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Biogeochemical Characteristics of a Tropical Lake: A study case from Lake Sentani, Papua, Indonesia

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von

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Statement of Original Authorship

Herewith, I assure that I have developed and written the enclosed PhD-thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The PhD-thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

Sulung Nomosatryo

Preface

The study was a part of collaborative research between GFZ-Potsdam and Research Center for Limnology (RCL), Indonesian Institute of Sciences (LIPI). The collaborative research was initiated in 2015 within Towuti Drilling Project (TDP) framework. The Towuti Drilling Project (TDP) is an international research program whose objective is to understand the long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediment. The project was conducted in Lake Towuti, a ferruginous lake in the tropical area. The TDP is part of a drilling program under the auspices of the International Continental Scientific Drilling Program (ICDP).

As an employee of the Research Center for Limnology (RCL)-Indonesian Institute of Sciences (LIPI), I was involved in the TDP project as part of the biogeochemistry group with the (RCL-LIPI) (PI Dr Cynthia Henny), GFZ-Potsdam, Germany (PI Dr Jens Kallmeyer) and UBC, Vancouver Canada (PI Dr Sean Crowe).

After the commencement of the drilling, another collaborative project between RCL-LIPI and GFZ-Potsdam was initiated to study the biogeochemistry of lakes in Papua. The study was designed as a pilot study to obtain a first biogeochemical characterization of a number of lakes in Papua. After some initial reconnaissance surveys, we focused on the unique Lake Sentani, which became my PhD project. This lake comprises several lithologies in the catchment and can be a potential location for studying a single lake's biogeochemical characteristic in the different sub-basin. It also can be a trigger to do some advanced research projects in the future. The University of Papua (UNIPA) and the University of Cendrawasih were also involved.

The thesis is composed of an introduction (chapter 1) and three main chapters (2-4), followed by a synthesis and conclusion (chapter 5). The first chapter introduces the research background, a short description of the study sites, the main objectives of this work and the outline of the thesis. The main chapters consist of three first-author manuscripts. The three publications are synthesised in chapter 5, in which the major conclusions and future perspectives are summarized.

Acknowledgments

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I am incredibly grateful to Dr Cynthia Henny, my senior scientist in the Research Center for Limnology-LIPI (BRIN), for the support and advice during my PhD study and also to the former and current director of the Research Center for Limnology-LIPI (Research Center for Limnology Water Resources-BRIN) (Dr Tri Widianto, Dr Fauzan Ali and Dr Hidayat) for their general support. My colleagues in the Research Center for Limnology-LIPI (Research Center for Limnology Water Resources-BRIN), University of Papua (Manokwari), the late Herry Kopalit (Univerity of Papua, Manokwari) and colleagues in Cendrawasih University, Papua for discussion, support, managing research collaboration and field work organization. Axel Kitte is thanked for his invaluable assistance in the field and the lab.

My colleagues from the Geomicrobiology group at GFZ-Potsdam are thanked for their assistance in the lab., fruitful comments and critical questions during the numerous group meetings. Many thanks go to the co-authors for aid in the paper writing, numerous discussions and a productive and comfortable working on the paper publication.

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Summary

Biogeochemical analyses of lacustrine environments are well-established methods that allow exploring and understanding complex systems in the lake ecosystem. However, most were conducted in temperate lakes controlled by entirely different physical conditions than in tropical climates. The most important difference between the temperate and tropical lakes is lacking seasonal temperature fluctuations in the latter, which leads to a stable temperature gradient in the water column. Thus, the water column in tropical latitudes generally is void of perturbations that can be seen in their temperate counterparts. Permanent stratification in the water column provides optimal conditions for intact sedimentation. The geochemical processes in the water column and the weathering process in the distinct lithology in the catchment leads to the different biogeochemical characteristic in the sediment. Conducting a biogeochemical study in this lake sediment, especially in the Sediment Water Interface (SWI) helps reveal the sedimentation and diagenetic process records influenced by the internal or external loading.

Lake Sentani, the study area, is one of the thousands of lakes in Indonesia and located in the Papua province. This tropical lake has a unique feature, as it consists of four interconnected sub-basins with different water depths. More importantly, its catchment is comprised of various different lithologies. Hence, its lithological characteristics are highly diverse, and range from mafic and ultramafic rocks to clastic sediment and carbonates. Each sub-basin receives a distinct sediment input. Equally important, besides the natural loading, Lake Sentani is also influenced by anthropogenic input. Previous studies have elaborated that there is an increase in population growth rate around the lake which has direct consequences on eutrophication. Considering these factors, the government of The Republic of Indonesia put Lake Sentani on the list of national priority lakes for restoration. This thesis aims to develop a fundamental understanding of Lake Sentani's sedimentary geochemistry and geomicrobiology with a special focus on the effects of different lithologies and anthropogenic pressures in the catchment area.

We conducted geochemical and geomicrobiology research on Lake Sentani to meet this objective. We investigated geochemical characteristics in the water column, porewater, and sediment core of the four sub-basins. Additional to direct investigations of the lake itself, we also studied the sediments in the tributary rivers, of which some are ephemeral, as well as the river mouths, as connections between riverine and the lacustrine habitat.

The thesis is composed of three main publications about Lake Sentani and supported by several publications that focus on other tropical lakes in Indonesia. The first main publication investigates the geochemical characterization of the water column, porewater, and surface sediment (upper 40-50 cm) from the center of the four sub-basins. It reveals that besides catchment lithology, the water column heavily influences the geochemical characteristics in the lake sediments and their porewater. The findings indicate that water column stratification has a strong influence on overall chemistry. The four sub-basins are very different with regard to their water column chemistry. Based on the physicochemical profiles, especially dissolved oxygen, one sub-basin is oxygenated, one intermediate i.e. just reaches oxygen depletion at the sediment-water interface, and two sub-basins are fully meromictic. However, all four sub-basins share the same surface water chemistry. The structure of the water column creates differences on the patterns of anions and cations in the porewater. Likewise, the distinct differences in geochemical composition between the sub-basins show that the lithology in the catchment affects the geochemical characteristic in the sediment. Overall, water column stratification and particularly bottom water oxygenation strongly influence the overall elemental composition of the sediment and porewater composition.

The second publication reveals differences in surface sediment composition between habitats, influenced by lithological variations in the catchment area. The macro-element distribution shows that the geochemical characteristics between habitats are different. Furthermore, the geochemical composition also indicates a distinct distribution between the sub-basins. The geochemical composition of the eastern sub-basin suggests that lithogenic elements are more dominant than authigenic elements. This is also supported by sulfide speciation, particle distribution, and smear slide data.

