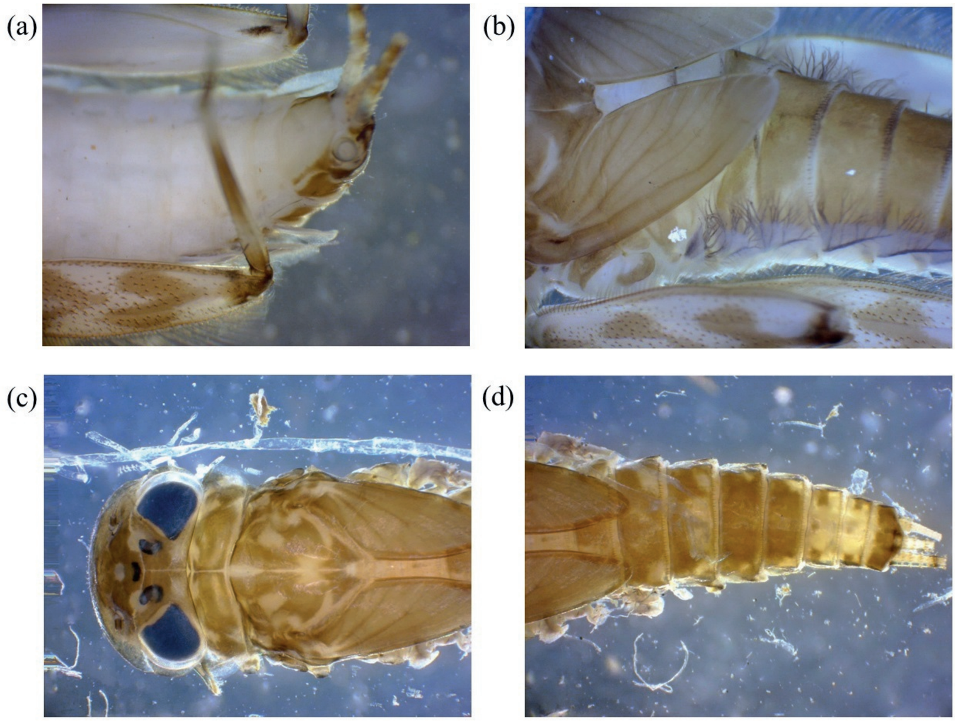


Figure A.20: (a):*Asionurus sp 1* gill 7 ventral, (b):*Asionurus sp 1* gills 1–5, (c)*Asionurus sp 1* head and thorax,(d):*Asionurus sp 1* abdomen and gills

posterior margin with row of blunt projections. Cerci with swimming hair fringe. Free-living.

Family Baetidae–Cloeon

Head prognathous, gills with paired lamellae which are plate-like on abdominal segments 1–7. Body cylindrical in cross-section. Lack mandibular tusks. Terminal filament well developed, all gills double (gill 7 is single). Cerci with swimming hair fringe. Free-living.

Family Baetidae–Procloeon

Head prognathous, gills with paired lamellae which are plate-like on abdominal segments 1–7. Body cylindrical in cross-section. Lack mandibular tusks. Terminal filament well developed, gills 1–5 double, distinctly asymmetrical and each bears a small dorsal flap (gill 6 and 7 are single). Cerci with swimming hair fringe. Free-living.

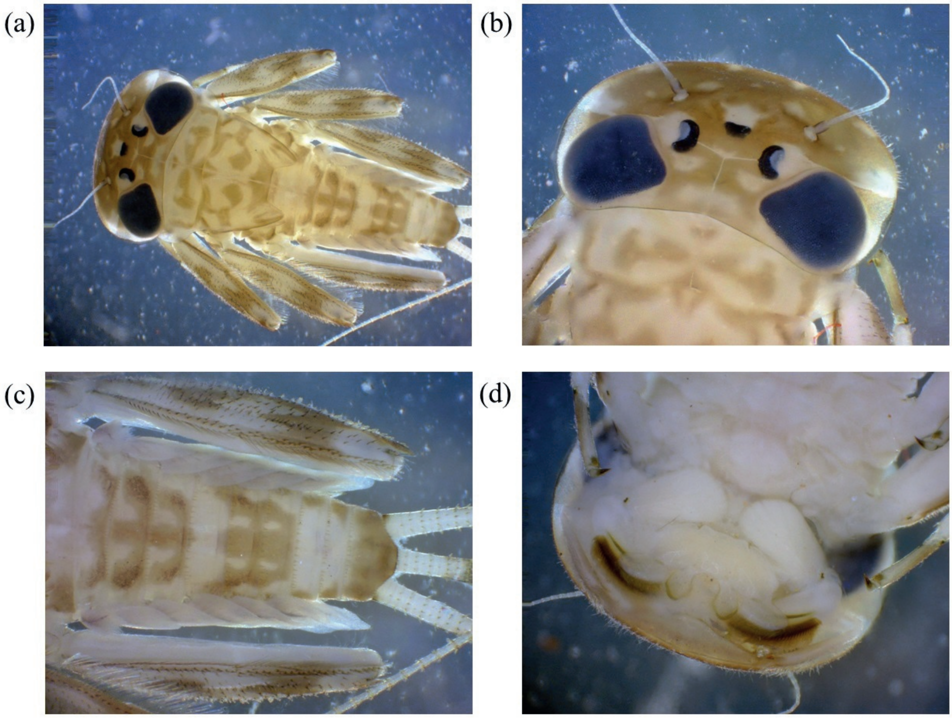


Figure A.21: (a):*Asionurus sp 2* body pattern, (b):*Asionurus sp 2* head and pronotum, (c)*Asionurus sp 2* abdomen,(d):*Asionurus sp 2* ventral head

Family Baetidae–Platybaetis

Head prognathous, gills with single lamellae which are plate-like on abdominal segments 1–7. Body cylindrical in cross-section. Lack mandibular tusks. Cerci well developed but terminal filament (middle tail) much reduced and less than half length of cerci; all gills single, tarsal claws with teeth. Ventral surface of thorax without thread-like thoracic gills, tibiae lack a transverse row of setae, but legs are fringed with long fine setae.

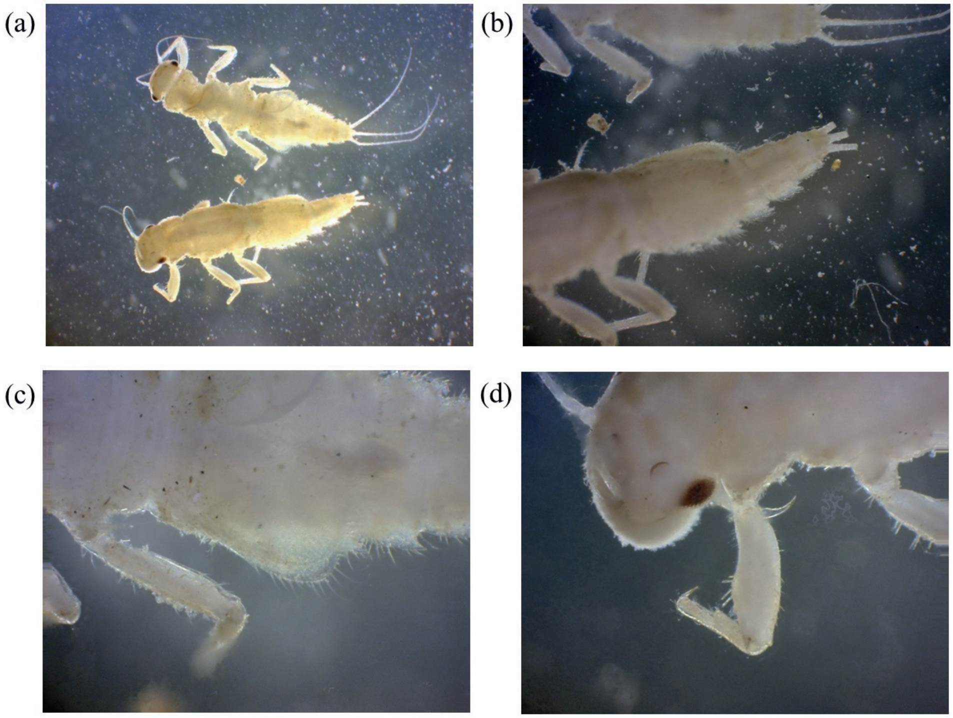


Figure A.22: (a):*Caenis* habitus, (b):*Caenis* gill covers, (c)*Caenis* gill covers and setae,(d):*Caenis* foreleg

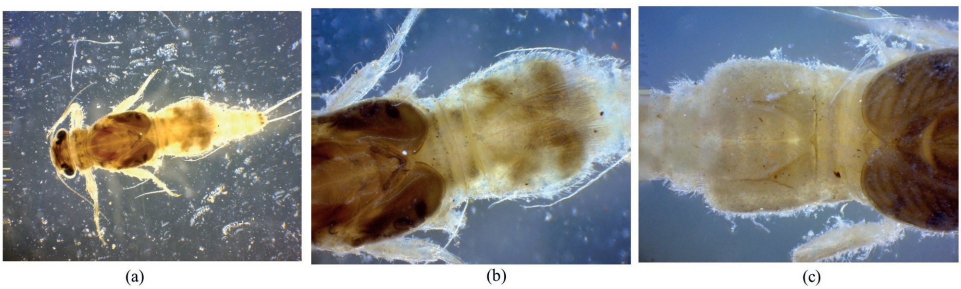


Figure A.23: (a):*Caenis* habitus, (b):*Caenis* gill cover and hind thorax, (c)*Caenis* gill cover overlapping and showing triangular ridge area and first gill

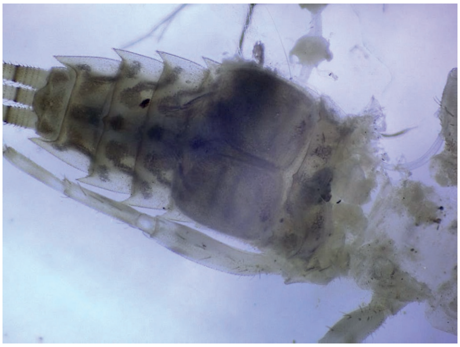


Figure A.24: Operculate gills on abdominal segment 2 not overlapping at midline and lacking triangular ridge

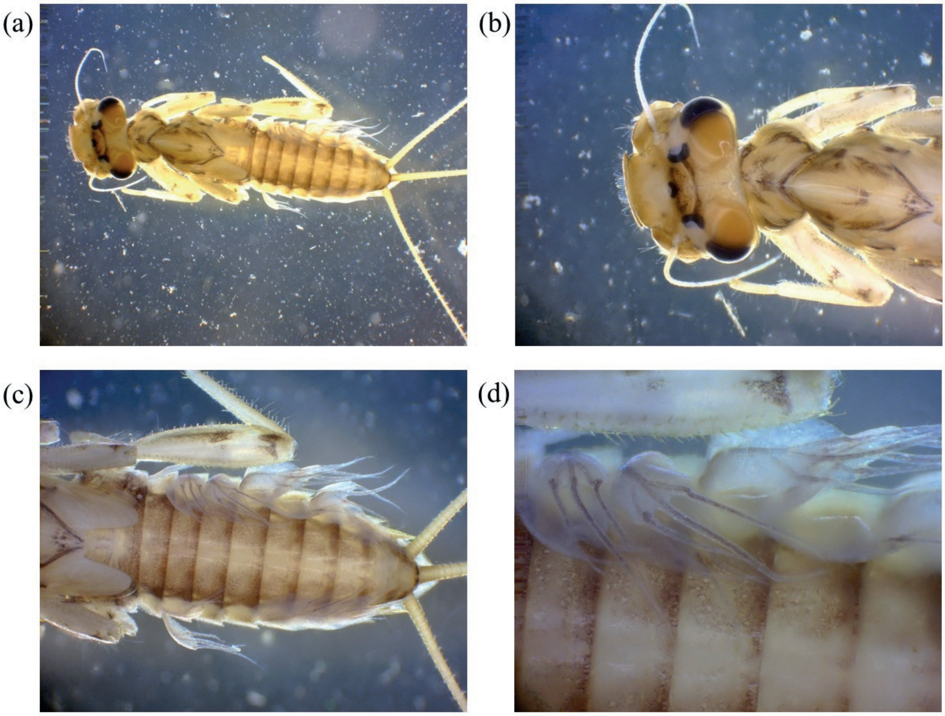


Figure A.25: (a): *Choroterpes sp 1* body, (b): *Choroterpes sp 1* head and thorax, (c): *Choroterpes sp 1* abdomen, (d): *Choroterpes sp 1* gills trifurcate

Family Leptophlebiidae Choroterpides

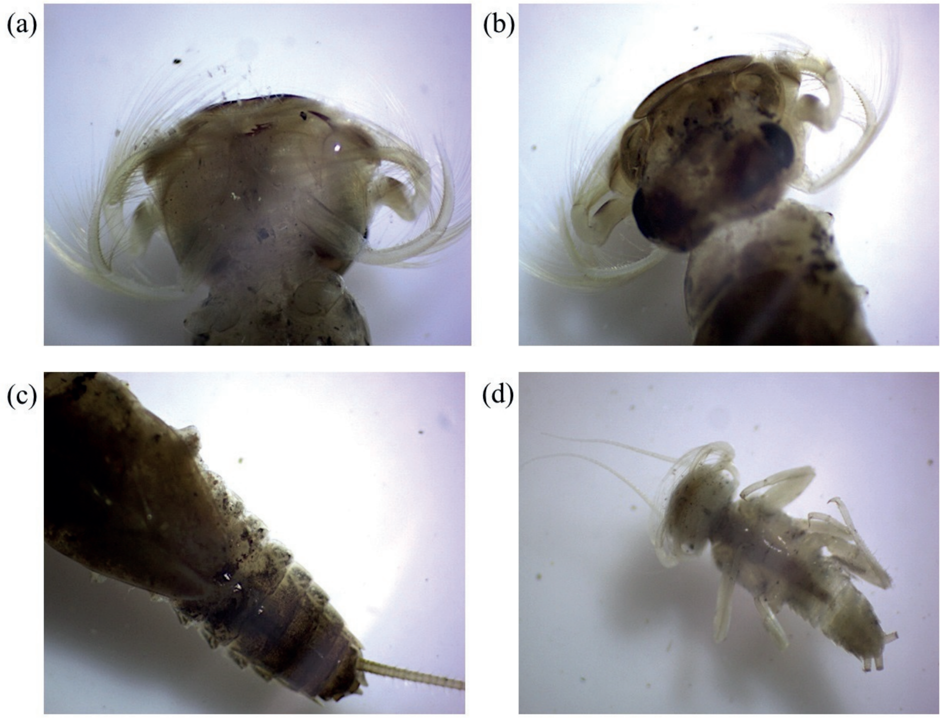


Figure A.26: (a): *Choroterpides* head and antenna, (b): *Choroterpides* head and eye, (c): *Choroterpides* abdomen, (d): *Choroterpides* legs

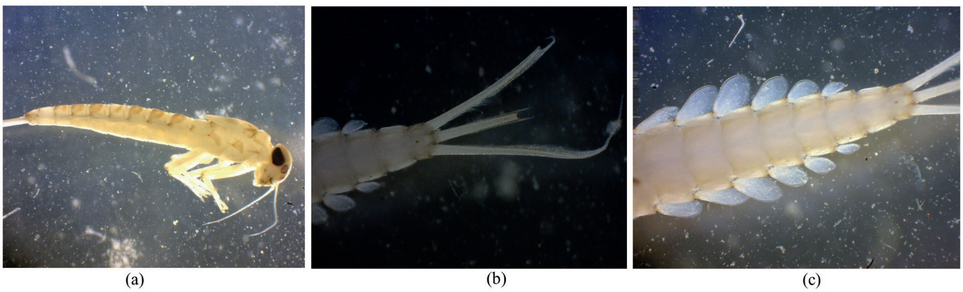


Figure A.27: (a): *Baetis sp 1* body lateral, (b): *Baetis sp 1* gills on abdomen ventral, (c): *Baetis sp 1* cerci with swim hairs