The third publication is a geomicrobiological study of the surface sediment. We compare the geochemical composition of the surface sediment and its microbiological composition and compare the different signals. Next Generation Sequencing (NGS) of the 16S rRNA gene was applied to determine the microbial community composition of the surface sediment from a great number of locations. We use a large number of sampling sites in all four sub-basins as well as in the rivers and river mouths to illustrate the links between the river, the river mouth, and the lake. Rigorous assessment of microbial communities across the diverse Lake Sentani habitats allowed us to study some of these links and report novel findings on microbial patterns in such ecosystems. The main result of the Principal Coordinates Analysis (PCoA) based on microbial community composition highlighted some commonalities but also differences between the microbial community analysis and the geochemical data. The microbial community in rivers, river mouths and sub-basins is strongly influenced by anthropogenic input from the catchment area. Generally, Bacteroidetes and Firmicutes could be an indicator for river sediments. The microbial community in the river is directly influenced by anthropogenic pressure and is markedly different from the lake sediment. Meanwhile, the microbial community in the lake sediment reflects the anoxic environment, which is prevalent across the lake in all sediments below a few mm burial depth. The lake sediments harbour abundant sulfate reducers and methanogens. The microbial communities in sediments from river mouths are influenced by both rivers and lake ecosystems. This study provides valuable information to understand the basic processes that control biogeochemical cycling in Lake Sentani. Our findings are critical for lake managers to accurately assess the uncertainties of the changing environmental conditions related to the anthropogenic pressure in the catchment area.

Lake Sentani is a unique study site directly influenced by the different geology across the watershed and morphometry of the four studied basins. As a result of these factors, there are distinct geochemical differences between the habitats (river, river mouth, lake) and the four sub-basins. In addition to geochemistry, microbial community composition also shows differences between habitats, although there are no obvious differences between the four sub-basins. However, unlike sediment geochemistry, microbial community

composition is impacted by human activities. Therefore, this thesis will provide crucial baseline data for future lake management.

Zusammenfassung

Biogeochemische Studien werden schon seit langer Zeit durchgeführt. Die meisten Studien wurden jedoch in Seen der gemäßigten Zonen durchgeführt, in denen ganz andere physikalische Bedingungen herrschen als in Seen mit tropischem Klima. Der wichtigste Unterschied zwischen gemäßigten und tropischen Seen ist das Fehlen saisonaler Temperaturschwankungen in letzteren, was zu einem stabilen Temperaturgefälle in der Wassersäule führt. Die Wassersäule wird daher nicht durch wechselnde Oberflächentemperaturen gestört. Die permanente Schichtung in der Wassersäule bietet optimale Bedingungen für eine intakte Sedimentation. Geochemischen Prozesse in der Wassersäule und Verwitterungsprozesse in den unterschiedlichen Lithologien im Einzugsgebiet führen zu unterschiedlichen biogeochemischen Eigenschaften im Sediment. Die Durchführung einer biogeochemischen Studie in diesem Seesediment, insbesondere an der Sediment-Wasser-Grenzfläche (SWI), hilft dabei, die Sedimentations- und diagenetischen Prozessaufzeichnungen aufzuzeigen, die durch interne oder externe Belastung beeinflusst werden.

Der See Sentani, das Untersuchungsgebiet, ist einer von tausenden Seen in Indonesien, der in der Provinz Papua liegt. Der See wurde ausgewählt, weil er die Einzigartigkeit der tropischen Seen repräsentiert, und mit vier Unterbecken verbunden ist, welche in unterschiedlichen Wassertiefen liegen. Des Weiteren, weist sein Einzugsgebiet unterschiedliche Lithologien auf. Die Lithologie ist sehr vielfältig und reicht von mafischem und ultramafischem Gestein bis hin zu klastischen Sedimenten und Karbonaten. Somit erhält jedes Teileinzugsgebiet einen anderen Sedimenteintrag. Ebenso wichtig ist, dass dieser See neben der natürlichen Belastung auch von anthropogenen Einträgen aus seinem Einzugsgebiet beeinflusst wird. Frühere Studien haben gezeigt, dass die Zunahme des Bevölkerungswachstums eine Eutrophierung zur Folge hat. In Anbetracht dieser Faktoren wurde der See von der Regierung der Republik Indonesien zu einem der vorrangig zu restaurierenden nationalen Seen erklärt.

Ziel dieser Arbeit ist es ein grundlegendes Verständnis der Sedimentgeochemie und

Geomikrobiologie des Sentani-Sees zu entwickeln, mit besonderem Augenmerk auf die Auswirkungen verschiedener Lithologien und anthropogener Einflüsse im Einzugsgebiet. Um dieses Ziel zu erreichen, führten wir geochemische und geomikrobiologische Untersuchungen am Sentani-See durch. Wir untersuchten die geochemischen Merkmale in der Wassersäule, im Porenwasser und im Sedimentkern der vier Teileinzugsgebiete. Wir untersuchten nicht nur den See selbst, sondern auch die Sedimente in den Nebenflüssen, von denen einige nur saisonal Wasser führen, sowie die Flussmündungen, welche die Verbindung zwischen dem fluvialen und dem lakustrinen Lebensraum darstellen.

Die Arbeit ist eine Synthese aus drei Publikationen über den Sentani-See und wird durch mehrere Veröffentlichungen über andere tropische Seen in Indonesien ergänzt. Die erste Publikation untersucht die geochemischen Bedingungen in der Wassersäule, des Porenwassers und des Oberflächensediments (obere 40-50 cm) in den Zentren der vier Becken des Sees. Sie zeigt, dass neben der Lithologie des Einzugsgebiets auch die Wassersäule die geochemischen Eigenschaften der Seesedimente und ihres Porenwassers beeinflusst. Die Ergebnisse zeigen, dass die Schichtung der Wassersäule einen starken Einfluss auf die Gesamtchemie hat. Die vier Teilbecken unterscheiden sich jedoch sehr stark in ihrer Wassersäulenchemie. Ausgehend von den physikalisch-chemischen Profilen, insbesondere dem gelösten Sauerstoff, ist ein Teilbecken sauerstoffreich, in einem weiteren erreicht die Sauerstoffkonzentration Werte um Null an der Sediment-Wasser-Grenzfläche, und zwei Teilbecken sind vollständig meromiktisch. Alle vier Teilbecken weisen jedoch die gleiche Oberflächenwasserchemie auf. Die Struktur der Wassersäule führt zu Unterschieden in den Profilen der Anionen und Kationen im Porenwasser. Ebenso zeigen die deutlichen Unterschiede in der geochemischen Zusammensetzung zwischen den Teilbecken, dass die Lithologie im Einzugsgebiet die geochemischen Merkmale im Sediment beeinflusst. Insgesamt haben die Schichtung der Wassersäule und insbesondere die Sauerstoffanreicherung des Bodenwassers einen starken Einfluss auf die elementare Gesamtzusammensetzung des Sediments und die Zusammensetzung des Porenwassers.

Die zweite Veröffentlichung zeigt, dass die Zusammensetzung des Oberflächensediments zwischen den Lebensräumen durch die lithologischen Unterschiede im Einzugsgebiet beeinflusst wird. Die Makroelementverteilung zeigt, dass die geochemischen Merkmale zwischen den Lebensräumen unterschiedlich sind. Darüber hinaus weist die unterschiedliche geochemische Zusammensetzung auch auf eine unterschiedliche Verteilung zwischen den Teilbecken hin. Die geochemische Zusammensetzung des östlichen Teilbeckens deutet darauf hin, dass lithogene Elemente dominanter sind als authigene Elemente. Dies wird auch durch die Sulfid-Speziation, die Partikelverteilung und die Daten der Smear-Slide Analyse bestätigt.

Bei der dritten Veröffentlichung handelt es sich um eine geomikrobiologische Studie des Oberflächensediments. Wir stellen die geochemische Zusammensetzung des Oberflächensediments und seine mikrobiologische Zusammensetzung gegenüber und vergleichen die verschiedenen Signale. Next Generation Sequencing (NGS) des 16S rRNA-Gens wurde angewandt, um die Zusammensetzung der mikrobiellen Gemeinschaft des Oberflächensediments an einer großen Anzahl von Standorten zu bestimmen. Wir verwenden eine große Anzahl von Probenahmestellen in allen vier Teilbecken sowie in den Flüssen und Flussmündungen, um die Verbindungen zwischen den Flüssen, den Flussmündungen und dem See aufzuzeigen. Eine statistische Analyse der mikrobiellen Gemeinschaften in den verschiedenen Lebensräumen des Sentani-Sees ermöglichte es uns, einige dieser Verbindungen zu untersuchen und einige neue Erkenntnisse über mikrobielle Muster in solchen Ökosystemen zu gewinnen. Das Hauptergebnis der Hauptkoordinatenanalyse (PCoA) auf der Grundlage der Zusammensetzung der mikrobiellen Gemeinschaften zeigte einige Gemeinsamkeiten, aber auch Unterschiede zwischen der Analyse der mikrobiellen Gemeinschaften und den geochemischen Daten auf. Die mikrobielle Gemeinschaft in Flüssen, Flussmündungen und in den vier Teilbecken wird stark von anthropogenen Einträgen aus dem Einzugsgebiet beeinflusst. Im Allgemeinen könnten Bacteroidetes und Firmicutes ein Indikator für Flusssedimente sein. Die mikrobielle Gemeinschaft im Fluss wird direkt durch den anthropogenen Druck beeinflusst und unterscheidet sich deutlich von den Seesedimenten. Die mikrobielle Gemeinschaft in den Seesedimenten spiegelt das anoxische Milieu wider, das im gesamten See in allen Sedimenten unterhalb einiger mm Tiefe vorherrscht. Die Seesedimente beherbergen eine Vielzahl von Sulfatreduzierern und Methanogenen. Die mikrobiellen Gemeinschaften in den Sedimenten von Flussmündungen werden sowohl von den Ökosystemen der Flüsse als auch der Seen beeinflusst. Diese Studie liefert wertvolle Informationen zum Verständnis der grundlegenden Prozesse, die den biogeochemischen Kreislauf im Sentani-See steuern. Die Studie bietet den Verantwortlichen Managern des Sees wertvolle Informationen, um die Unsicherheiten der sich ändernden Umweltbedingungen im Zusammenhang mit dem anthropogenen Druck im Einzugsgebiet zu erfassen.

Der Sentani-See wird direkt von der unterschiedlichen Geologie im Wassereinzugsgebiet und der Morphometrie der vier untersuchten Teilbecken und deren Einzugsgebieten beeinflusst, was ihn zu einem einzigartigen Untersuchungsgebiet macht. Dies bietet eine außergewöhnliche Gelegenheit, den Einfluss verschiedener Umweltfaktoren auf die Sedimentzusammensetzung unter identischen klimatischen und hydrologischen Bedingungen zu untersuchen.

Der Sentani-See ist ein einzigartiges Untersuchungsgebiet, das direkt von der unterschiedlichen Geologie im Wassereinzugsgebiet und der Morphometrie der vier untersuchten Einzugsgebiete beeinflusst wird. Als Ergebnis dieser Faktoren gibt es deutliche geochemische Unterschiede zwischen den Lebensräumen (Fluss, Flussmündung, See) und den vier Teileinzugsgebieten. Neben der Geochemie weist auch die Zusammensetzung der mikrobiellen Gemeinschaften Unterschiede zwischen den Lebensräumen auf, obwohl es keine offensichtlichen Unterschiede zwischen den vier Teileinzugsgebieten gibt. Im Gegensatz zur Geochemie der Sedimente wird die Zusammensetzung der mikrobiellen Gemeinschaften jedoch durch menschliche Aktivitäten beeinflusst. Daher wird diese Arbeit wichtige Grundlagendaten für die künftige Bewirtschaftung der Seen liefern.

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1 Introduction

1.1 General introduction to lakes

Over 71 % of Earth's surface is covered by water, of which over 99% are found in oceans (Wetzel, 2001). Even though the amount of water in freshwater lakes (0.009% of total water in the biosphere) and rivers (<0.001%) is relatively small, they are fundamentally important for survival of terrestrial life (Wetzel, 2001). Additional to being a very important water supply rivers and lakes also serve other purposes, the most important ones being recreation, transportation, and food supply.

Scientifically, to differentiate from ocean water which has a relatively constant chemical composition and appreciable salinity (35-39 grams of salt per kg of water), the inland freshwaters commonly contain only 0.01 gram of salt per kg of water (Tundisi & Tundisi, 2011), although there are also saline lakes, which are not part of this study. The inland freshwater ecosystems such as lakes, rivers, reservoirs, and also estuaries, and marshlands in the coastal region have a discernible structure. They can be differentiated based on their morphometry and their drainage basins. The chemical processes and mechanisms occurring in the inland water system are highly dependent on the geochemistry of the bedrock and the soils in the drainage basins (Tundisi & Tundisi, 2011). Also, the biotic and abiotic interactions between water, minerals, organic matter and the organisms inhabiting these ecosystems are controlled by physical factors like light penetration, heat, waves, and currents (Goldman & Horne, 1983).

Water movement has a strong influence on almost all processes in the lake as it controls the mass movement of dissolved and suspended matter from the catchment into the lake and mixing different water masses in the lake. While the water remains well mixed in the catchments and the tributary rivers, stratification can occur. Once the water reaches the lake basin, irrespective of whether the basin was formed naturally or artificially, the water column will undergo stratification based on its physical properties and thereby cause chemical and biological stratification. The physical structure of the lake water column is influenced by the distribution of light and temperature and can be classified as seen in Fig. 1.1. The zonation in the lake can change over time, the reasons can be natural or anthropogenic eutrophication (the ageing of the lake because of nutrient input) (Goldman & Horne, 1983) or non-nutrient element pollution (Wetzel, 2001).