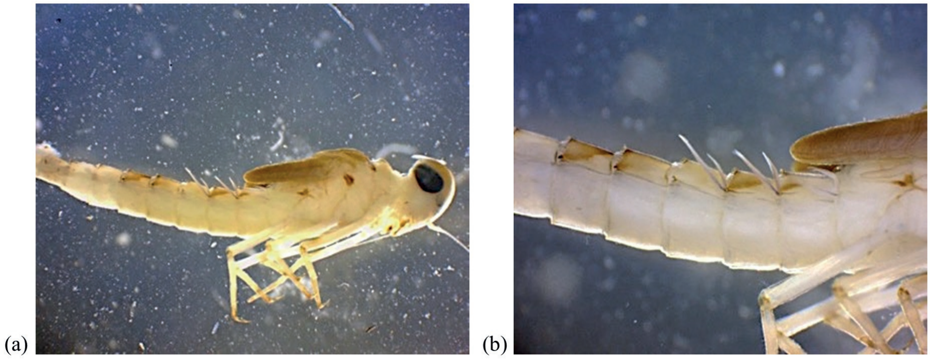


Figure A.28: (a): *Procloeon sp 1* lateral view, (b): *Procloeon sp 1* gills 1–3

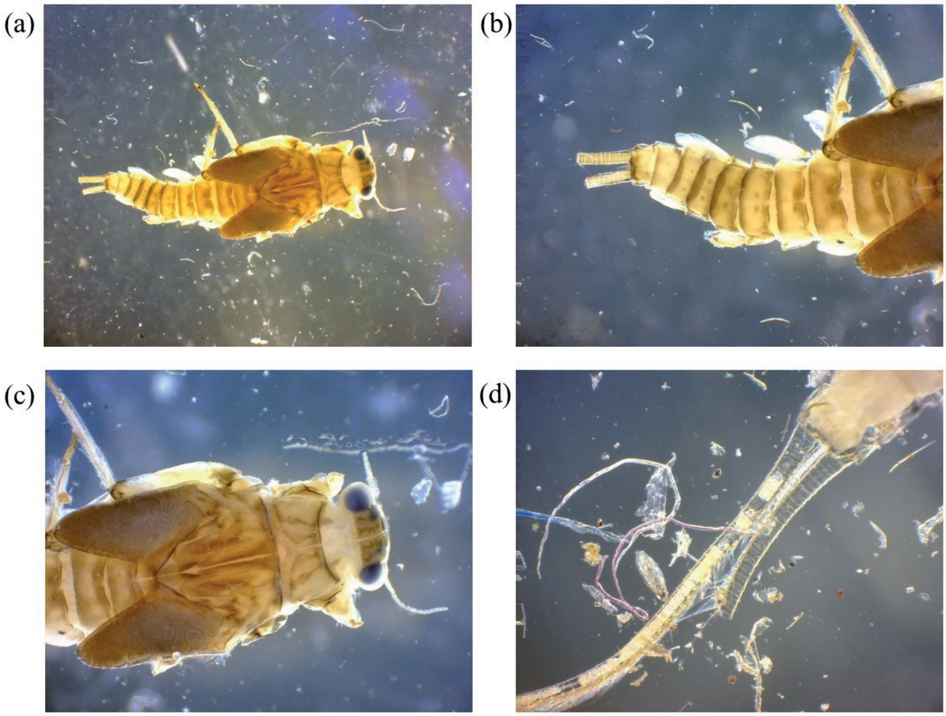


Figure A.29: (a): *Platybaetis* body dorsal view, (b): *Platybaetis* abdomen dorsal view, (c):*Platybaetis*head and thorax, (d): *Platybaetis*cerci and reduced middle filament

Family Potamanthidae – Potamanthindus

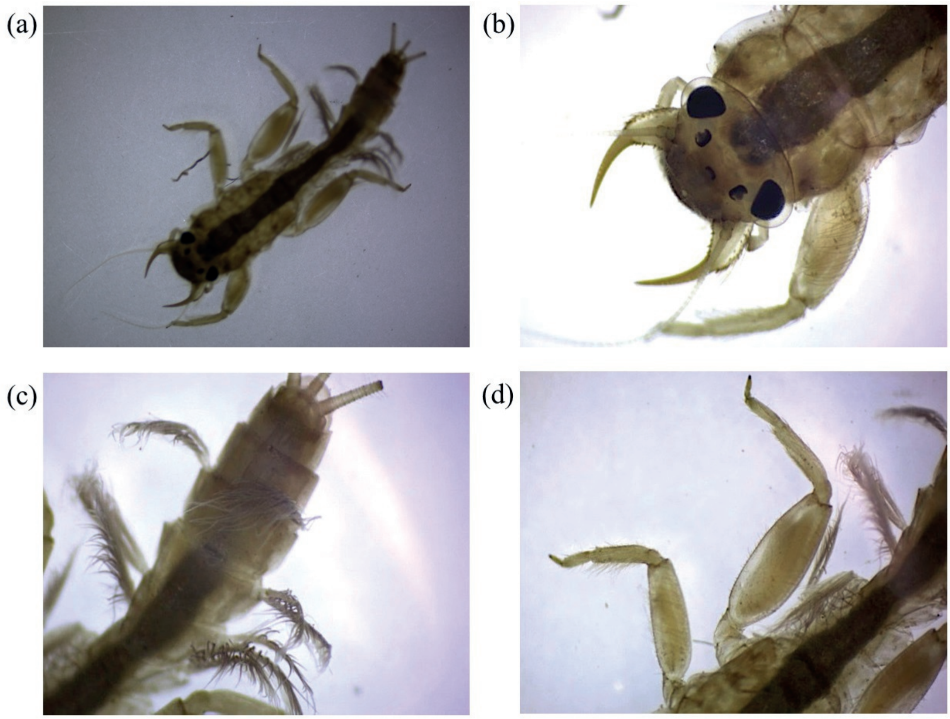


Figure A.30: (a):*Potamanthindus sp* body ,(b): *Potamanthindus sp* head and antenna, (c): *Potamanthindus sp* abdomen gills, (d):*Potamanthindus sp* legs

Order ODONATA (Dragonflies and damselflies)

At least two sub-orders present, the Anisoptera (Dragonflies) and Zygoptera (Damselflies). All Odonata have acharacteristic hinged labium which consists of a submentum and prementum with an elbowed connection, and a pair of labial palps with movable hooks. Damselflies have three terminal or caudal gills and dragonflies have rectal gills inside the abdomen, and last segment has three spine like structures. Key to Odonata of Myanmar

1 Body slender with three long terminal or caudal gills, head wider than thorax and abdomen..**Suborder ZYGOPTERA**.........2

1′ Body stout without three long terminal or caudal gill, the last segment has three spine like structures ....**Suborder ANISOPTERA**.......3

2(1) Caudal gills saccoid (balloon like) (Fig.00); head lacking posterior-lateral extensions but lateral margins with spines.. ....**Family Megapodagrionidae**

2′ Caudal gills leaf-like but with basal half thicker than apical half of lamellae; clear divide between base and apical halves; head with posterior-lateral extensions...**Family Protoneuridae**

3(2) Antennae filiform with >4 segments; labium ladle or spoon-like, curved over the front of the head...**Family Corduliidae**

3′ Antennae 4 segmented with 3rd segment flattened and enlarged; labial mask flat...**Family Gomphidae** 4

4(3) Anal pyramid with 3 equal spines ....**Gomphidae sp 1**

4′ Anal pyramid with a long respiratory siphon ....**Gomphidae sp 2 *Labrogomphus***

ANISOPTERA – Dragonflies

Family Gomphidae

Larvae stout without terminal gills but with an anal pyramid of 3 triangular structures; labium flattened; antennae 4 segmented with 3rd segment flattened and enlarged; fore tarsi 2 segmented.

(a) (b) (c) (d)

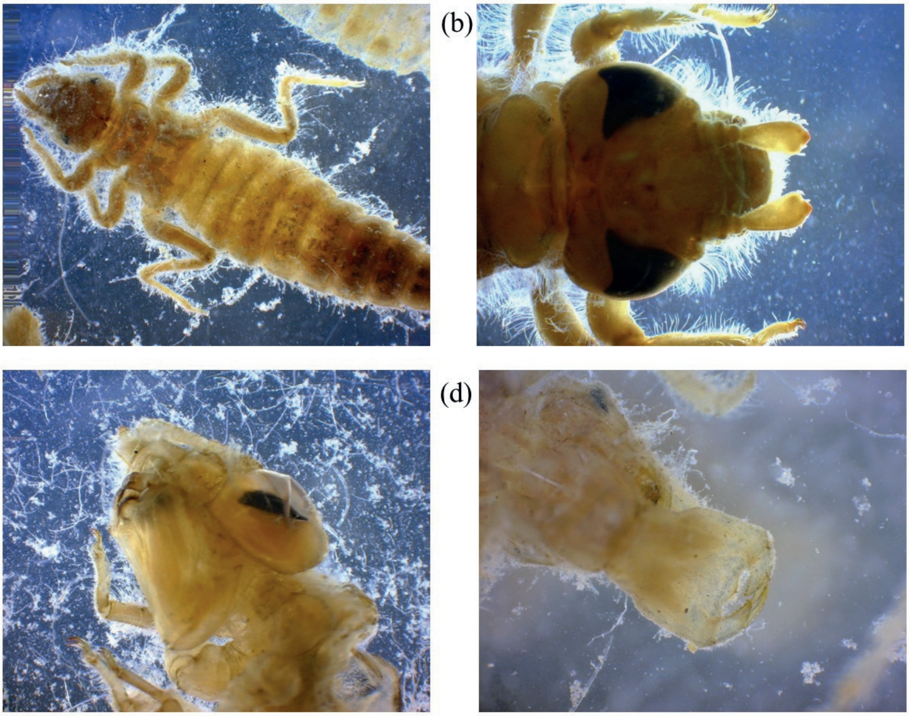
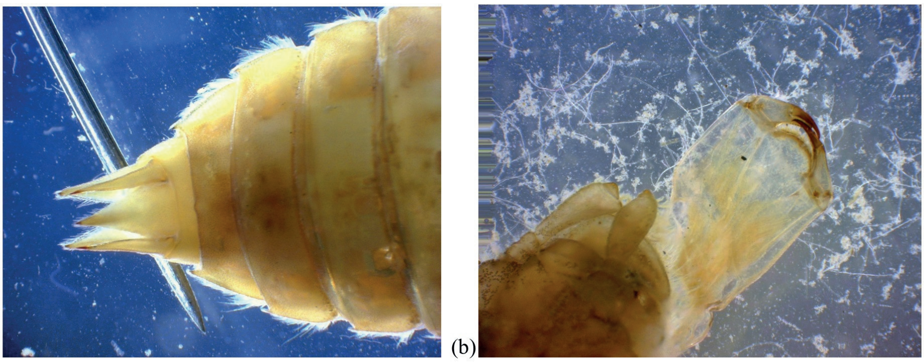


Figure A.31: (a): *Gomphidae sp 1* body, (b): *Gomphidae sp 1* antennae, (c):*Gomphidae sp 1* Labial mask flat, (d): *Gomphidae sp 1* Labium dorsal view



(a) (b)

Figure A.32: (a): *Gomphidae sp 1* anal pyramid , (b): *Gomphidae sp 1* labium

Family Corduliidae

Labium ladle or spoon like curved over the front of the head; labial palps with edges with small crenulations (not large teeth)with each tooth with setae apically; head

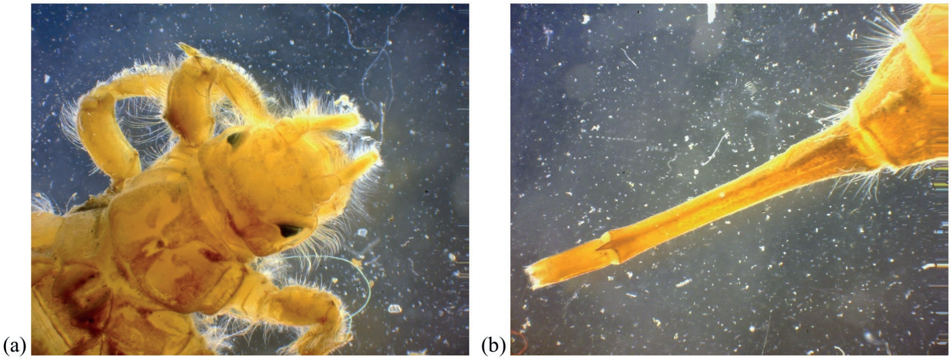


Figure A.33: (a): *Gomphidae sp 2* Labrogomphus head , (b): *Gomphidae sp 2* Labrogomphus respiratory siphon

without medial horn; lateral spine on abdominal segment VIII shorter than length of segment.

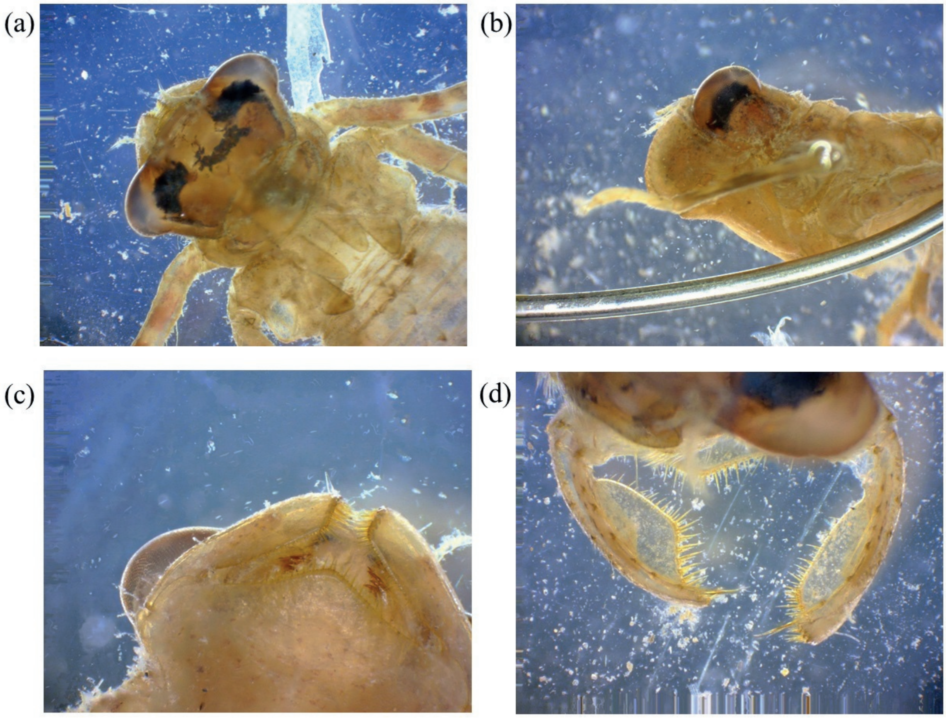


Figure A.34: (a): **Corduliidae** head and thorax , (b): **Corduliidae** ladle shaped mask, (c):**Corduliidae** labium , (d): **Corduliidae** labial palps

ZYGOPTERA – Damselflies

Larvae slender with three (may be 2) terminal gills (caudal gills).

Family Megapodagrionidae

Antennal segment 1 not elongate, less than combined length of remaining segments; with 3 caudal gills; abdomen without lateral gills; caudal gills saccoid (balloon like, but may be collapsed on preservation); labial palps with a single seta and prementum lacks setae.

(a)  (b) 

Figure A.35: (a): **Megapodagrionidae** head and thorax , (b): **Megapodagrionidae** antennae,

(a)  (b) 

Figure A.36: (a):**Megapodagrionidae** ventral labium , (b): **Megapodagrionidae** ventral labium

Family Protoneuridae

Antennal segment 1 not elongate, less than combined length of remaining segments; with 3 caudal gills; abdomen without lateral gills; caudal gills; prementum triangular; caudal filaments with basal half thick compared with thin

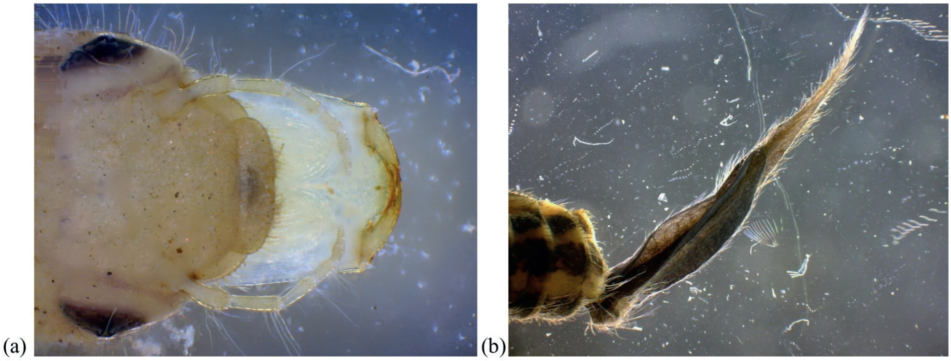


Figure A.37: (a): **Megapodagrionidae** dorsal labium, (b): **Megapodagrionidae** saccoid gills

lamellae of apical half, clear divide between the two halves; prementum with 2 setae.

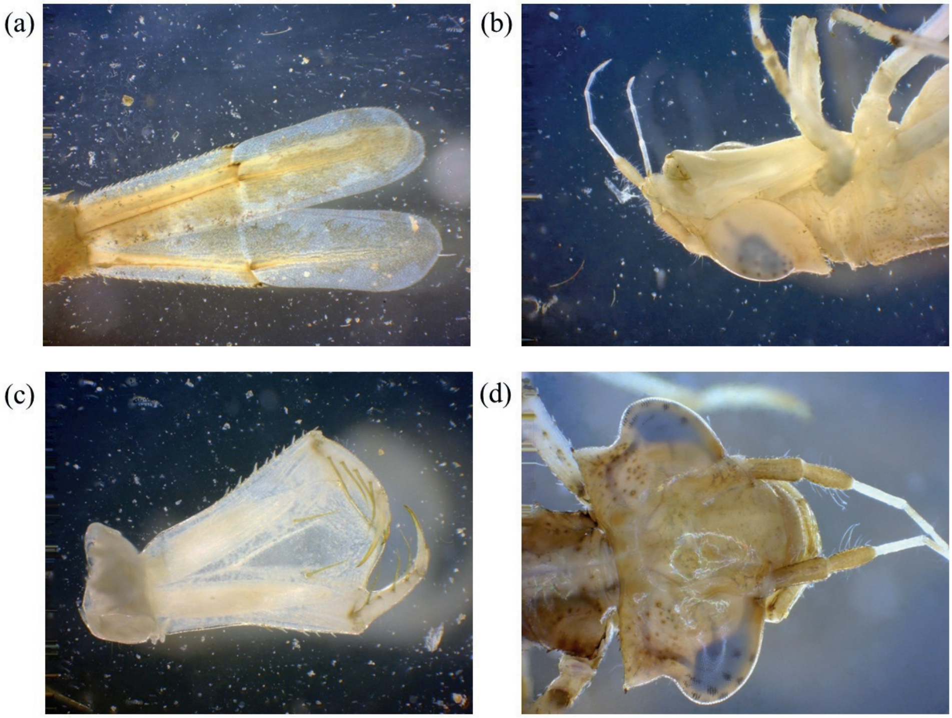


Figure A.38: (a): **Protoneuridae** anal gills (3), (b): **Protoneuridae** Labium and antennae, (c):**Protoneuridae**mentum and labial palps, (d): **Protoneuridae**head and antenna

ORDER PLECOPTERA (STONEFLIES)

Characters: Abdomen with paired segmented cerci (2 tails), gills may be present on the thoracic segments, or at the base of and between the cerci. Body usually dors-ventrally flattened and head is prognathous.