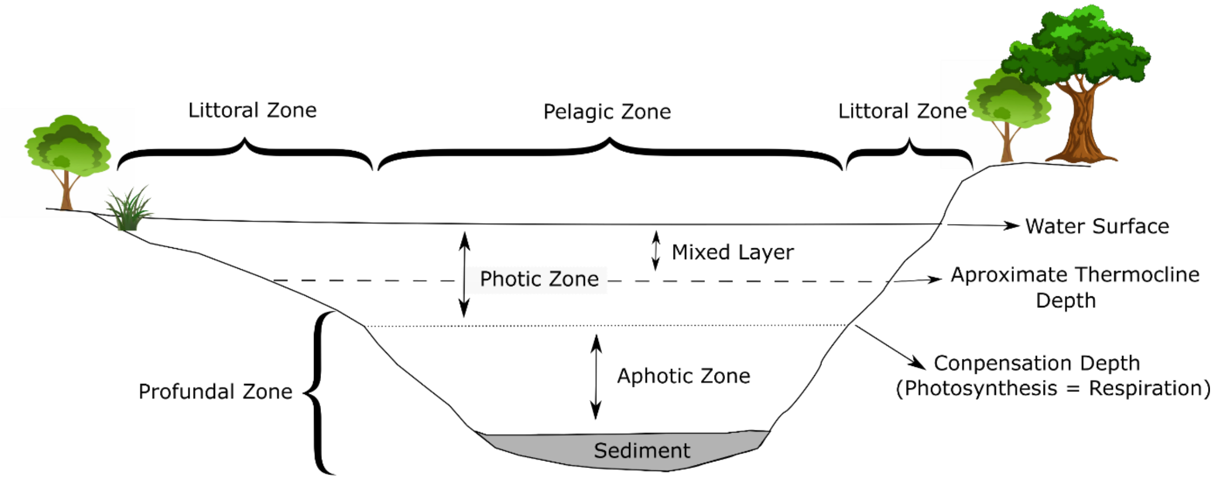


Figure 1.1 *The zonation in the lake system (modified after Goldman & Horne (1983)). The littoral habitat extends from the shore to a depth where mixed surface water reaches the lake bed. The deepest plant growth area is the transition between the littoral and profundal zone. The transition from a photic to an aphotic zone is usually defined as the depth where light intensity falls below 1% of surface levels.*

Lakes are among the most vulnerable ecosystems on earth, and are easily subjected to a variety of stresses originating from within and outside their drainage basins. Nowadays, degradation of a lake system is usually a result of high levels of anthropogenic pressures as a consequence of rapid population and economic growth in the catchment area (Talling, 2001). The reason for elevated population growth around lakes is the fact that they provide a wide range of important values, such as water resources and fisheries, and thereby help to sustain human livelihoods and to support economic activities. Lakes also can accumulate large amounts of terrestrial carbon in their sediments and are major emitters of methane to the atmosphere, which makes them a significant component of the global carbon cycle. Therefore, variation in the element input will impact the biogeochemical processes in the lake system.

1.2 Biogeochemical cycles in lakes

In very general terms, Biogeochemistry studies the mutual interactions between organisms (bio) and their environment (geo) and the chemical compounds and processes that are involved. This study focuses on aquatic biogeochemistry as we are studying the relationship between dissolved ions and gasses, and particulate organic matter or minerals in an aquatic environment and its interactions with the (microbial) inhabitants of this ecosystem. In particular, it focuses on organic and nutrient cycling whose availability determines the distribution of life in lake environments.

Microorganisms play a crucial role in the cycling of the organic matter. Most of the microbially mediated processes are fueled by the degradation of organic matter (Canfield et al., 2005). Autotrophic and heterotrophic processes are the basis for biological utilization of the available solar and chemical energy in the aquatic lake system. Oxygenic photosynthesis is an example of photolithoautotrophy whereas heterotrophic organisms utilize inorganic electron acceptors such as NO_3^-, SO_4^{2-}, Fe-oxides, and Mn-oxides to decompose organic matter (Canfield, 1994; Ferdelman et al., 2006)

Each element undergoes multiple transformations during its biogeochemical cycling, changing from inorganic to organic and from reduced to oxidized forms and back. Understanding the different element cycles can provide crucial understanding of the overall biogeochemical pathways and processes in an ecosystem. In the following, the most important element cycles are presented.

1.2.1 Sulfur cycle

Sulfur cycling in aquatic sediments involves both reductive and oxidative processes (Jørgensen, 1990) (Fig. 1.2) and these have often been neglected in studies of organic matter cycling in freshwater sediments, mainly due to the much lower sulfur (mostly sulfate) concentration levels in freshwater environments (µM range) as compared to the marine realm with seawater sulfate concentration of 28 mM. In the well-mixed and oxygenated epilimnion oxidative processes prevail and sulfur is most commonly found in its most highly oxidized form sulfate (SO_4^{2-}). Below the oxycline, in the anoxic hypolimnion, sulfate can be reduced to sulfide in two ways: assimilatory sulfate reduction, in which sulfate is reduced to form a bioessential compound at an energy cost to the organism, and dissimilatory sulfate reduction, in which the organism gains energy for growth and maintenance from the reduction of sulfate (Canfield et al., 2005). Although many organisms, like higher plants, algae, fungi, and many bacteria, use sulfate as a source of sulfur for biosynthesis, assimilatory sulfate reduction is of little quantitative importance as sulfur comprises only 1% of the dry mass of organisms. Therefore, dissimilatory sulfate reduction is quantitatively dominating, particularly in anoxic sediments, where anaerobic sulfate reducing microorganisms use sulfate as an electron acceptor for degradation of organic matter (Canfield, Thamdrup, & Hansen, 1993; Iversen & Jorgensen, 1993).

Once sulfide is produced, a portion of the sulfide will react with Fe(II) other reduced metals like Mn^{2+} to form various metal (mono)sulfide phases, eventually, the bulk of the sulfide will usually end up in pyrite (Canfield et. al. 2015; Jorgensen 1996). However, sulfide can also be reoxidized back to sulfate, via diverse sulfur intermediates, by either abiotic geochemical or microbially mediated reactions that involve oxygen, nitrate, Manganese (Mn(IV), Iron (Fe(III)) and other potential oxidants (Rickard 2012).

Sulfate (SO_4^{2-}) and sulfide (H_2S) are the quantitatively most important compounds in the anoxic and oxic parts of the sulfur cycle. Sulfate can be reduced microbially by several pathways utilizing a limited range of organic substrates. Some reaction pathways only lead to a partial oxidation of the electron donors, with acetate being the most important product of these incomplete reaction pathways (eq 1-6). The reactions can be expressed as follow:

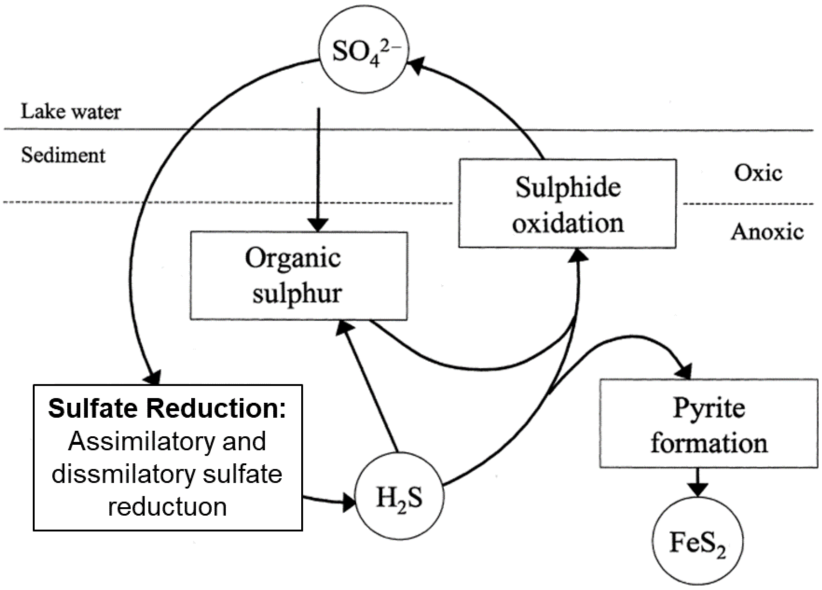


Figure 1.2 *Schematic presentation of the sulfur cycle in the lake (modified from Jørgensen, 1988).*

Incomplete oxidation of lactate:

$2CH_3CHOHCOO^- + SO_4^{2-} \rightarrow 2\ CH_3COO^- + 2HCO_3^- + H_2S$ ....(eq. 1)

Incomplete oxidation of valerate:

$2CH_3(CH_2)_3CO_2^- + SO_4^{2-} \rightarrow 2\ CH_3COO^- + 2\ CH_3CH_2COO^- + H_2S$.....................(eq. 2)

Complete oxidation of lactate:

$2CH_3CHOHCOO^- + 3\ SO_4^{2-} \rightarrow 6HCO_3- + HS^- + H^+$ ....(eq. 3)

Oxidation of acetate:

$CH3COO^- + SO_4^{2-} \rightarrow 2\ HCO_3^- + HS^-$...(eq. 4)

Oxidation of H_2:

$4H_2 + SO_4^{2-} + H^+ \rightarrow 4H_2O + HS^-$ ....(eq. 5)

Anaerobic Oxidation of Methane (AOM) or methanotrophic sulfate reduction:

$CH_4 + SO_4^{2-} = HCO_3^- + HS^- + H_2O$ ....(eq. 6)

Several bacteria have the metabolic potential to oxidize H_2S with various electron acceptors and gain energy in the process (Jørgensen, 1982). The H_2S is not directly re-oxidized to sulfate but via thiosulfate ($S_2O_3^{2-}$) as an intermediate (Jørgensen, 1990). There are three possibilities for thiosulfate to further react, either oxidation to sulfate (eq. 7), reduction with organic matter as an electron donor (eq. 8), or disproportionation to sulfate and sulfide (eq. 9).

$2\ S_2O_3^{2-} + 5O_2 = 4\ SO_4^{2-}$ .... (eq. 7)
$S_2O_3^{2-} + CH_3COO^- + H+ = 2\ HS^- + 2\ CO_2 + H_2O$ .... (eq. 8)
$S_2O_3^{2-} + H_2O = HS^- + SO_4^{2-} + H^+$ .... (eq. 9)

Further, pyritization also can occur in the presence of excess H_2S according to the following reaction:

$FeS + H_2S \rightarrow FeS_2 + H_2$ .... (eq. 10)

1.2.2 The phosphorus cycle

Phosphorus is the tenth most abundant element on earth (0.1% by weight) and a vital functional and structural component of all living organisms. It occurs universally in living cells as phosphate in essential biomolecules such as nucleic acids (DNA and RNA), in the energy transfer system (NADPH and ATP) and in cell membranes (phospholipids) (Canfield et al., 2005). Phosphorus is not involved in redox cycling but it is mainly incorporated into cells. Phosphorus release and adsorption processes commonly take place in the phosphorus cycle.

In lake systems, inorganic phosphorus occurs in both soluble and insoluble forms. Soluble inorganic phosphorus exists as one of the dissociated forms of phosphoric acid (H_3PO_4). The most common in nature is $H_2PO_4^-$ or HPO_4^{2-}, depending on pH (Stumm and Morgan, 1996).

$H_2PO_4^- = HPO_4^{2-} + H^+$, $Ka=10^{-7.2}$ ....(eq. 11)

Surface water typically has low dissolved inorganic phosphate (DIP, >0.1 µM). This general pattern is caused by DIP uptake, net biomass production, and net release of dissolved organic phosphate (DOP) followed by the mineralization of both dissolved and particulate organic phosphorus with depth (Fig. 1. 3).

Phosphate (PO_4) released during organic matter mineralization may become adsorbed to a variety of sediment surfaces (Katsev, 2016), particularly iron oxides. In most lacustrine environments, phosphorus is transferred to the sediment from the overlying water column primarily in the form of organic P, as part of settling organic matter (Katsev, 2016). Inorganic phosphorus is not infinitely soluble; it forms insoluble precipitates with many divalent cations, of which Ca^{2+} and Fe^{2+} are the most important ones in natural environments. Of the possible authigenic P-bearing minerals, the most important in lake environments is probably vivianite ($Fe_3(PO_4)$) (Williams et al., 1976; Fagel et al., 2005; Rothe et al., 2014), a ferrous phosphate mineral that can form under reducing conditions and may become a significant long-term sink of phosphorus. Another important phosphate mineral is carbonate fluorapatite (CFA, $Ca_5(PO_4)_3(X)$, where X consist of variable of proportions of CO_3^{2-}, F^-, and OH.