Key to the Plecoptera

1 Head with 2 ocelli on occiput; (Fig.58)..2

1′ Head with 3 ocelli on occiput; anal gills absent (Fig 64)..............................
....**PERLIDAE:** ***Togoperla*** 5

2(1) Anal gills present ....**PERLIDAE:** ***Neoperla***...........3

2′ Anal gills absent .... **PERLIDAE:** ***Etrocorema***......... 6

3(2) Body covered with hairs; head and thorax nearly uniform brown and lacking distinct markings ....***Neoperla* sp 2**

3′ Body with hairs on lateral margins of segments; head and thorax with distinct light markings 4

4(3) Head with narrow anterior band of brown and a central light band and a posterior marking; pronotum with a large central light marking edged with brown .... ***Neoperla* sp 1**

4′ Head with broad anterior band of brown and posterior light band and a narrow brown band posteriorly; pronotum light without dark edges ....
.... ***Neoperla* sp 3**

5(1) Head mainly brown with a light M-shaped central marking, paired elongated spots in front of ocelli and large light patches posterior to ocelli and on posterior margin ....***Togoperla* sp 1**

5′ Head predominantly light with anterior band of brown, brown stripe in front of posterior ocelli and between ocelli (posterior of head light).....................
....***Togoperla* sp 2**

6(2) Pronotum with distinct ‘collar’ .... ***Etrocorema* sp 1**

6′ Pronotum without a ‘collar’ .... ***Etrocorema* sp 2**

Family Perlidae–Neoperla

Body not cockroach-like; thorax only slightly wider than rest of body. Head with 2 ocelli at occiput; two pairs of posterior supracoxal gills on thoracic segment 3; posterior margin of mesosternum without setal fringe. occipital ridge with few short setae, not a close set row; body with sparse clothing of brown setae. Lateral margin of pronotum with fringe incomplete and anal gills present.

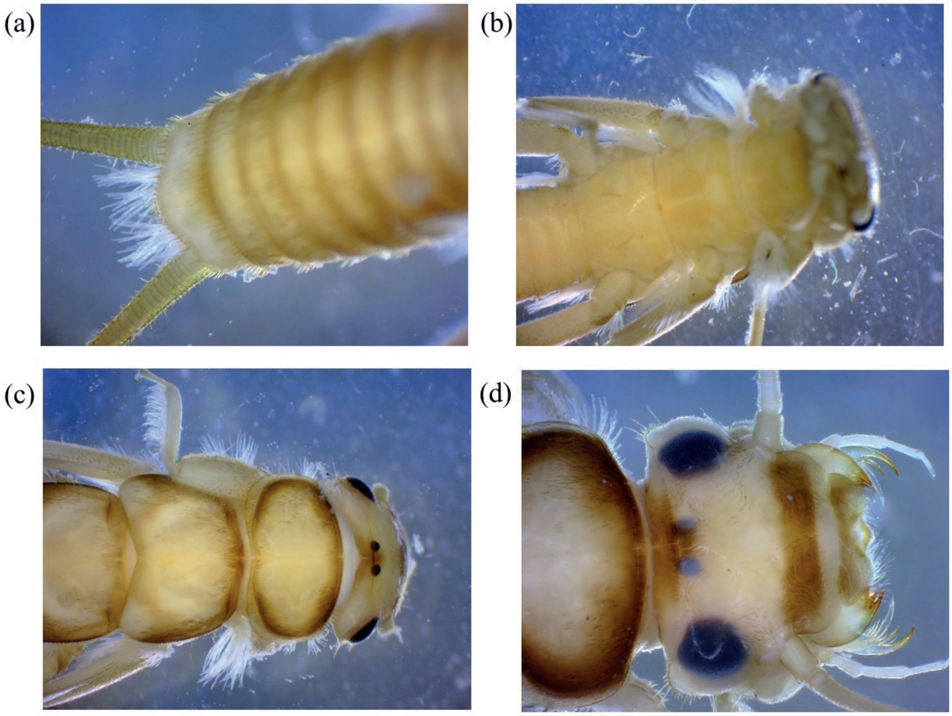


Figure A.39: (a): *Neoperla*sp 1 anal gills, (b): *Neoperla* sp 1 coxal gills, (c):*Neoperla* sp 1head and thorax, (d): *Neoperla* sp 1head and 2 ocelli

Family Perlidae–Etrocorema

Body not cockroach-like; thorax only slightly wider than rest of body. Head with 2 ocelli at occiput; anal gills absent. Coxal gills present at base of legs. Thorax and abdomen without a median row of long silky setae.

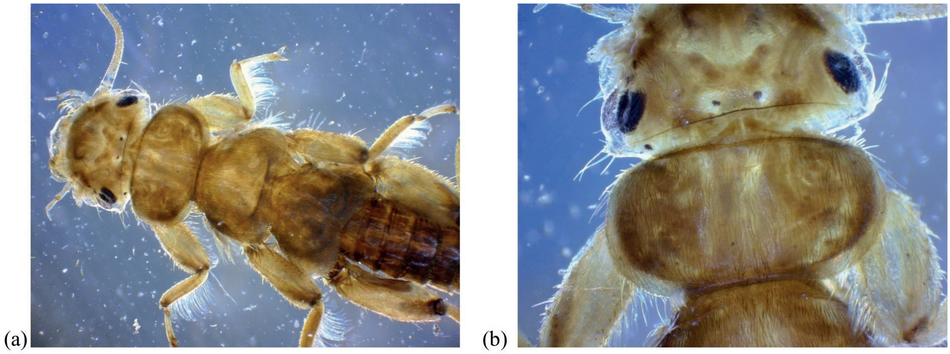


Figure A.40: (a): *Neoperla* sp2 head and abdomen, (b): *Neoperla* sp2 hairy body

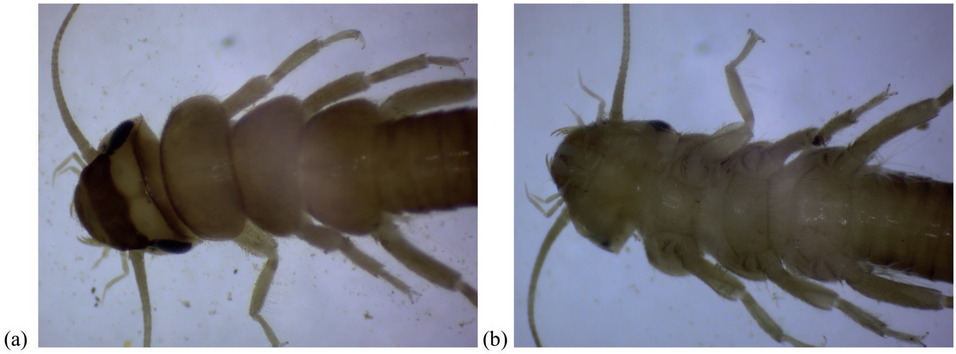


Figure A.41: (a): *Neoperla*sp 3 head and thorax, (b): *Neoperla* sp 3 abdomen

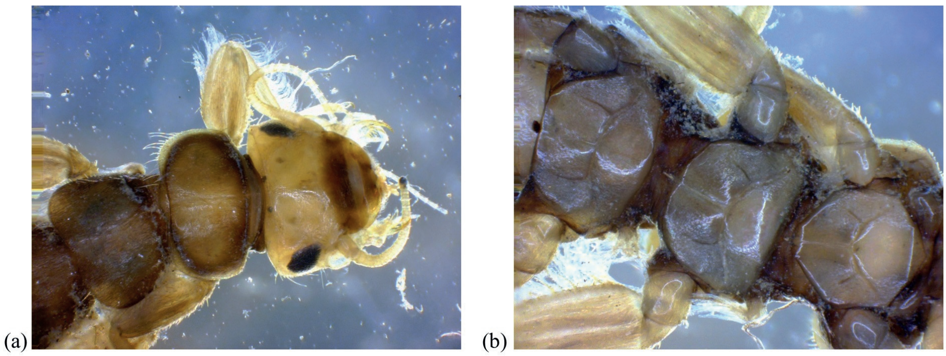


Figure A.42: (a): *Etrocorema* sp 1 head with collar, (b): *Etrocorema* sp 1 sternum

Family Perlidae–Togoperla

Body not cockroach-like; thorax only slightly wider than rest of body. Head with 3 ocelli at occiput; anal gills absent. Coxal gills present at base of legs. Thorax and

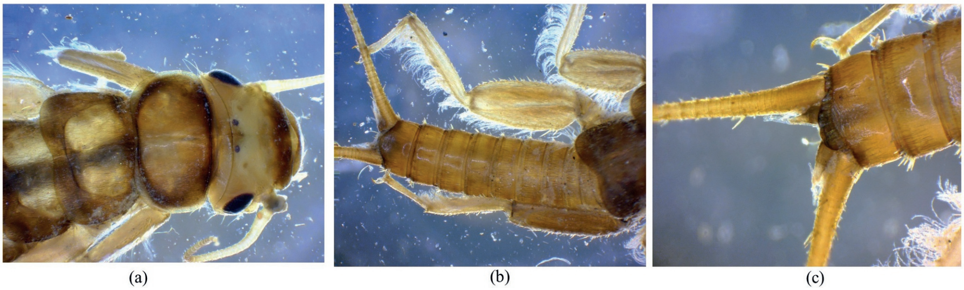


Figure A.43: (a): *Etrocorema* sp 2 head without collar, (b): *Etrocorema* sp 2 anal section no gills, (c): *Etrocorema* sp 2ventral no gills

abdomen without a median row of long silky setae.

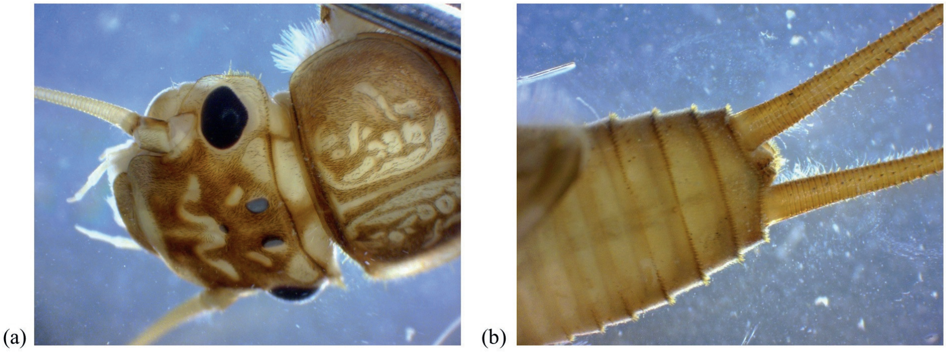


Figure A.44: (a): *Togoperla* sp 1 head andpronotum markings , (b): *Togoperla* sp 1 Anal gills absent

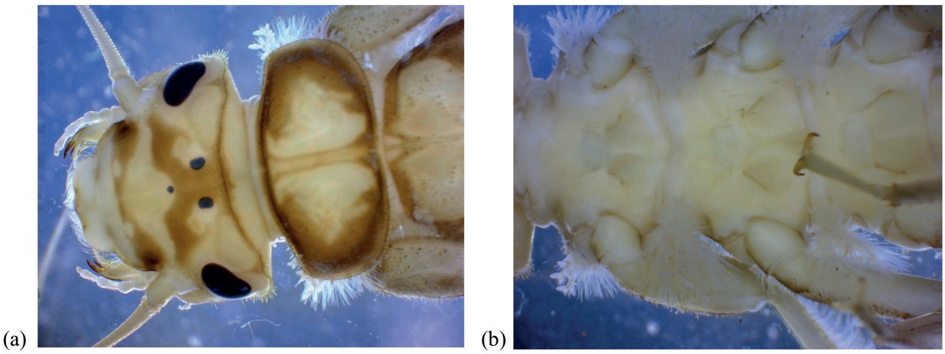


Figure A.45: (a): *Togoperla* sp 2 head andpronotum markings , (b): *Togoperla* sp 2 coxal gills

(a) (b)

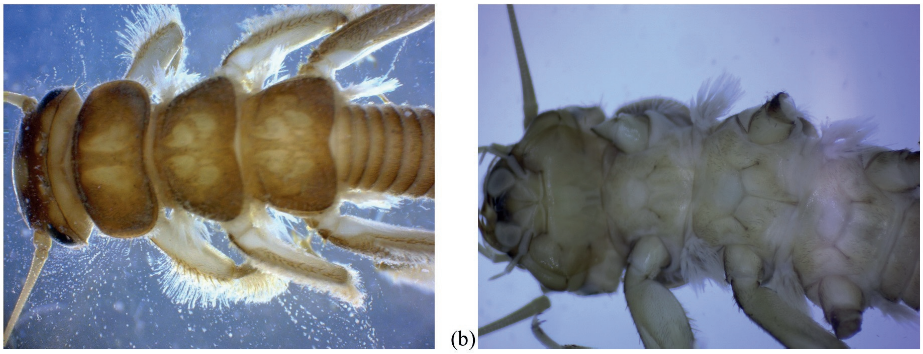


Figure A.46: (a): *Togoperla* sp 3 head, (b): *Togoperla* sp 3 gills

ORDER HEMIPTERA (True Bugs)

Mouthparts consist of a stylet (sucking mouthparts), rostrum triangular to long and segmented; body sclerotized.

Key to Hemiptera of Myanmar

1 Antennae shorter than head and not visible from above 2

1′ Antennae longer than head and clearly visible from above ....**Family Hebridae**............. ***Timasius***

2(1) Eyes on stalks and anterior portion of head with distinct tubercles ....**Family Gelastocoridae** ....***Nerthra***

2′ Eyes not on stalks and head lacking anterior tubercles 3

3(2) Rostrum long and slender, extending to hind coxae; forelegs weakly raptorial with 3 segments.. ....**Family Aphelocheiridaes**...........***Aphelocheirus***

3′ Rostrum short, not extending beyond fore coxae; forelegs with 2 segments if raptorial and 3 if not raptorial 4

4(3) Forelegs strongly raptorial with 2 segments... ....**Family Naucoridae**.................. ***Naucoris***

4′ Forelegs not raptorial and with 3 segments...5

5(4) Rostrum without grooved, body cylindrical and slightly flattened, length (≥ 3 mm) ....**Family Micronectidae**

5′ Rostrum with grooved, body cylindrical and slightly flattened, length (≤ 3 mm)...**Family Corixidae**

Family Hebridae–Timasius

Dorso–ventrally flattened; antennae longer than head fore leg not raptorial and similar to mid and hind legs, tarsi 2-segmented, head and pronotum clearly separate not fused.

Figure A.47: Habitus of Timasius, showing long antennae

Family Naucoridae–Naucoris

Dorso–ventrally flattened; fore leg raptorial with large, flat and broad femur; head and pronotum clearly separate not fused, eyes not on stalks. Antennae shorter than head, inserted beneath the eyes and not visible from above; ocelli absent.

(a) (b) (c)

Figure A.48: (a):Naucoridae dorsal view (large animal about 15–20mm long), (b):Naucoridae head, (c): Naucoridae ventral raptorial forelegs

Family Aphelocheiridae – Aphelocheirus

Dorso–ventrally flattened; fore leg raptorial but much less than Naucoridae; rostrum long and narrow and segmented; head and pronotum clearly separate not fused; head longer than wide. Antennae shorter than head, inserted beneath the eyes and not visible from above; ocelli absent.

Family Gelastocoridae–Nerthra

Dorso–ventrally flattened; fore leg raptorial with 2 segments, tarsal claw single; rostrum short and not extending beyond fore coxae; head with eyes on stalks and distinct anterior tuberclesand pronotum clearly separate not fused; head shorter

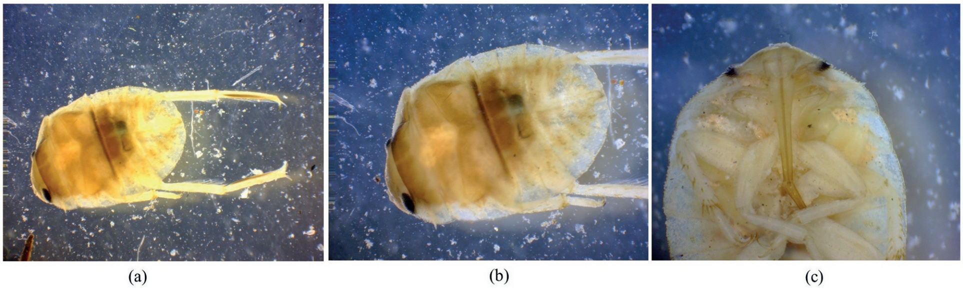


Figure A.49: (a): *Aphelocheirus* juvenile body, (b): *Aphelocheirus* body, (c): *Aphelocheirus* segmented rostrum – stylet

than wide. Antennae shorter than head, inserted beneath the eyes and not visible from above; ocelli absent.