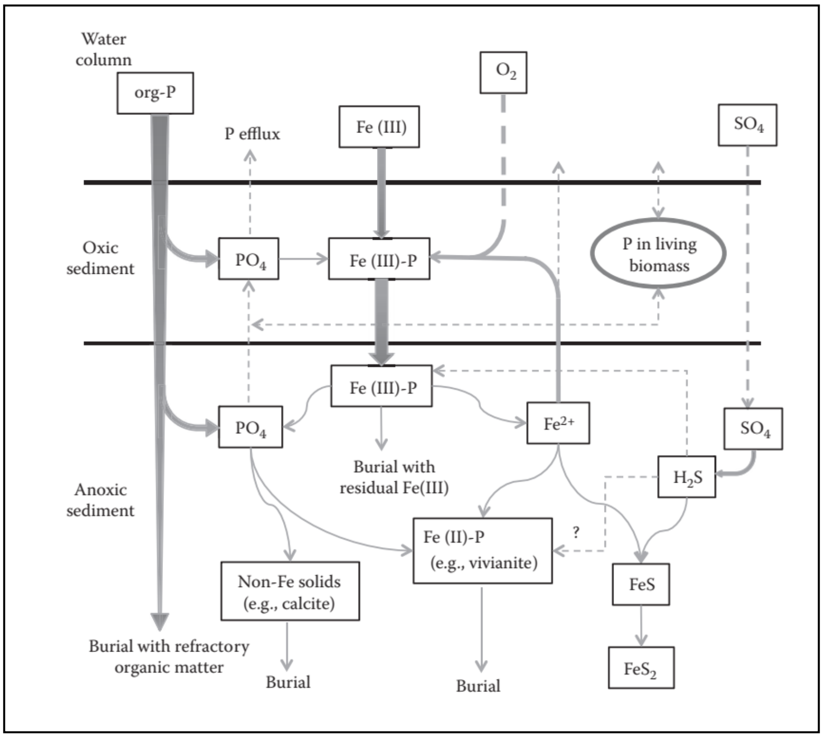


Figure 1.3 *Simplified diagram of P cycling in sediments (Katsev, 2016)*

1.2.3 Carbon cycle

The carbon cycle is of central importance to aquatic biogeochemistry. Through oxidation and reduction, the biogeochemical cycles of other important elements of life (N, P, and S) are connected to the carbon cycle through biological processes that capitalize on the presence of organic carbon and oxygen. In the global system, only 0.002% of the total carbon inventory on Earth is bound in living biomass which also represents only 2% of the reactive carbon pool, represented by particulate and dissolved organic matter, dissolved inorganic carbon, and atmospheric CO_2 (Hedges & Keil, 1995). Degradation of organic matter or the weathering of limestone will produce inorganic carbon. If it is liberated to the atmosphere, the speciation of inorganic matter is as CO_2 and if it enters the water system, it is mostly as HCO_3^- (Canfield et al., 2005).

Once the inorganic matter enters the lake water system, it can undergo fixation by autotrophic organisms (plants or algae) and becomes part of the living biomass (LPOC [Living Particulate Organic Matter]) (Fig. 1. 4). However, upon the death of the organism the LPOC starts to decompose and the dead biomass is usually first converted to Dissolved Organic Carbon [DOC] through hydrolysis/fermentation reactions and subsequently converted back to inorganic carbon (CO_2 formation) by heterotrophic metabolism (Canfield, 1994).

Aerobic and anaerobic heterotrophic microorganisms are responsible for a large proportion of organic carbon oxidation in the aquatic environment. Organisms that utilize oxygen are called aerobes, which can be further differentiated into facultative aerobes can adapt their metabolism to function with or without the presence of oxygen or obligate ones that can only function in the presence of oxygen (Canfield et al., 2005). Under oxygen-deficient (anaerobic) conditions, catabolic reactions are coupled to terminal electron acceptors other than oxygen. Anaerobic decomposition of organic carbon takes place via a wide range of hydrolysis/fermentation reactions that break down the macromolecular structure into smaller organic compounds and hydrogen. The products from hydrolysis and fermentation are further oxidized to H_2O and CO_2 by a number of respiring microorganisms using a variety of inorganic compounds as electron acceptors.

The order of electron acceptor use is controlled by the thermodynamic gain of the respective process (Froehlich et al., 1979). Electron acceptors with the highest energy gain are used first.

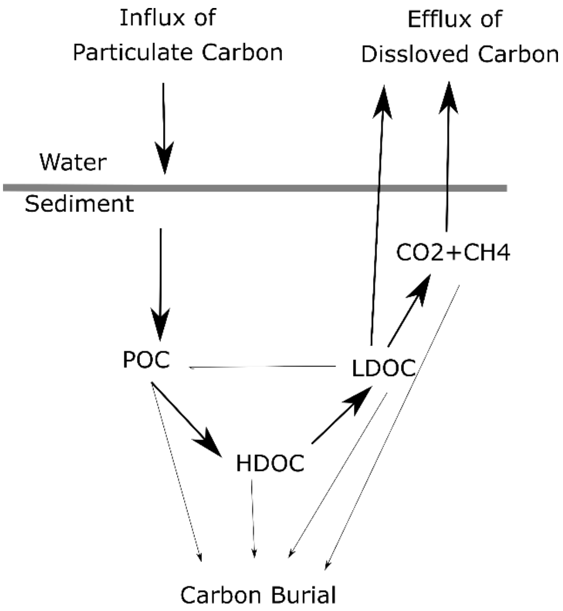


Figure 1.4 *Schematic of the major pathways of organic matter transformation in sediments (Canfield et al., 2005). Arrow thickness gives some sense for the quantitative role of processes. Abbreviation: POC (Particulate Organic Matter), HDOC (High Molecular-weight Dissolved Organic Matter), LDOC (Low Molecular-weight Dissolved Organic Matter).*

Aerobic carbon oxidation

$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + xO_2 \rightarrow xCO_2 + yNH_3 + zH_3PO_4 + xH_2O$ .... (eq. 12)

Denitrification

$CH_3COOH + 1.6NO_3^- + 1.6H^+ \rightarrow 2CO_2 + 0.8N_2 + 2.8H_2O$ .... (eq. 13)

Mn Reduction

$CH_3COOH + 4MnO_2 + 8H^+ \rightarrow 2CO_2 + 4Mn^{2+} + 6H_2O$...................................... (eq. 14)

Fe Reduction

$CH_3COOH + 8FeOOH + 16H^+ \rightarrow 2CO_2 + Fe^{2+} + 14H_2O$ .... (eq. 15)

Sulfate Reduction

$CH_3COOH + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S + 2H_2O$.. (eq. 16)

Acetoclastic methanogeneis:

$CH_3COOH + 4H_2 \rightarrow 2CH_4 + 2H_2O$... (eq. 17)

1.3 Fate and transport of inorganic compounds from the catchment to the lake

Lacustrine sediment is a mixture of materials from both terrestrially derived material from the drainage basin (catchment) or within the lake itself. During transport from its source to its place of deposition it also records many different processes and conditions. Weathering and erosion in the catchment exert the most fundamental control on the chemistry in lacustrine sediment (Stallard & Edmond, 1983). Organic and inorganic material from the catchment will be transported to the lake via the river as fluvial sediment along the river bed or as suspended matter in the water column. However, while in most cases water is the quantitatively most important transport medium and therefore responds to variations in precipitation, aeolian (i.e. wind-driven) input in arid regions also can contribute to the composition of the lacustrine sediment. Once the materials enter the lake, some of the material will settle relatively quickly on the lake floor and not undergo further transformations, other compounds will participate in a wide range of biogeochemical reactions, thereby changing or completely losing the geochemical information from the catchment stored in them. Hence, quickly settling, mostly inert minerals and the chemical elements stored in them are termed detrital, whereas those that undergo transformation are termed diagenetic.

Additional to material derived from external sources, other material is produced in the water column, e.g., phyto- and zooplankton, as well as mineral precipitates. After deposition at the lake floor diagenetic processes will continue to modify the deposited material, leading to compositional changes in the solid phase as well as in the pore water. Diagenetic processes continue deep into the sediment column, leading to increasing transformation of the deposited material. Hence, the elemental and mineralogical composition of the sediment at the sediment-water interface (SWI) provides the most accurate estimate of the composition and quantity of material that was transferred from the catchment and the water column to the sediment (Martin-Puertas et al., 2017) and diagenetic mineral transformations (Rothwell & Croudace, 2015).

1.3.1 Classification of sediment components

Sediments are mixtures of various organic and inorganic compounds; analysis and quantification of the individual compounds are essential for any geochemical interpretation. The terms 'authigenic' and 'allogenic' are at the heart of sediment component classification as they describe the most important difference between compounds, namely their origin. However, these terms are not being used unequivocally. The term 'authigenic' is used in three different ways (Boyle, 2001). First, in the geological literature it is used for minerals formed within the sediment after burial. Second, in most palaeolimnological literature it refers to a sediment component formed within the lake, irrespective whether this happened in the water column or at the surface of the sediment, and is essentially synonymous with the term 'endogenic'. Under this definition, components formed within the sediment are termed 'diagenetic'. Third, some operational classification schemes use 'authigenic' to refer to the readily extractable element fraction, thereby including any extractable allogenic contribution.

Furthermore, Boyle (2001) summarizes that the classification of the sediment can be grouped based on the particle's origin into *authigenic* (= endogenic, particles formed within the lake of inorganic and/or biological origin), *hydrogenic* (particles formed within the lake of inorganic origin), *biogenic* (= biophile, derived from biological sources), *allogenic* (particles derived from outside the lake), *anthropogenic* (= technogenic, materials derived from human sources); *cosmogenic* (from space); *aeolian* (windblown allogenic particles), *minerogenic* (= lithogenic, terrigenous, derived from catchment mineral sources), *diagenetic* (supplied through post-burial modification of the sediment). We will use this definition in our study.

1.3.2 Influence of Lake Sediment Composition on Element Detection and Interpretation

Lake sediments are important terrestrial recorders of environmental change over a range of timescales, recording both catchment-scale dynamics and regional climatic variability. They can provide long, continuous, higher-resolution archives comparable to those from oceans and ice cores. Compared to oceans, the greater influence of the catchment on lacustrine sediment composition means that in most cases, changes on land are directly transmitted to lake sediments (Davies, Lamb, & Roberts, 2015). Therefore, the elemental composition of a lake sediment can be used as an indicator of the provenance of the sediment (Fig. 1.5).

Elements such as Al, Si, K, Ti, Fe, Rb and Zr usually are used as indicators of detrital input (Davies et al., 2015). They are also called lithogenic elements because they are immobile, and relatively conservative after deposition (Boës ert al., 2011). From those elements, Titanium (Ti) is often used as a proxy for erosion and transport of silt and fine sand and therefore is a reliable indicator of catchment input (Metcalfe et al., 2010). It is commonly associated with silts, either as Fe–Ti oxides or Ti-rich magnetites, occurring in Fe-rich clastic mineral particles (Davies et al., 2015).

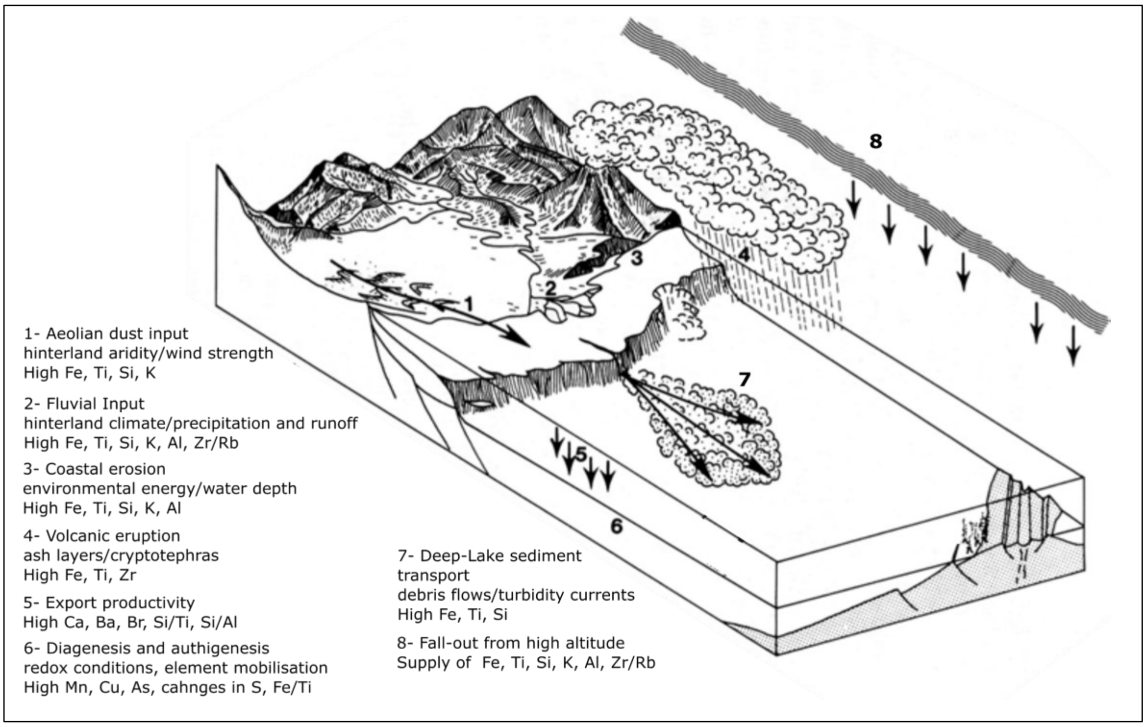


***Figure 1.5** Element pathways to and within the marine environment, with environmental indicators. Terrigenous/lithogenic elements (Fe, Ti, Si, K and Al) are typically land-derived from erosion of continental rocks, and indicative of sediment transport from land to the deep-lake. Si and Ca may be supplied by surface water productivity and volumetrically substantial. Volcanic eruptions is also important element sources. Diagenesis and authigenesis within sediments are important processes for element recycling (Modified and implemented to lake system from Rothwell & Croudace (2015))*

Iron (Fe) and manganese (Mn) concentration profiles can provide information about changing redox conditions (Davison, 1993). The behavior of these redox-sensitive elements depends on the environmental condition in the lake's water column, particularly oxygen concentrations, as they become easily reduced under sub- or anoxic conditions. In a reducing environment, the solubility of Fe and Mn increases, but Mn is more readily affected (Boyle, 2001), so an increase in Fe/Mn ratios can indicate the anaerobic conditions. A shift to higher Fe/Mn may therefore point to a lowering of bottom-water oxygen content during enhanced stratification, or de-oxygenation from organic decay following enhanced biological productivity linked to changing nutrient input (Davies et al., 2015).