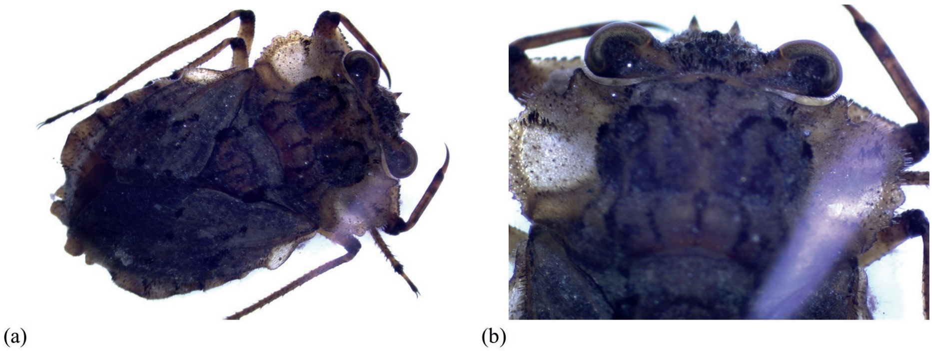


Figure A.50: (a):Habitus of *Nerthra*, (b):Head and thorax of *Nerthra*

Family Micronectidae

Body cylindrical and slightly flattened; head and pronotum clearly separate not fused. Antennae shorter than head, inserted beneath the eyes and not visible from above; ocelli absent; rostrum short, broad and clearly triangular with grooves (not segmented); small species with length less than 3mm. Usually found in still waters, wetlands or backwaters.

Family Corixidae

Body cylindrical and slightly flattened; head and pronotum clearly separate not fused. Antennae shorter than head, inserted beneath the eyes and not visible from above; ocelli absent; rostrum short, broad and clearly triangular and with distinct

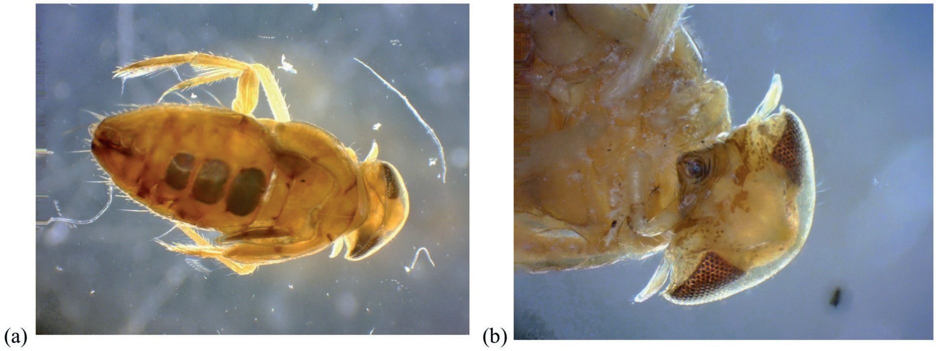


Figure A.51: (a):Micronectidae juvenile body, (b):Micronectidae ventral head and rostrum

grooves (not segmented); large species with length greater than 5mm and may be up to 10mm. Usually found in still waters, wetlands or backwaters.

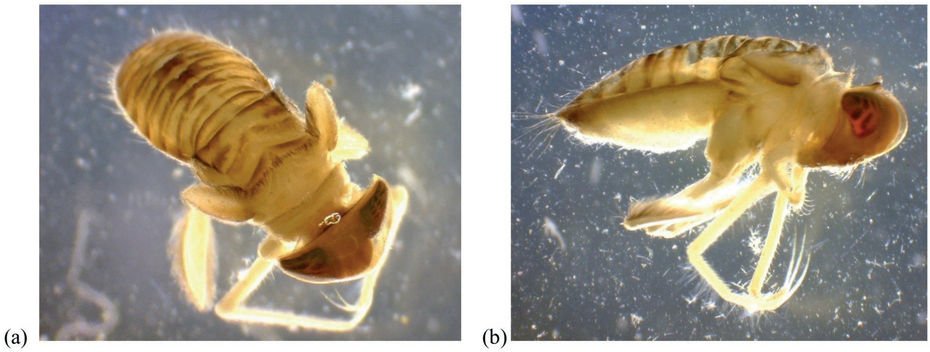


Figure A.52: (a):Corixidae juvenile dorsal, (b):Corixidae juvenile lateral

Figure A.53: Corixidae juvenile grooved rostrum

ORDER TRICHOPTERA (CADDISFLIES)

Characters: Free-living or portable case dwellers. Three pairs of legs, last abdominal segment with hook-like anal claws. Thorax with three well developed segments, pronotum sclerotized, meso- and meta- notum may or may not be sclerotized. Abdomen membranous with a sclerotized plate occasionally present in some groups. Filamentous gills present or absent.

Key to Trichoptera of Myanmar

1 Abdomen usually swollen, broader and deeper than thorax; constructing portable purse-like cases of silk which may include filamentous algae or sand grains ....**Family HYDROPTILIDAE** 2

1′ Larvae free-living or living in a fixed retreat; first abdominal segment without dorsal or lateral humps, anal claws large on well developed abdominal prolegs or larvae constructing portable cases, first abdominal segment with dorsal and/or lateral humps, anal claws small on an apparent 10^{th} abdominal segment formed by the fusion of the abdominal prolegs 3

2(1) Larvae constructing a conical silk purse .... ***Oxyethira***

2′ Larvae constructing a silk case covered with sand grains and algae .... ***Hydroptila***

3(1) Pronotum, mesonotum and metanotum all with obvious sclerotisation 8

3′ Pronotum sclerotized, mesonotum and metanotum membranous 4

4(3) Free living larva, head long >3x longer than wide, head and pronotum spotted ....**Family STENOPSYCHIDAE** .... ***Stenopsyche***

4′ Larva with a sand grain case or case made of vegetation; head <2x longer than wide 5

5(4) Larvae with sand grain case spiraled like a gastropod snail shell .... **Family HELICOPSYCHIDAE** .... ***Helicopsyche***

5′ Case not spiraled, may be made of sand or vegetation 6

6(5) Sand grain case, shield–shaped .... **Family MOLANNIDAE**......***Molanna***

6′ Case of various materials, sand or vegetation (hollow aquatic plant stems or sticks), usually elongate; mesothoracic legs very long .... **Family LEPTOCERIDAE**.............7

7(6) Case made of sand grains ....***Oecetis***

7′ Case of reeds or sticks ....***Triplectides***

8(3) Abdomen with distinctive gills; anal prolegs with a tuft of setae............ ....**Family HYDROPSYCHIDAE**.........9

8′ Abdomen lacking gills; anal prolegs lacking tuft of setae...13

9(8) Head length at least 2-3x width; head and thorax narrower than abdomen ....***Oestropsyche***

9′ Head length equal width or up to 2x longer than width; head and thorax wider or equal to width of abdomen...10

10(9) Head length 2x width...***Diplectrona***

10′ Head length equal width..11

11(10) Head flat dorsally; trochantin on foreleg not forked 12

11′ Head not flattened dorsally; trochantin usually forked ....***Potamyia***

12(11) Head with clear ridge (carina) around margins of head; submentum triangular but truncated (flat) at anterior margin ....***Macrostemum***

12′ Head without carina round margins of head; submentum conical or triangular..***Amphipsyche***

13(8) Thoracic terga all heavily sclerotized; tarsal claws all of similar size ....**Family ECNOMIDAE**..............***Ecnomus***

13′ Thoracic terga weakly sclerotized or part of mesonotum membranous...14

14(13) Abdominal tergum 9 with a sclerotized plate lined with sparse setae; sternum lacking sternal plates on thorax and abdominal segment 1; mesonotum sclerotized in posterior half only; all legs with long claws...........*Family ODONTOCERIDAE*...................15

14′ Abdominal tergum lacking sclerotized plate; meta thorax with dark sclerotized area and with membranous area at edge and medially; prolegs and midlegs with claws which are longer than metathoracic claws...............
.............................**Family DIPSEUDOPSIDAE**........***Pseudoneureclipsis***

15(14) Head with striped markings...***Marilia* sp 1**

15′ Head without striped markings...***Marilia* sp 2**

Family Hydroptilidae – Oxyethira

Final instar larvae have a swollen abdomen broader and deeper than head and thorax; abdominal prolegs not well developed; head and thorax sclerotized. Case conical without external ornamentation.

Figure A.54: Last instar larva of *Oxyethira*

Family Hydroptilidae – Hydroptila

Final instar larvae have a swollen abdomen broader and deeper than head and thorax; abdominal prolegs not well developed; head and thorax sclerotized. Case ovoid covered in sand grains and filamentous algae.

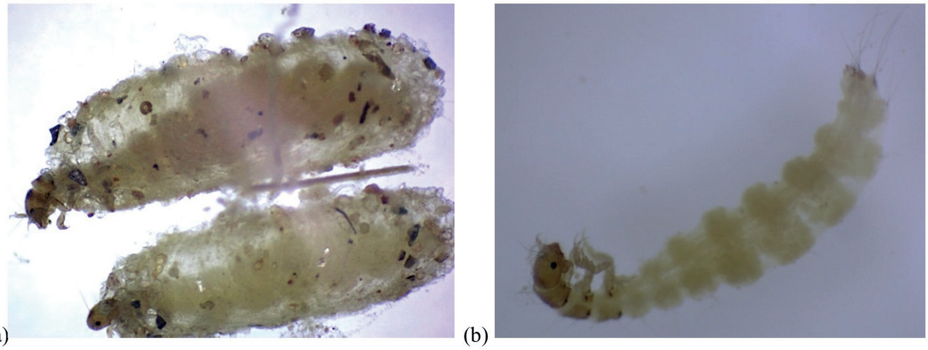


Figure A.55: (a): Cases and larvae of *Hydroptila*, (b): *Hydroptila* removed from case

Family Stenopsychidae–Stenopsyche

Dorsum of only prothorax scerotised, meso- and meta-notum membranous; not in helical shell, claws of anal prolegs not comb-like; larvae free living. Anal prolegs long at least 4 times longer than claws; labrum sclerotized; trochantin of fore leg pointed and paired, legs not strongly flattened; abdominal segment 9 membranous without sclerotized plate; tarsi of fore leg not modified into chelae (pinchers); head more than 2 times longer than wide.

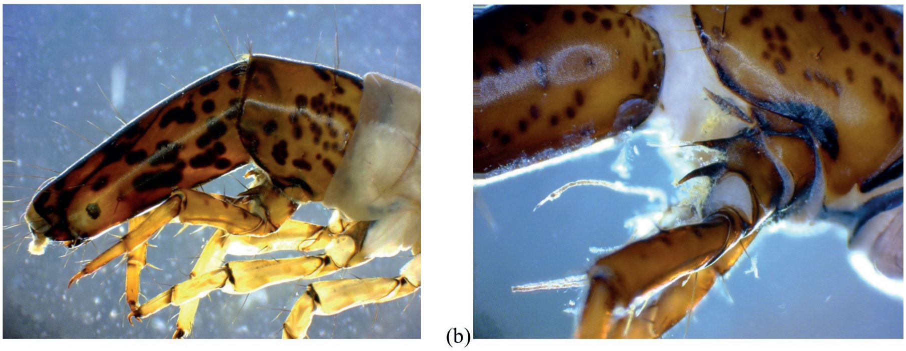


Figure A.56: (a):*Stenopsyche* sp 1 lateral head, (b):*Stenopsyche* foreleg trochantin paired and thorax

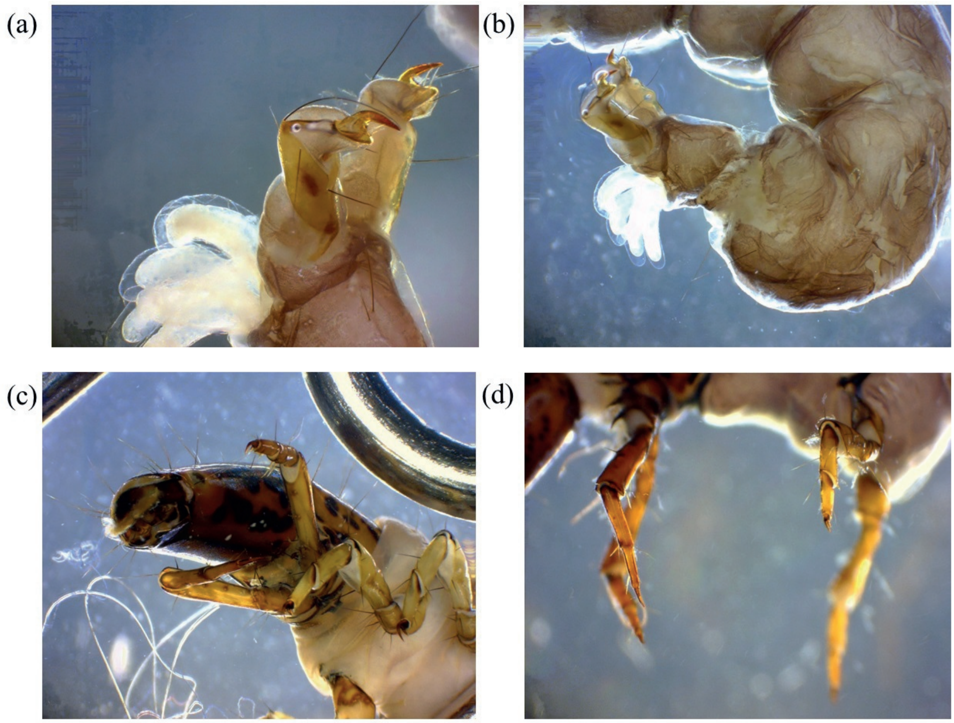


Figure A.57: (a):*Stenopsyche* sp 1 hind claws, (b):*Stenopsyche* sp 1 abdomen no plate, (c):*Stenopsyche*sp 1 ventral head, (d):*Stenopsyche* sp 1 fore and mid legs

Family Helicopsychidae - Helicopsyche

Case of sand grains in a spiral like a small snail.

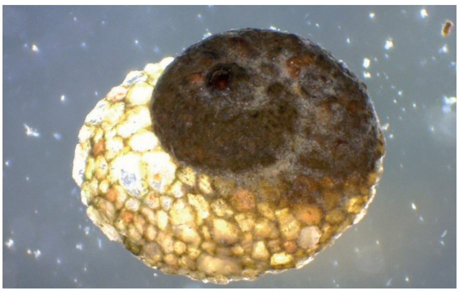


Figure A.58: *Helicopsyche* shell (habitus).

Family Hydropsychidae– Macronematinae – Macrostemum

All three thoracic segments sclerotized; abdominal gills present ventrally; anal prolegs long with a brush of setae; head flat with a clear ridge (carina) round outside of head; head ventrally without separation by ventral apotome; posterior ventral apotome less than half length of ventral part of head; abdominal gills with numerous filaments arising uniformly from central stalk; head carina with long hairs; trochantin not forked; submentum triangular but flat at top.

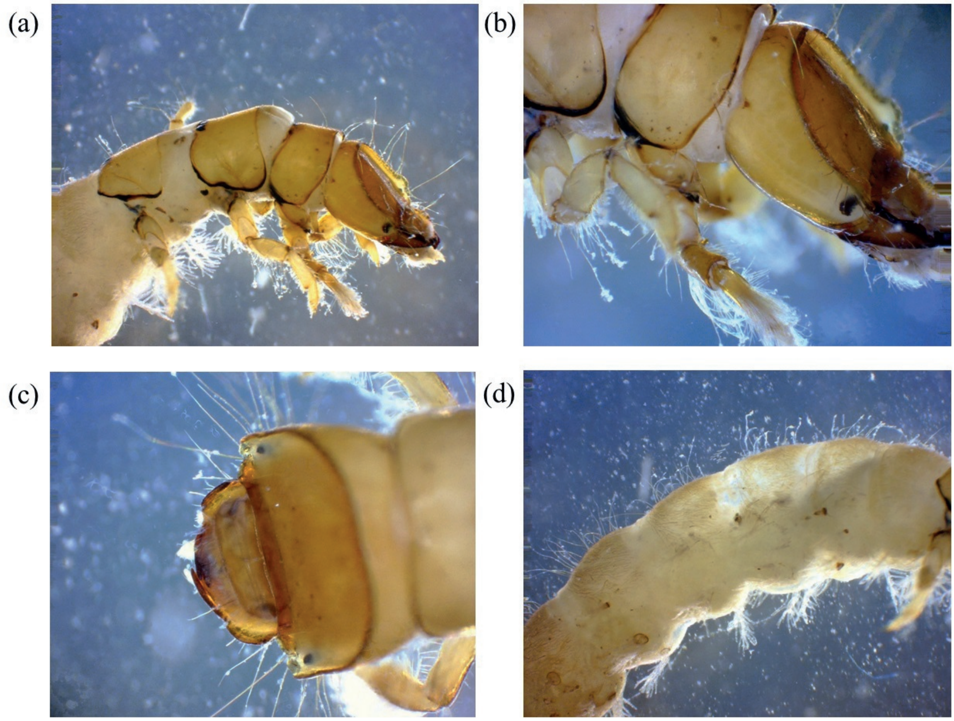


Figure A.59: (a): *Macrostemum* lateral head and thorax, (b):*Macrostemum*head, (c): *Macrostemum*dorsal fronto-clypeus, (d): *Macrostemum*abdominal gills

Family Hydropsychidae– Macronematinae – Amphipsyche

All three thoracic segments sclerotized; abdominal gills present ventrally; anal prolegs long with a brush of setae; head flat without a clear ridge (carina) round outside of head, but tufts of setae at corners of head; head ventrally without separation by ventral apotome; posterior ventral apotome less than half length of ventral part of head; abdominal gills with numerous filaments arising uniformly from central stalk; trochantin not forked; submentum conical or triangular.

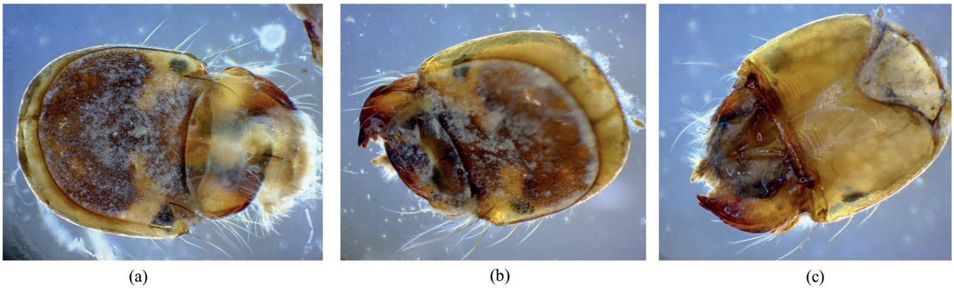


Figure A.60: (a): *Amphipsyche* dorsal flat head, (b):*Amphipsyche*head and frontal setal tufts, (c): *Amphipsyche* ventral head and conical submentum

Family Hydropsychidae - Potamyia

All three thoracic segments sclerotized; abdominal gills present ventrally; anal prolegs long with a brush of setae; head ventrally without separation by ventral apotome; posterior ventral apotome less than half length of ventral part of head; abdominal gills with numerous filaments arising from base of central stalk; trochantin usually forked.

Family Hydropsychidae - Oestropsyche

All three thoracic segments sclerotized; abdominal gills present ventrally; anal prolegs long with a brush of setae; head long 2-3x width, posterior ventral apotome less than half length of ventral part of head; abdominal gills with numerous filaments arising uniformly from central stalk; mesosternum lacking gills.

Family Hydropsychidae – Diplectrona

All three thoracic segments sclerotized; abdominal gills present ventrally; anal prolegs long with a brush of setae; head long 2x width, posterior ventral apotome less than half length of ventral part of head; abdominal gills with numerous filaments arising uniformly from central stalk.

Family Odontoceridae - Marilia

Dorsum of each thoracic segment sclerotized; no gills on underside of abdomen; abdominal prolegs without terminal tuft of setae; abdominal tergum IX with a sclerites; stone case; without sternal plates on thorax and abdominal segment 1; pronotum anterolateral margin not produced into sharp points; mesonotal plate subdivided into two sections.

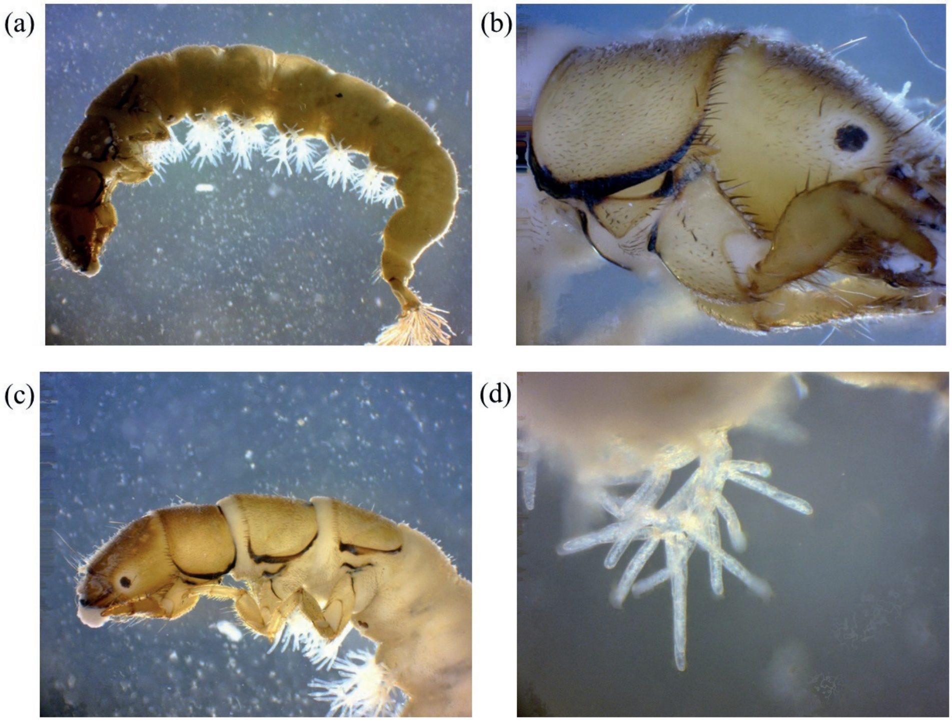


Figure A.61: (a): *Potamyia* body lateral, (b):*Potamyia* lateral head and trochantin, (c): *Potamyia* thorax, (d): *Potamyia* gills

Family Dipseudopsidae Pseudoneureclipsis

All thoracic nota weakly sclerotized although meso and meta nota with median part of plate membranous; no ventral abdominal gills; anal prolegs lack tuft of setae; abdominal segment IX without a sclerites; meta thorax with dark bars present; claws of pro and mesothorax with long claws, much longer than on metathoracic legs.

Family Molannidae Molanna

Case made of sand and shield shaped; pronotum sclerotized, meso and meta notum membranous.

Family Leptoceridae – Oecetis

Anal prolegs short, larvae with case of sand grains.

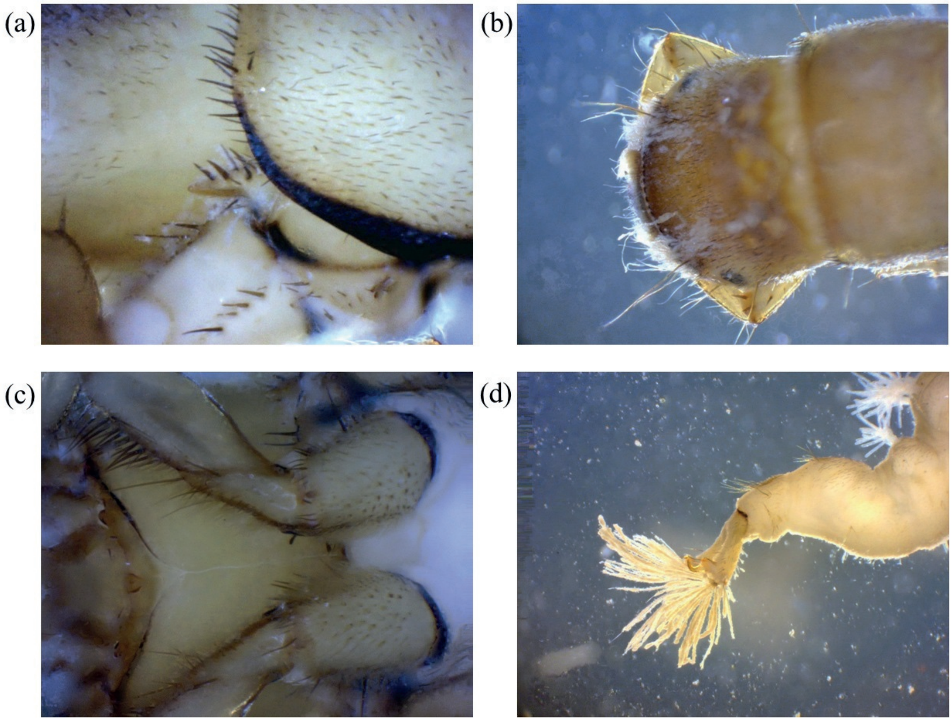
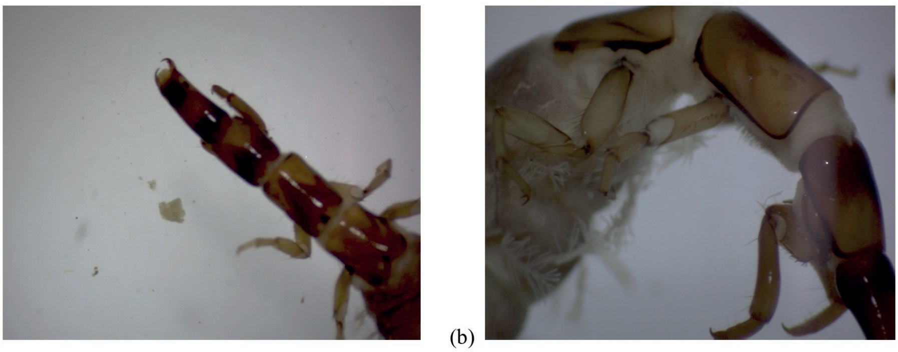


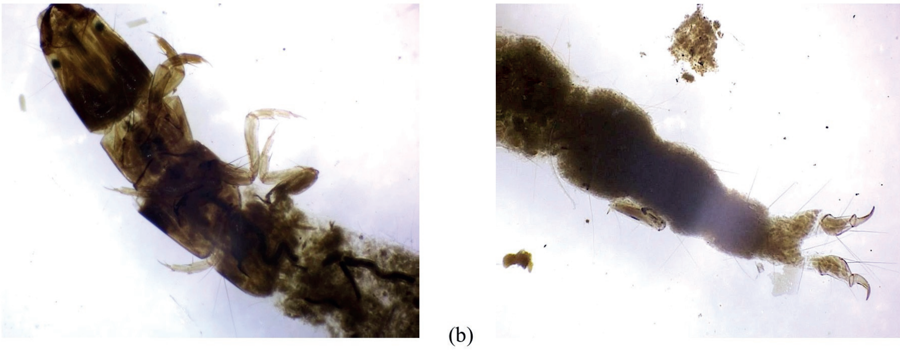
Figure A.62: (a): *Potamyia* trochantin, (b):*Potamyia* frontoclypeus, (c): *Potamyia* ventral head, (d): *Potamyia* anal claws



(a) (b)

Figure A.63: (a):Head and thorax of *Oestropsyche*, (b):*Oestropsyche* lateral thorax

Figure A.64: Anal prolegs of *Oestropsyche*



(a) (b)

Figure A.65: (a): Head and thorax of *Diplectrona*, (b): Anal prolegs of *Diplectrona*

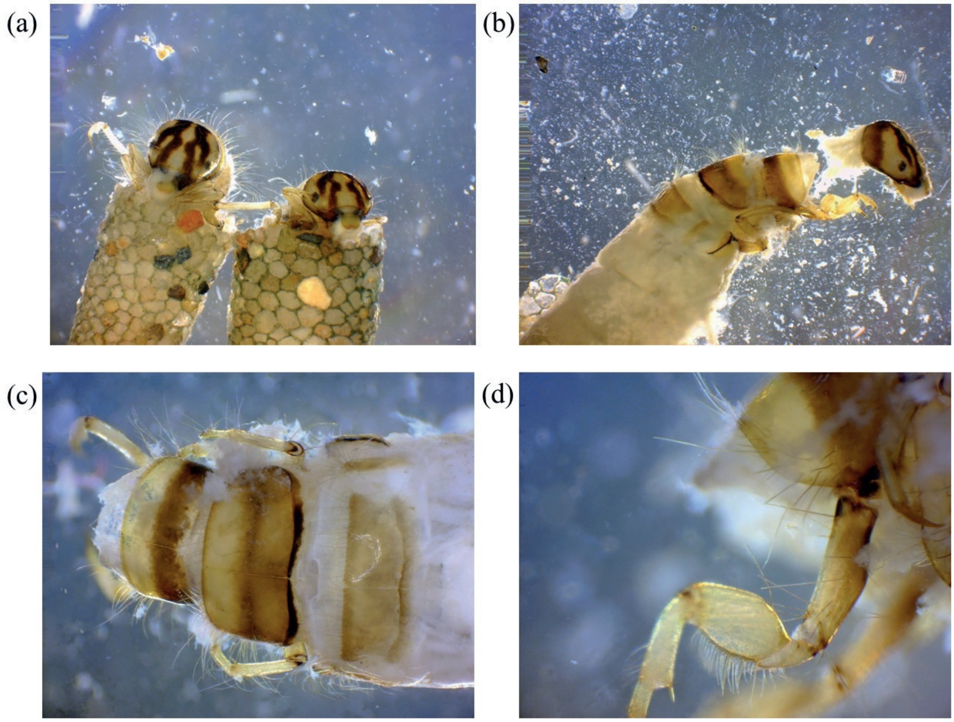


Figure A.66: (a): *Marilia* sp1 striped head, (b): *Marilia* sp1 head and thorax lateral, (c):*Marilia* sp1 sclerotized thorax, (d): *Marilia* sp1 foreleg and trochantin

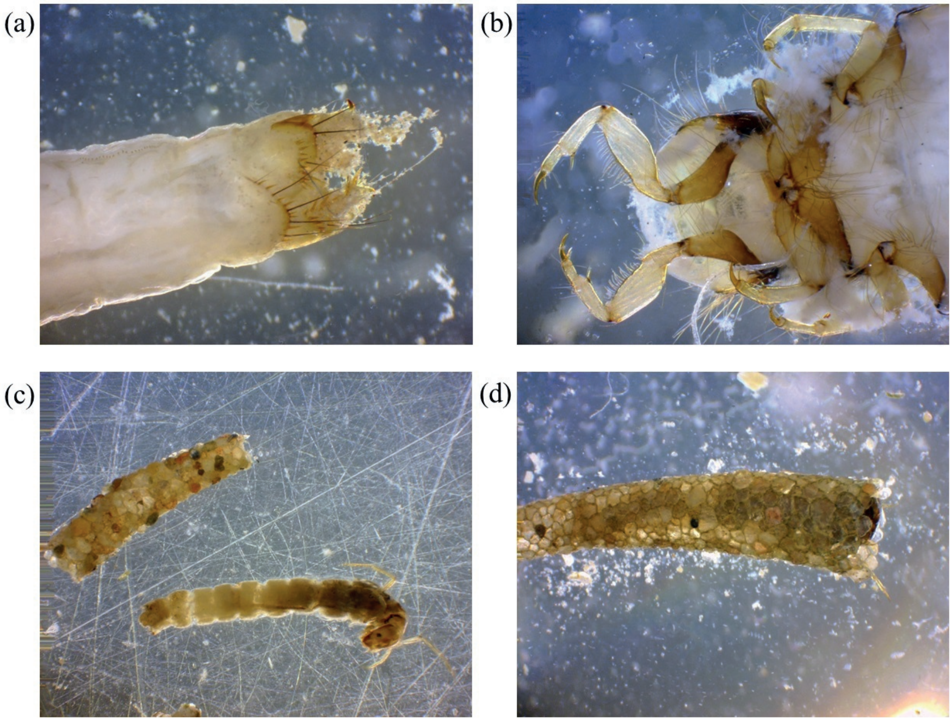


Figure A.67: (a): *Marilia* sp1 anal prolegs, (b): *Marilia* sp1 sternum, (c):*Marilia* sp2 body and case no striped head, (d): *Marilia* sp2 in case

Caddisfly Pupae

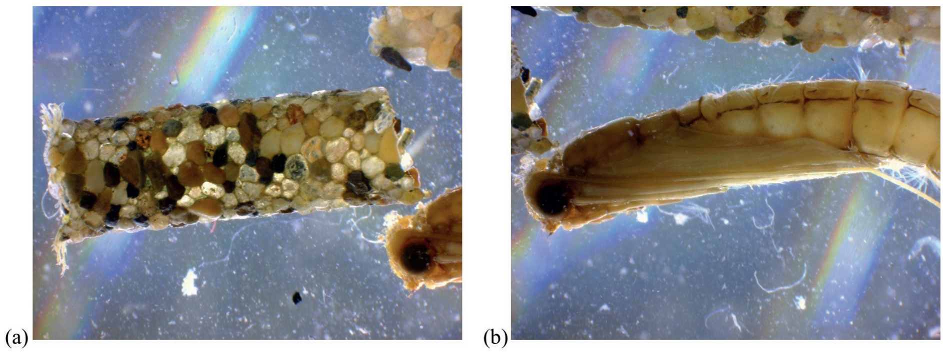


Figure A.68: Caddisfly pupae

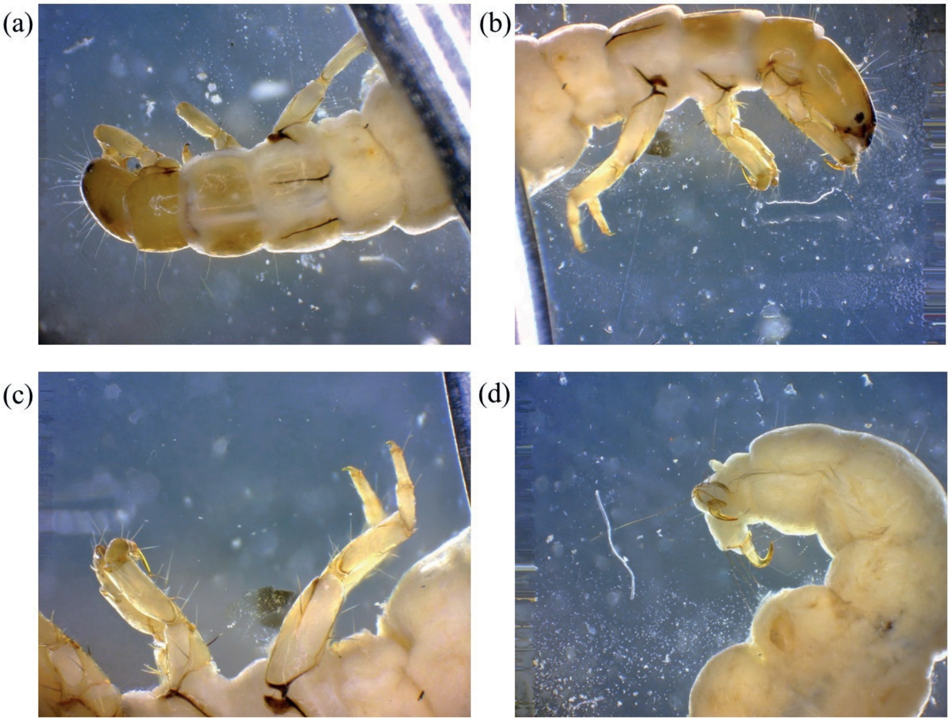


Figure A.69: (a): *Pseudoneureclipsis* thorax sclerotised, (b): *Pseudoneureclipsis* lateral thorax, (c): *Pseudoneureclipsis* long and short claws, (d): *Pseudoneureclipsis* anal claws

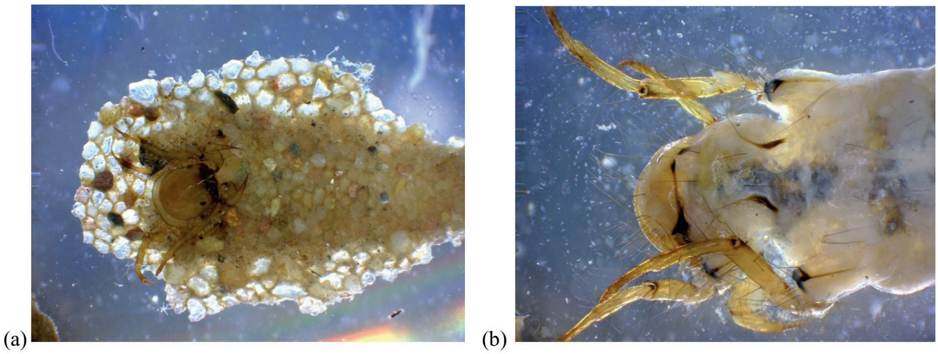


Figure A.70: (a): *Molanna* in distinctive case, (b):*Molanna* thorax, pronotum sclerotized

(a) (b) (c) (d)

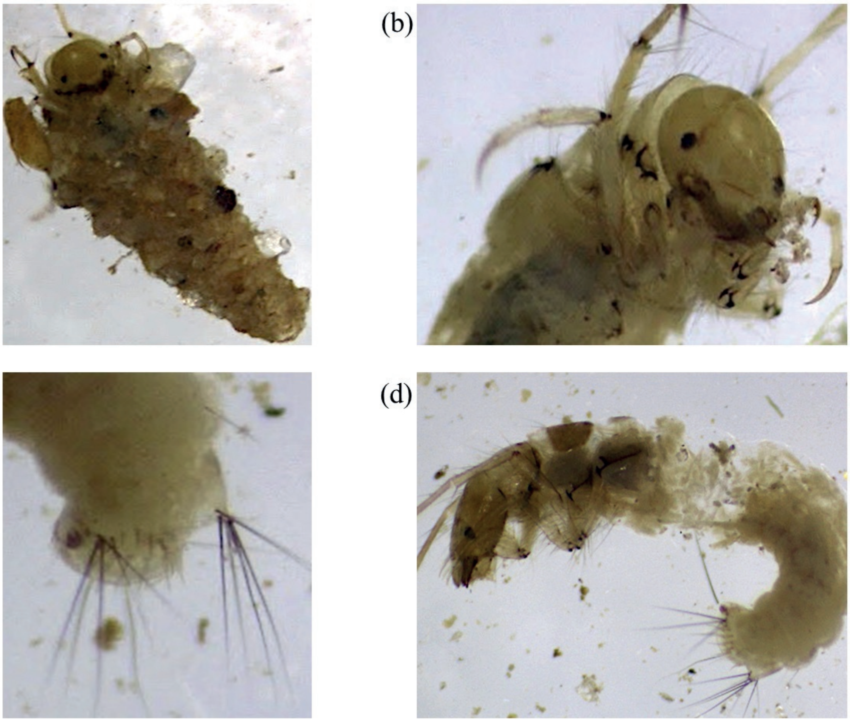


Figure A.71: (a): *Oecetis* habitus and case, (b):*Oecetis* head and legs, (c):*Oecetis*anal tufts , (d): *Oecetis*body removed from case

Order LEPIDOPTERA (Moths)

Prolegs present on ventral of abdominal segments each with hooks–like crochets; legs reduced with 3 short segments, no obvious claws. Among five common genera (Elophila, Eoophyla, Parapoynx, Potamomusa, and Paracymoriza), the specimen of Eoophyla were present in this study area.

Family Crambidae Eoophyla

Thorax and abdomen with lateral gills; head dorso–ventrally flattened, prognathous.

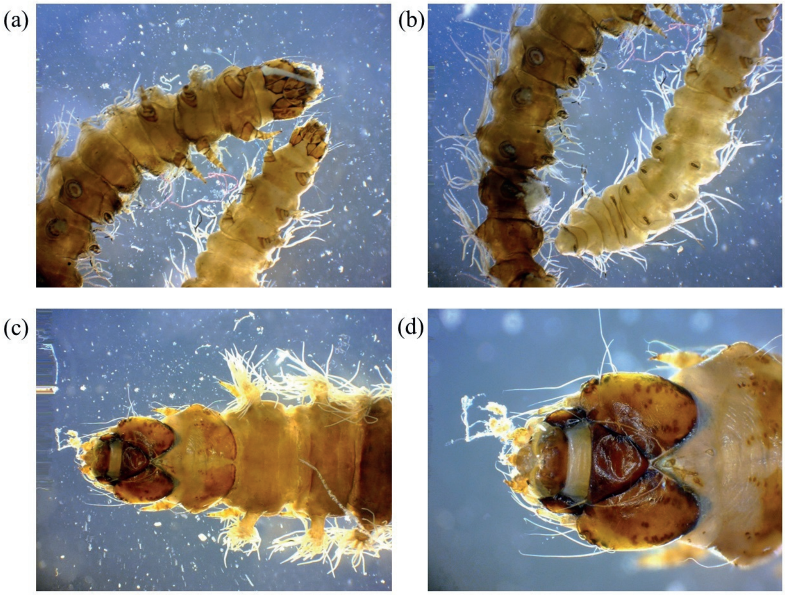


Figure A.72: (a): *Crambidae* head and abdomen ventral, (b): *Crambidae* ventral abdomen, (c): *Crambidae* dorsal head and thorax, (d): *Crambidae* dorsal head

(a) (b) (c)

Figure A.73: (a): *Crambidae* ventral abdominal parapods, (b):*Crambidae* dorsal abdomen, (c):*Crambidae* ventral abdominal parapods

Order COLEOPTERA (Beetles)

Key to Coleoptera of Myanmar

1 Wings and elytra present ....**COLEOPTERAAdult**..........2

1′ Wings and elytra absent ....**COLEOPTERA Larvae**...........6

2(1) Elytra completely covering abdominal segments.......................................3

2′ Elytra short covering only first abdominal segment, abdomen exposed ....**Family STAPHYLINIDAE**

3(2) Head with two pair of compound eyes, meso and metathoracic legs short...**Adult GYRINIDAE**

3′ Head with one pair of compound eyes, meso and metathoracic legs long 4

4(3) First abdominal segment divided into right and left sides, tarsi with 5 segments and with paired claws,; mesoscutellum not visible............................. ....**Adult NOTERIDAE**

4′ First abdominal segment not divided into right and left sides, tarsi with 3 to 5 segments 5

5(4) Metathoracic legs without swim hairs, antennae not club shaped, legs and claws long with tarsal segment 5 elongate, as long as previous 4 segments combined...**Adult ELIMIDAE**

5′ Metathoracic legs with swim hairs, antennae club shaped, pronotum wide similar width to elytra..**Adult HYDROPHILIDAE**

6(1) Dorsoventrally flattened; spherical shaped body shell, head and legs not visible from dorsal view..**PSEPHENIDAE**

6′ Body elongate, linear...7

7(6) Antennae long, usually longer than thorax..............................**SCIRTIDAE**

7′ Antennae shorter than thorax, usually shorter than head 8

8(7) Abdominal segment 10 with 2 pairs of terminal hooks, segments 1–9 with lateral gills..**GYRINIDAE**

8′ Abdomen without lateral gills or terminal hooks.......................................
....**ELMIDAE**.........9

9(8) Last abdominal segment elongated with length »> than width................
....**Elmidae sp 3**

9′ Last abdominal segment short length approx. equal to length.................
....10

10(9) Body covered with distinct tubercles............................. **Elmidae sp 1**

10′ Body not with tubercles, but almost smooth.....................**Elmidae sp 2**

Family Elmidae (Riffle beetles)

Larvae cylindrical, movable operculum with gills under last abdominal segment; body usually fully sclerotized. Legs with 3-4 segments; tarsi with a single claw; antennae short with 3 segments; abdomen with 9 segments.

Adult head with 1 pair of eyes; meso and metathoracic legs long; head lacks a trunk or snout; elytra long covering entire abdomen; tarsal segment 3 not bilobed; first abdominal segment not divided into right and left sides; tarsi with 5 segments; metathoracic legs without swim hairs; antennae not club shaped; legs and claws long with tarsal segment 5 elongate, as long as previous 4 segments combined.

Family Noteridae

Head with 1 pair of eyes and lacks snout; elytra covers entire abdomen; tarsal segment 3 not bilobed; first abdominal segment divided into right and left sides; tarsi with 5 segments; metathoracic legs swim hairs; antennae not club shaped; tarsus with paired claws; mesoscutellum not visible, pronotum separated from mesothoracic wings (elytra) by a straight suture, and no triangular section at midline of elytra.

Family Psephenidae (Water pennies)

Dorsoventrally flattened; spherical shaped body shell. Only group that looks like this. Usually found in flowing waters on rocks.

Family Gyrinidae (Whirligig beetles)

Head with biting mouthparts; lateral feathery gills on first 8 abdominal segments; 2 pairs of gills on 9th segment and 2 pairs of hooks at the end of the 10th segment.

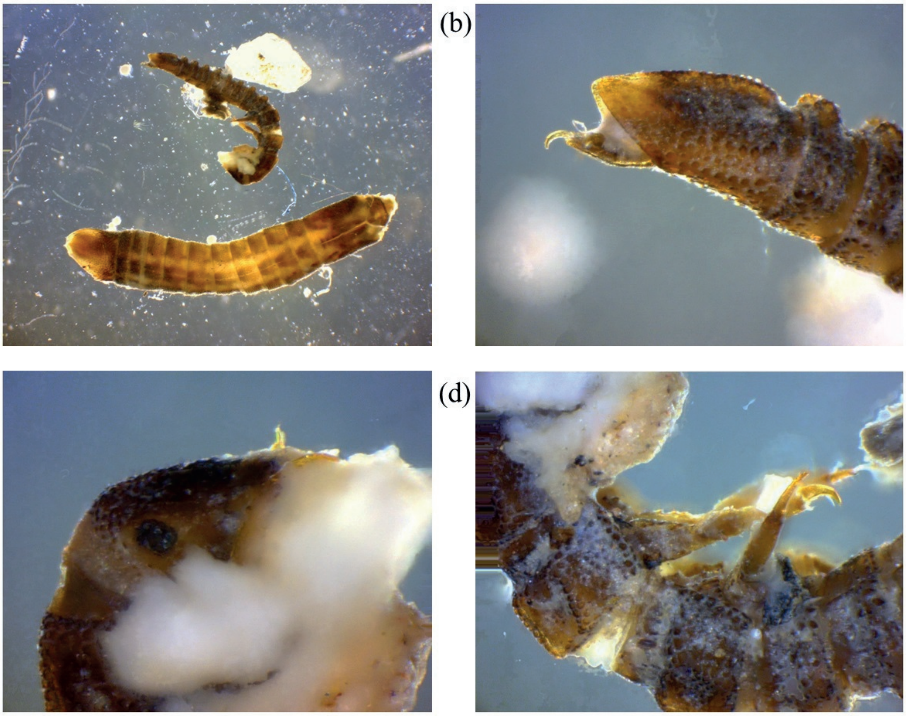


Figure A.74: (a): **Elmidae** 1 (top) 2 spp body, (b):**Elmidae** sp 1 anal region with hooks and operculum, (c):**Elmidae** sp1 head with antenna, (d): **Elmidae** sp 1legs and claws

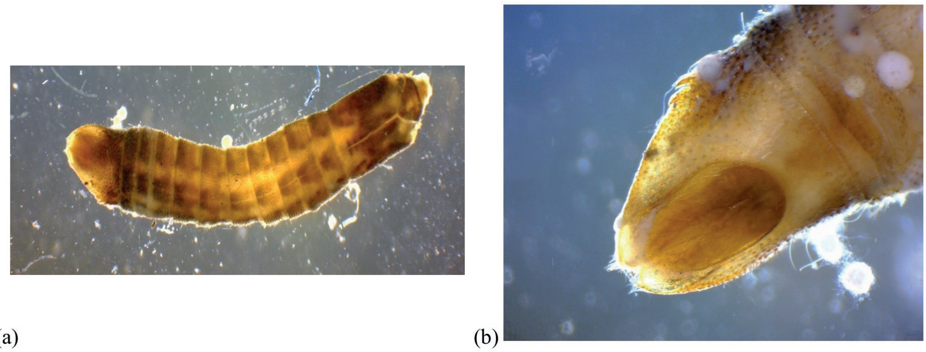
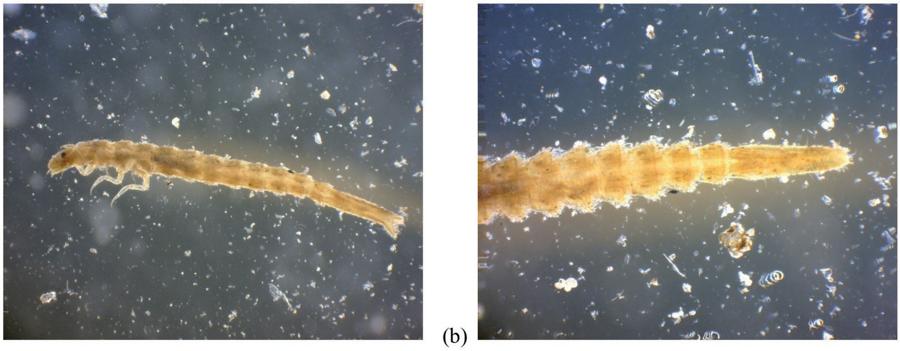


Figure A.75: (a): **Elmidae** 2 spp body, (b):**Elmidae** sp 2 operculum

Family Hydrophilidae

Head with one pair of compound eyes; meso- and metathoracic legs long; tarsi with 3–5 segments; antennae 7–9 segmented with club-shaped terminal segments.



(a) (b)

Figure A.76: (a): Elmidae sp 3 body, (b):Elmidae sp 3 long last abdominal segment

(a) (b) (c)

Figure A.77: (a): Elmidae adult dorsal body, (b):Elmidae head, thorax and legs ventral, (c): Elmidae adult ventral sternum

Family Staphylinidae

Body long and narrow, head thorax and abdomen width similar; elytra short covering only 1st or 2nd abdominal segment; abdomen exposed.

Family Scirtidae

Larvae with a long and narrow body, crawling beetle larva with very long multi-segmented antennae, usually longer than thorax.

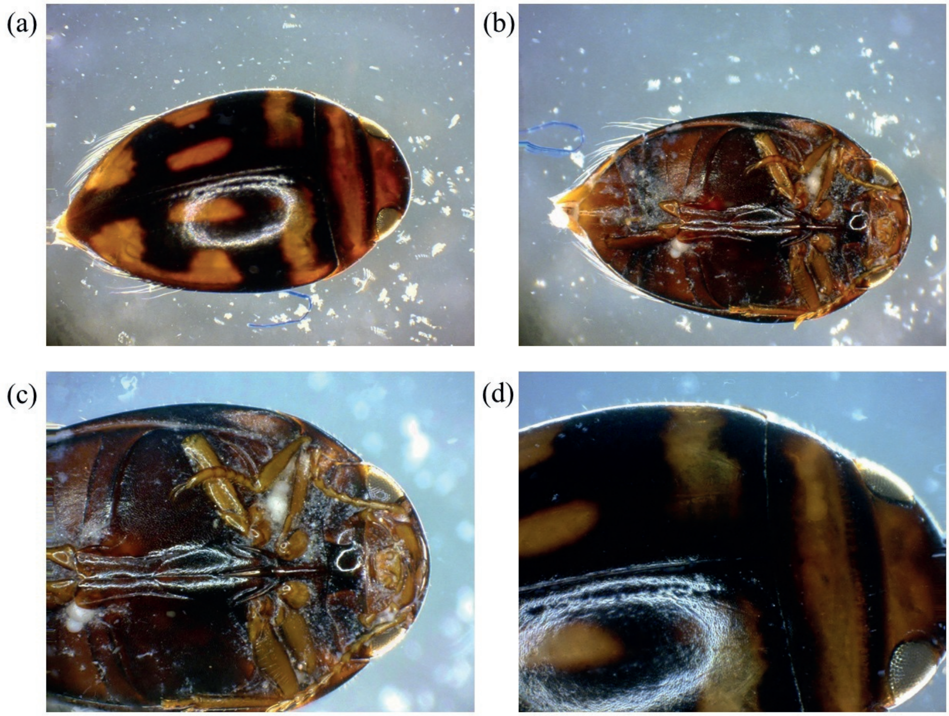


Figure A.78: (a): Noteridae dorsal patterned elytra, (b):Noteridae ventral body, (c): Noteridae ventral legs and antennae, (d): Noteridae no scutellum

(a) (b) (c)

Figure A.79: (a): Psephenidae dorsal shape, (b):Psephenidae ventral body , (c): Psephenidae ventral 3 segmented legs and single claw

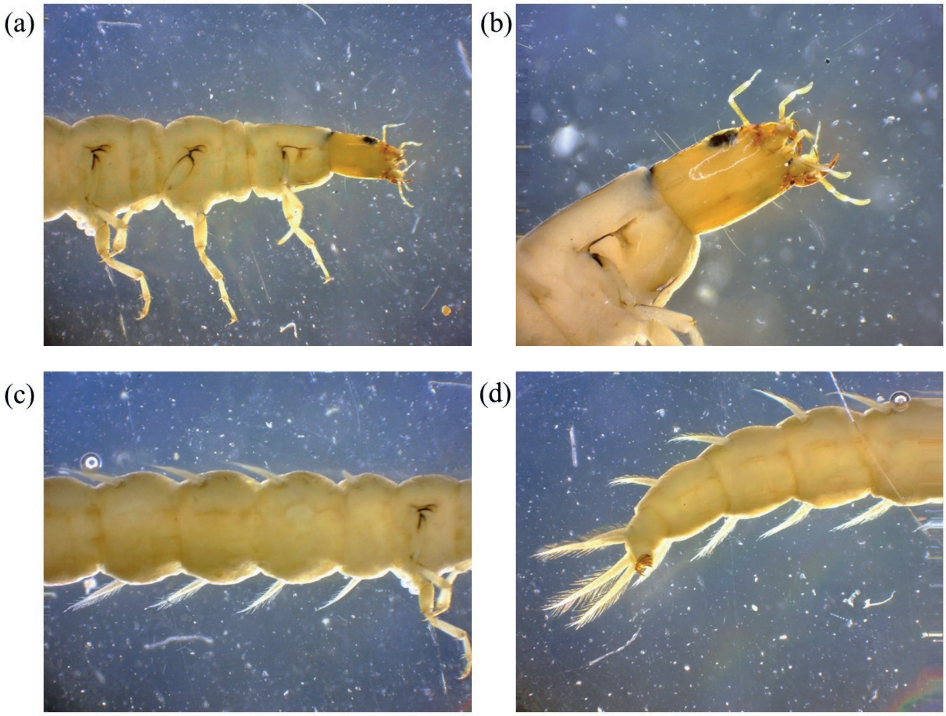


Figure A.80: (a):Gyrinidae head and thorax, (b):Gyrinidae head, biting mouthparts, (c): Gyrinidae abdominal processes, (d): Gyrinidae abdominal processes and anal processes

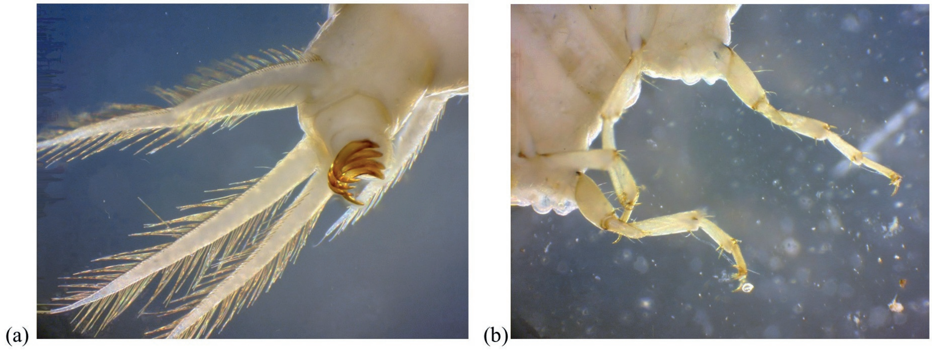


Figure A.81: (a): Gyrinidae Anal prolegs and processes, (b):Gyrinidae legs

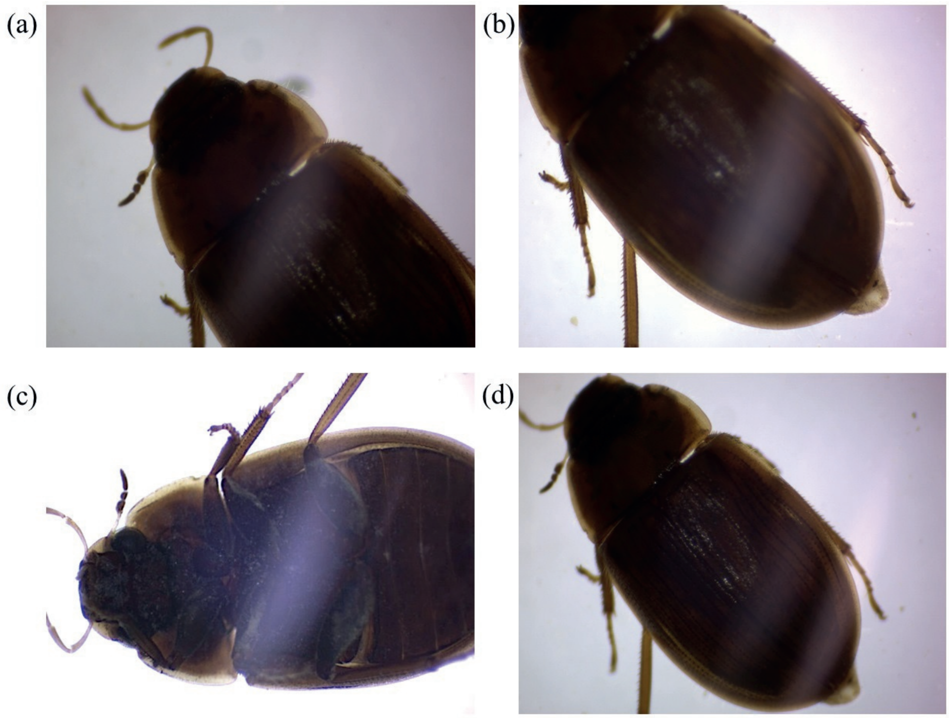


Figure A.82: (a): Hydrophilidae antennae (lower), (b):Hydrophilidae elytra over abdomen, (c): Hydrophilidae ventral view , (d): Hydrophilidae habitus

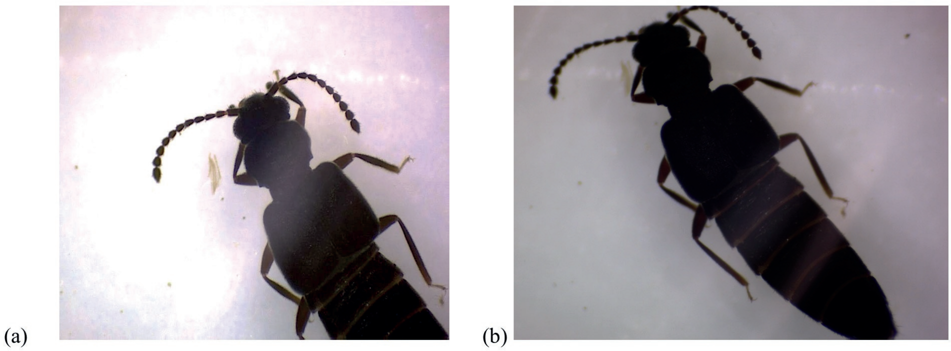
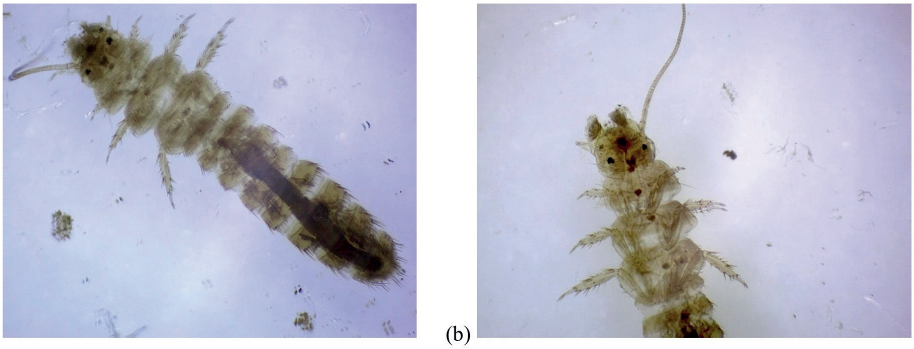


Figure A.83: (a): Staphylinidae head and thorax showing exposed abdomen and short elytra, (b):Staphylinidae body



(a) (b)

Figure A.84: (a): Scirtidae habitus, (b):Scirtidae head showing long antenna

Order DIPTERA (True flies)

The Dipteran pupae are less well known around the world than larvae, and identification keys for dipteran pupae for Asian countries are still unknown. However, three specimen of dipteran pupae were collected in this study. Here, the key for pupae is based on Madden (2017) To identify he dipteran pupae which were not recorded in this study, Madden (2008) is recommended.

Dipteran larvae lack true legs; prolegs may be present on thoracic segments; body shape variable from cylindrical with a complete head capsule to a maggot–like body without obvious head and only mouth hooks present.

Key to Diptera (Pupae) of Myanmar

1 Pupa covered by last larval skin, sclerotized, without tubercles on body; puparium with two spiracles......................................**Ephydridae pupae**

1′ Pupa not cover by last larval skin...2

2(1) Leg sheaths straight, antennal sheaths long; end beyond ends of wing sheaths,
....**Tipulidae pupae**

2′ Leg sheaths curved or folded, antennal sheaths short; end before ends of wing sheaths..**Ceratopogonidae pupae**

Key to Diptera (Larvae) of Myanmar

1 Larvae with head sclerotized usually not retracted into first thoracic segment; body long and cylindrical ....**SUBORDER NEMATOCERA**....2

1′ Larvae without head capsule or partially head form; head retracted into thorax; first thoracic segment lacking prolegs ....
....**SUBORDER BRACHYCERA**.....5

2(1) Head retracted into first thoracic segment; body smooth or with creeping welts on abdomen, horizontally biting mouthparts; abdomen with 9 segments;
....**Family Tipulidae** 3

2′ Head fully developed, body long and narrow, cylindrical, lacking creeping welts 7

3(2) Abdomen with 4 anal processes; body covered in velvety hairs....................
....**Tipulidae sp 1**

3′ Abdomen with 2 anal processes or a bulbous respiratory structure 4

4(3) Abdomen with 2 long anal processes; creeping welts on abdominal segments...***Antocha***

4′ Abdomen with large bulbous anal gill area; lacking creeping welt..**Tipilidae sp 3**

5(1) Welts on abdominal segments encircle each segment; anal prolegs inconspicuous without hooks and lacking paired processes; respiratory siphon present at tip of anal segment...................................**Family Tabanidae**

5′ Paired creeping welts or parapods ventrally on abdominal segments 1–7; anal prolegs with distinct sclerotized hooks...6

6(5) Last abdominal segment with paired tubular processes; dorsal surface smooth lacking spines...**Family Empididae**

6′ Last abdominal segment with long paired processes fringed with setae; dorsal surface with spines on some abdominal segments ....**Family Athericidae**

7(2) One pair of prolegs on first thoracic and at the end of abdominal, anal prolegs and gills present, pair of prolegs on first thoracic segment and posterior abdominal segments.......................**Family Chironomidae**..................8

7′ Thoracic and abdominal segments similar, lacking prolegs or gills..***Ceratopogonidae***

8(7) Eye spot single 9

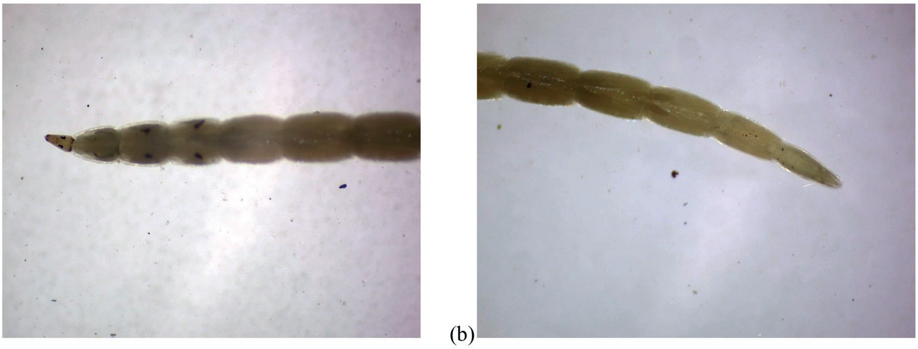
8′ Eye spot double ....**Chironominae**

9(8) Head long, with long antennae which may be retracted into head; anal prolegs long; eye spot peanut shaped ....**Tanypodiinae**

9′ Head short and antennae long or short but not retractile into head; anal prolegs short; eye spot usually round ....**Orthocladiinae**

Family Ceratopogonidae Larvae

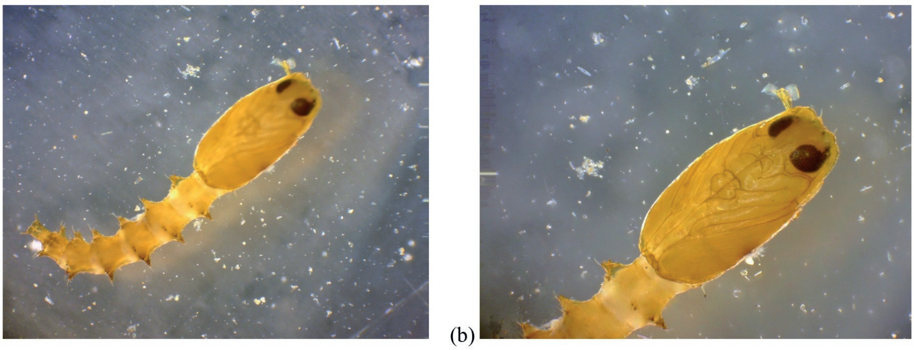
Larvae with thorax and abdomen similar width, head nor retracted; lacking thoracic and abdominal prolegs; last anal segment may have hairs posteriorly. When live body may swim with sigmoidal pattern and may appear rigid when collected with forceps.



(a) (b)

Figure A.85: (a): Ceratopogonidae head and thorax, (b):Ceratopogonidae abdomen

Family Ceratopogonidae Pupae



(a) (b)

Figure A.86: (a): Ceratopogonidae pupae, (b):Head of ceratopogonid pupae

Family Tipulidae larvae

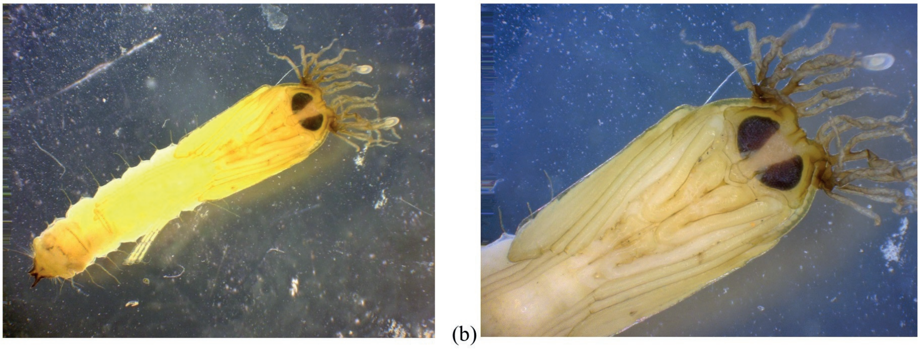
Head retracted into first thoracic segment. Last abdominal segment with long processes or if absent a lobed plate with a pair of spiracles present. Gill chamber near anal area may be enlarged and bulbous. Body may be smooth or with creeping welts on abdomen.

Family Ephydridae Pupae

(a) (b) (c)

Figure A.87: (a): Ephydridae pupae, (b):Ephydridae pupa habitus, (c): puparium with two spiracles

Family Tipulidae Pupae



(a) (b)

Figure A.88: (a): Tipulidae pupae, (b):Tipulidae pupae

Larvae have a sclerotized head capsule not retracted; a pair of prolegs on ventral part of first thoracic segment and on posterior part of abdomen; body long and narrow, cylindrical.

Family Chironomidae

Larvae have a sclerotized head capsule not retracted; a pair of prolegs on ventral part of first thoracic segment and on posterior part of abdomen; body long and narrow, cylindrical.

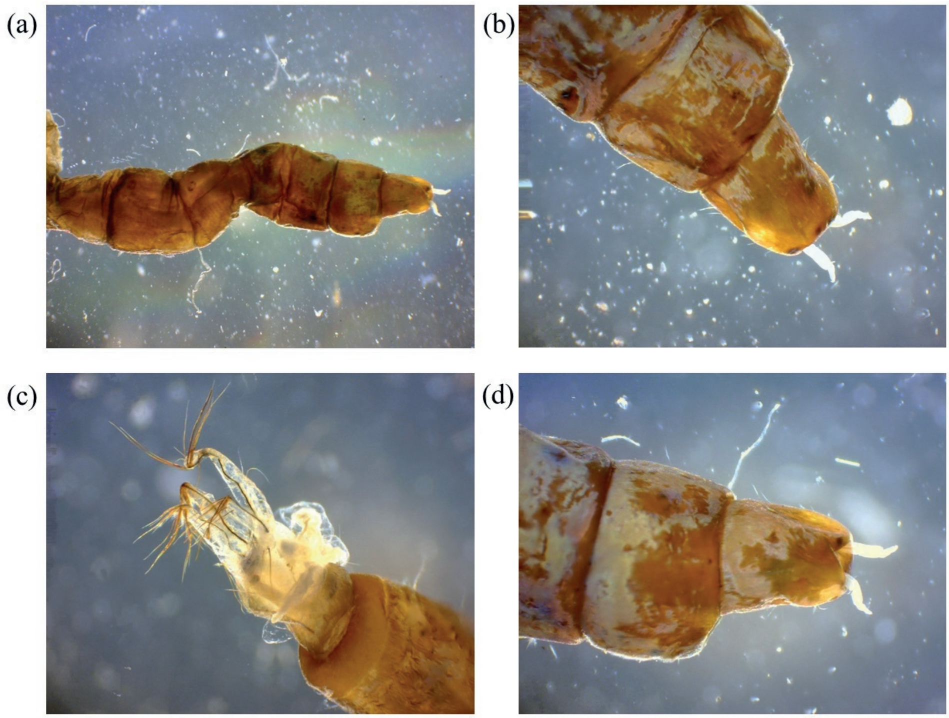


Figure A.89: (a): Tipulidae sp 1 body and head, (b):Tipulidae sp 1 head retracted dorsal, (c): Tipulidae sp 1 Anal processes, (d): Tipulidae sp 1 head retracted

Family Tipulidae- *Antocha*

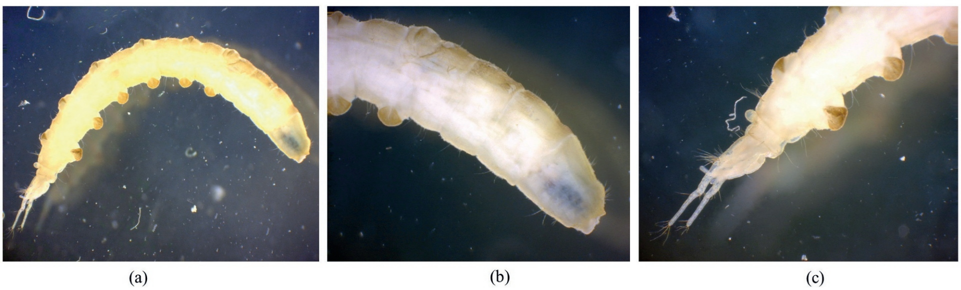


Figure A.90: (a): *Antocha* body with creeping welts, (b):*Antocha* head and creeping welts, (c): *Antocha* anal processes and creeping welts

Family Tabanidae

Large cylindrical animal with distinct ridges and prolegs on abdomen; head completely retracted; respiratory siphon present at tip of anal segment.

Family Tipulidae

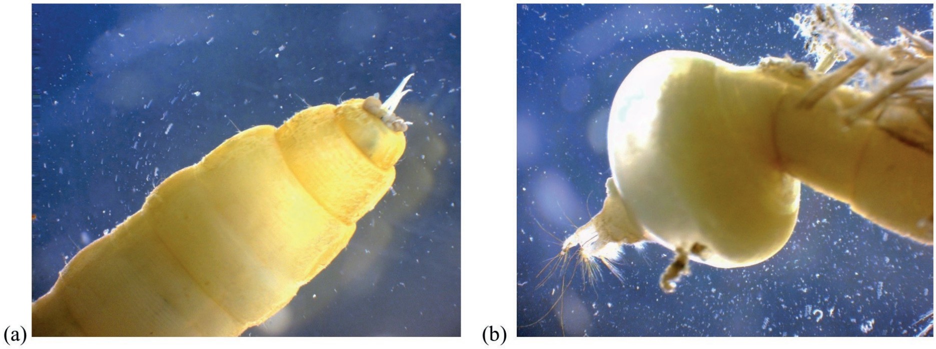


Figure A.91: (a): Tipulidae sp 3 Head retracted, (b):Tipulidae sp 3 bulbous anal gill area

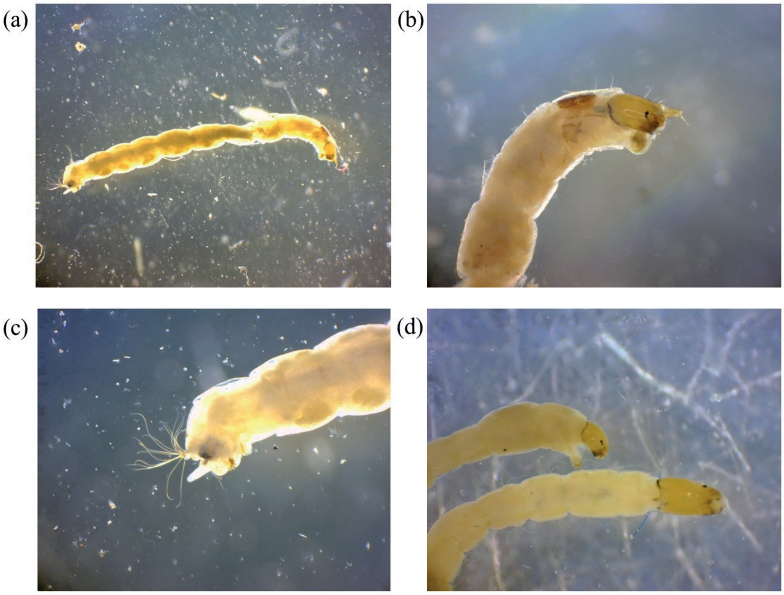


Figure A.92: (a): Chironomidae body, (b):Chironomidae Head and prolegs, (c): Chironomidae Anal prolegs and gills

Family Empididae

Paired creeping welts or parapods on 7 or 8 of the abdominal segments; head retracted but with curved sickle–shaped mandibles.

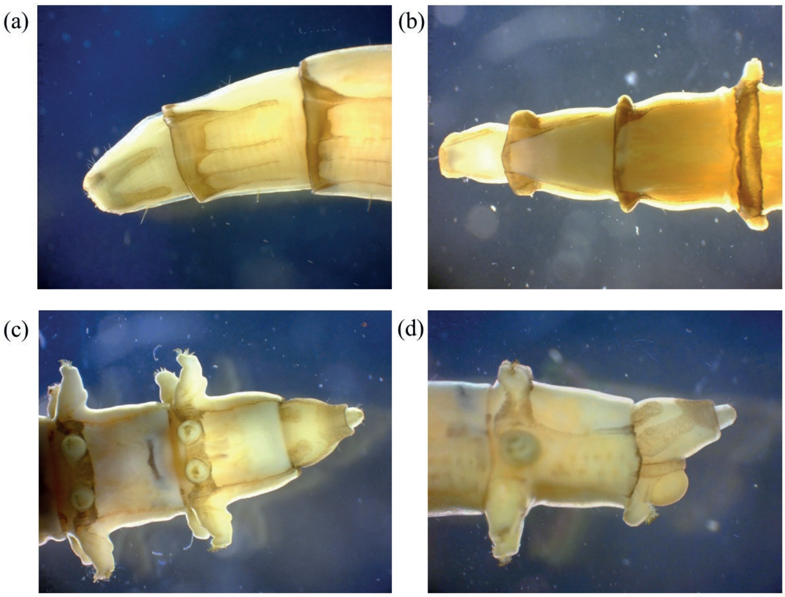


Figure A.93: (a): Tabanidae head, (b):Tabanidae head and thorax, (c): Tabanidae Anal siphon and creeping prolegs, (d): Tabanidae Anal siphon lateral view

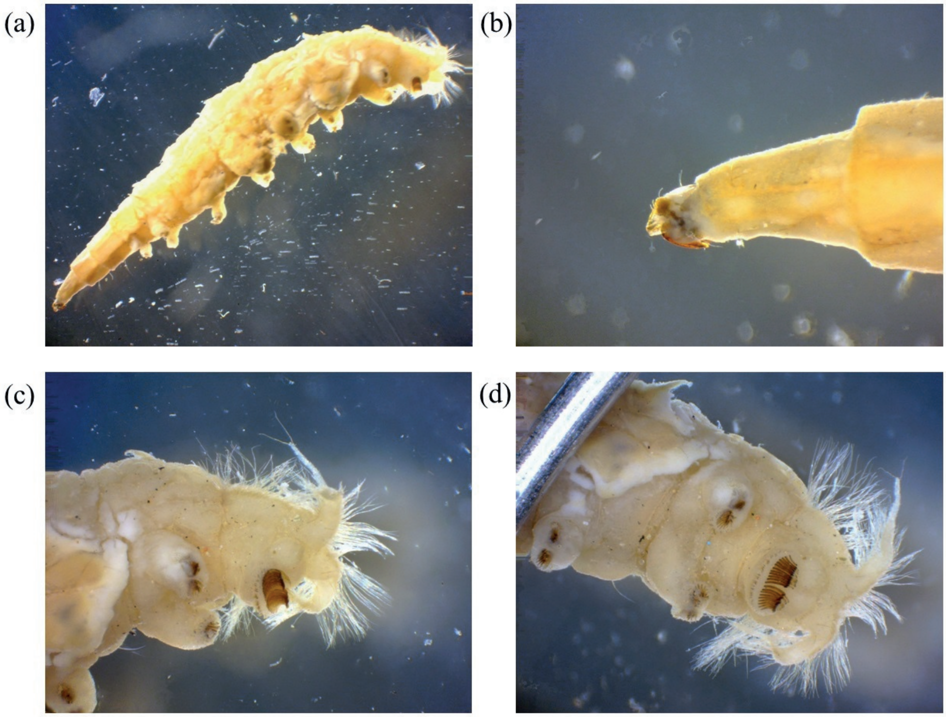


Figure A.94: (a): Empididae body, (b):Empididae head and mandibles, (c): Empididae anal prolegs and processes, (d): Empididae anal processes

Order MEGALOPTERA and NEUROPTERA

ORDER NEUROPTERA

There are three aquatic or semiaquatic families in the order Neuroptera. Family Sisyridae are aquatic representatives and they are parasites on sponges (F. Spongillidae) and were recoded in Myanmar. The mouthparts have needle-like sucking tube to pierce and suck, and ventral gills present on the abdomen. The other two families (F. Neurorthidae, F. Osmylidae) were not recorded in this study The genus Nipponeurothus (F. Neurorthidae) was presented in Taiwan by [189] but little is known of the biology of the Neurorthidae.

Family Sisyridae

Figure A.95: Sisyridae habitus

ORDER MEGALOPTERA

There are two families of Megaloptera (F. Sialidae and F. Corydalidae). Sialis has been found in China but the Corydalidae are common in Asia and better known (Banks, 1940). No specimens of Sialidae were found in this study rivers and irrigation channels. Corydalidae were collected in the upstream sites of the rivers in Myanmar.

Family Corydalidae

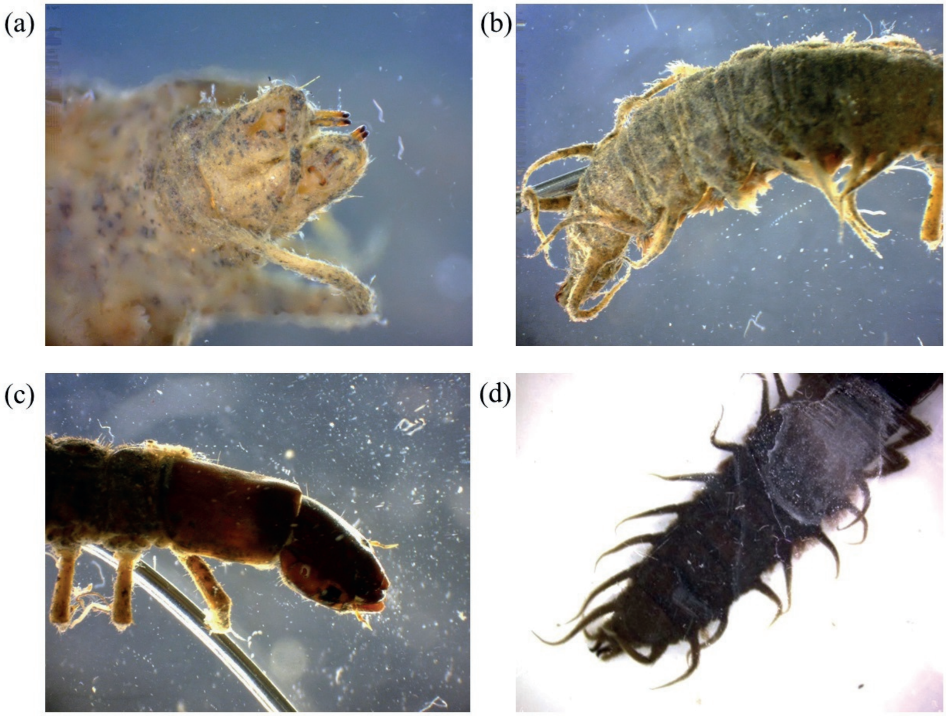


Figure A.96: (a): Corydalidae abdomen anal claws, (b):Corydalidae abdomen, (c):Corydalidae head and thorax, (d): Corydalidae abdomen

Curriculum Vitæ

Nyein Thandar KO

08-07-1985	Born in Kyaikhto, Mon State, Myanmar.

Education

2001–2006	BE in Civil Engineering Technological University, Mandalay, Myanmar
2011–2013	ME in Water Engineering and Management Asia Institute of Technology, Bangkok, Thailand
2016–2021	PhD in Water Management Faculty of Civil Engineering and Geosciences Delft University of Technology, Delft, Netherlands

Introduction

Nyein Thandar Ko (Ko) was born in Kyaikhto, Myanmar on 8^{th} July 1985. She graduated from Mandalay Technological University, Myanmar with Bachelor of Civil Engineering in December 2006. She started to work as a Assistant Lecturer in Civil Engineering Department at Loikaw Technological University, Myanmar from 2007 to 2008. Ko also served as an Professional Engineer on Cyclone Shelter Design and Construction Project for Myanmar Delta Region at Ministry of Science and Technology in Naypyitaw for two years from 2008 to 2009. After the project, Ko worked as a lecturer and provided lecturers in the Civil Engineering Department at Kyauksae Technological University, Myanmar from 2009 to 2011. In 2013, Ko got Master Degree in Water Engineering and Management from Asia Institute of

Technology, Bangkok, Thailand. Ko worked on water resources allocation trade-offs among hydropower, irrigation and environmental flows with the a case study of Kinda Dam in Myanmar using hydrological modelling. After receiving her master degree, she came back to Myanmar from Thailand for working as a lecturer in Civil Engineering Department at Yangon Technological University, Myanmar. Ko provided lectures for undergraduate and graduate classes in Water Resources Engineering. Ko came to the Netherlands as a Ph.D. candidate in Water Management Department at Delft University of Technology (TUDelft) in May 2016 with the support of Netherlands Fellowship Program. Ko focused on how to monitor river health with reliable and low cost monitoring tools for rivers in Myanmar. She has successfully developed a Preliminary Myanmar Aquatic Biomonitoring Assessment Index for Myanmar's Rivers. Ko has experience on field measurements to calibrate remote sensing data and to perform water quality.

List of Publications

Publications

- **Ko, N.T.**, Rutten, M., Conallin, J. (2017). Remote Sensing Analysis of Temperature and Suspended Sediment Concentration in Ayeyarwady River in Myanmar. Global Journal of Engineering and Technology Review., 2(3).

- **Ko, N.T.**,Suter, P., Conallin, J., Rutten, M., Bogaard, T. (2020). *The urgent need for river health biomonitoring tools for large tropical rivers in developing countries: preliminary development of a river health monitoring tool for Myanmar rivers*, Water, 12(5), 1408.

- **Ko, N.T.**,Suter, P., Conallin, J., Rutten, M., Bogaard, T. (2020). *Aquatic Macroinvertebrate Community changes downstream of the Hydropower generating dams in Myanmar-Potential negative impacts from increased power generation Dams impact on Aquatic Macroinvertebrate Community*, Frontiers in Water, 2, 57.

- **Ko, N.T.**, Suter, P., Conallin, J., Rutten, M., Bogaard, T. (2020). *Aquatic macroinvertebrate indicators in the Zawgyi irrigation channels and a river in the central dry zone of Myanmar*, Sustainability, 12(21), 8788.

Abstracts and Conference Proceedings

- **Ko, N.T.**,Jourdain, D., Babel, M. S., Perret, S. R. (2013). *Operation of a Hydropower System Considering Trade-Offs Among Paddy Production, Power Generation and Environmental Flows: A Case Study in Panlaung River Basin, Myanmar*, The Fourth International Conference on Science and Engineering,Yangon, Myanmar.

- **Ko, N.T.**,Jourdain, D., Babel, M. S., Perret, S. R. (2014). *Sustainable water resources allocations management of a dam in Myanmar*, The 7^{th} ASEAN Civil Engineering Conference,Institut Teknologi Bandung, Bandung, Indonesia.

- **Ko, N.T.**, Rutten, M., Conallin, J. (2017). *Remote Sensing Analysis of Temperature and Suspended Sediment Concentration in Ayeyarwady River in Myanmar*, *In EGU General Assembly Conference Abstracts (p. 5261), Vienna, Austria.*, Vienna, Austria.

- **Ko, N.T.**, Rutten, M., Conallin, J. (2017).*Changes in macroinvertebrates assemblages in regulated rivers in Myanmar: Macroinvertebrate as an indicator to study the potential impact of dams.*,20^{th} River Symposium and Environmental Flows Conference, Brisbane, Australia.

- Eulderink, J., Bogaard, T., **Ko, N. T.** (2019, January). *Modelling and assessing impacts of hydropower projects on the ecohydrology of Myanmar rivers.*, In Geophysical Research Abstracts (Vol. 21).

ISBN: 978-94-6419-425-8