1.4 Geomicrobiology (potential microorganism)

The main role of bacteria in a freshwater environment is the degradation of organic matter and the recycling of key elements like nitrogen, phosphorus, and sulfur, which are present within the various organic compounds. Heterotrophic microorganisms are responsible for most of the organic breakdown in freshwater environments, both in the water column and the sediment. Classification of freshwater bacteria in the water column depends on their metabolic activities mainly on the availability of oxygen (Canfield et al., 1993; Konhauser, 2009). In the suboxic zone, where O_2 is depleted but not fully reducing, mostly facultative anaerobes which are capable of aerobic respiration as long as oxygen is available, use an alternative Terminal Electron acceptor (TEA) like NO_3^-, NO_2^-, Mn(IV), and Fe(III) to mineralize the organic matter. In the anoxic zone with fully reducing conditions, anaerobic microorganisms that cannot use O_2 as an electron acceptor and are generally inhibited in the presence of O_2 dominate the ecosystem. The most important TEAs in the anoxic zone are SO_4^{2-} and CO_2. (Konhauser, 2009). Even in highly oligotrophic systems with low organic carbon concentrations, anaerobic processes dominate mineral transformation processes, as oxygen only penetrates a few mm into the sediment (Corzo et al., 2018).

1.4.1 Chemoheterotrophic pathways

1.4.1.1 Dissimilatory manganese reduction

Many bacterial genera are capable of carrying out Mn(IV) reduction. The most prominent ones are *Pseudomonas*, *Bacillus*, *Geobacter*, and *Shewanella*. Some of them are facultative anaerobes, and in the presence of O_2 may use it as a TEA instead, while some grow preferentially as Fe(III) reducers, only switching to the reduction of MnO_2 when it becomes available (Konhauser, 2009). For any of them, the dissimilatory Mn(IV) electron transport begins with the transfer of H_2 to a hydrogenase. The H_2 can come from the environment whereby the bacteria behave either chemolithoautotrophically as hydrogen-oxidizing bacteria or mixotrophically, whereby they assimilate organic compounds as their carbon source:

$H_2 + MnO_2 \rightarrow Mn^{2+} + 2OH^-$ $\Delta G°' = -166$ kJ mol-1 H_2 (or 2e-) .... (eq. 18)

More commonly, H_2 is removed from organic electron donors such as acetate (eq. 19). Under these conditions, the microorganisms behave chemoheterotrophically.

$CH_3COO^- + 4MnO_2 + 3H_2O \rightarrow 4Mn^{2+} + 2HCO_3^- + 7OH^-$ $\Delta G°' = -558$ kJ mol-1
acetate or -139 kJ/2e$^-$ (eq. 19)

1.4.1.2 Dissimilatory iron reduction

The amorphous (Goethite) and crystalline (hematite and magnetite) forms of Fe-oxides are the preferred sources of solid-phase ferric iron for Fe(III)-reducing bacteria in the sediment (Bloesch, 2009). Dissimilatory Fe(III) reduction is broadly distributed among several known bacterial genera e.g., Geobacter and Shewanella (Coleman, Hedrick, Lovley, White, & Pye, 1993). *G. metallireducens* and *S. putrefaciens* were among the first bacteria studied in a pure culture that could gain energy from coupling Fe(III) reduction to the oxidation of H_2 and/or simple fermentation products, including short- and long-chain fatty acids, alcohols, and various monoaromatic compounds (Konhauser, 2009):

$0.5H_2 + Fe(OH)_3 \rightarrow Fe^{2+} + 2OH^- + H_2O$ $\Delta G°' = -110$ kJ/2e- ....(eq. 20)

$CH_3COO^- + 8Fe(OH)_3 \rightarrow 8Fe^{2+} + 2HCO_3^- + 15OH^- + 5H_2O$ $\Delta G°' = -337$ kJ mol-1
acetate or -84 kJ/2e$^-$.....(eq. 21)

In a ferruginous lake, potential iron reducers are the second most abundant group concerning their relative abundances of OTUs among all taxa with proven phenotypes related to iron cycling (Vuillemin et al., 2018). The relative abundance of taxa tended to exist throughout the sediment by depth, successively appearing as *Deferrisoma, Geobacter, Thermincola, Geothrix* and *Anaeromyxobacter* (Vuillemin et al., 2018), illustrating the broad phylogenetic distribution of this metabolic pathway as well as its importance for the degradation of organic matter under ferruginous conditions.

1.4.1.3 Dissimilatory sulfate reduction

Within the domain Bacteria, many Sulfate Reducing Bacteria (SRB) belong to the phylum *Proteobacteria* (Konhauser, 2009). These species are typically mesophiles (*Desulfotomaculum*, *Desulfosporosinus*, and *Thermoacetogenium*), where they are prevalent in anoxic sediments but they are usually not found in the water column unless the oxygen concentrations are limited by stratification (Konhauser, 2009). In an oxic environment, the vegetative cells of SRB cannot survive (Perry, 1995).

There are two groups of SRB based on their metabolic pathway. The first group utilizes lactate, formate, propionate, butyrate, pyruvate, and aromatic compounds, which they typically oxidize to acetate, while the second group oxidizes acetate all the way to CO_2 (Konhauser, 2009). Many SRB from both groups are additionally able to grow chemolithoautotrophically, some using H_2 as the electron donor, while others show incredible metabolic plasticity in that they can oxidize hydrogen sulfide, sulfite (SO3-), thiosulfate, and elemental sulfur with oxygen, nitrate, or nitrite, as electron acceptors (e.g., Dannenberg et al., 1992).

$4H_2 + SO_4^{2-} \rightarrow H_2S + 2OH^- + 2H_2O$ $\Delta G^{\circ\prime} = -152$ kJ mol -1 or -38 kJ $2e^-$ .... (eq. 22)

$CH_3COO^- + SO_4^{2-} + H_2O \rightarrow H_2S + 2HCO_3^- + OH^-$ $\Delta G^{\circ\prime} = -48$ kJ mol -1 acetate or -12 kJ $2e^-$ (eq. 23)

Several heterotrophic species unable to carry out dissimilatory sulfate reduction are instead able to reduce elemental sulfur or sulfite to hydrogen sulfide (e.g., Moser and Nealson, 1996):

$H_2 + S_0 \rightarrow H_2S$ $\Delta G^{\circ\prime} = -28$ kJ/$2e^-$ .... (eq. 24)

$3CH_3COO- + 4SO_3^{2-} + 5H^+ \rightarrow 4H_2S + 6HCO_3^-$ $\Delta G^{\circ\prime} = -126$ kJ mol-1 acetate or -32 kJ/$2e^-$…….. (eq. 25)

1.5 Tropical lakes

With the equator running right through the country, Indonesia's lakes are characterized as tropical lakes that have only two seasons, the rainy and the dry season (Fig. 1. 6), but no temperature fluctuations. The absence of temperature changes fosters physical stratification. Therefore, biogeochemical processes in the ecosystems of these lakes will have different characteristics than those that occur in lakes from temperate areas. However, studies on tropical limnology are rarely carried out when compared to these studies conducted in temperate regions. From the over 12.000 references of limnological research that are listed in Scopus, tropical limnology accounts for only 2.79% (Santoso & Toruan, 2020). This is a gross underrepresentation of these ecosystems, even when accounting for the fact that not more than 10% of the world's lakes are tropical, based on random sampling from maps (Lewis, 1996). Due to this general lack of research, the special characteristics of tropical lakes system are still largely unknown (Escobar et al., 2020).

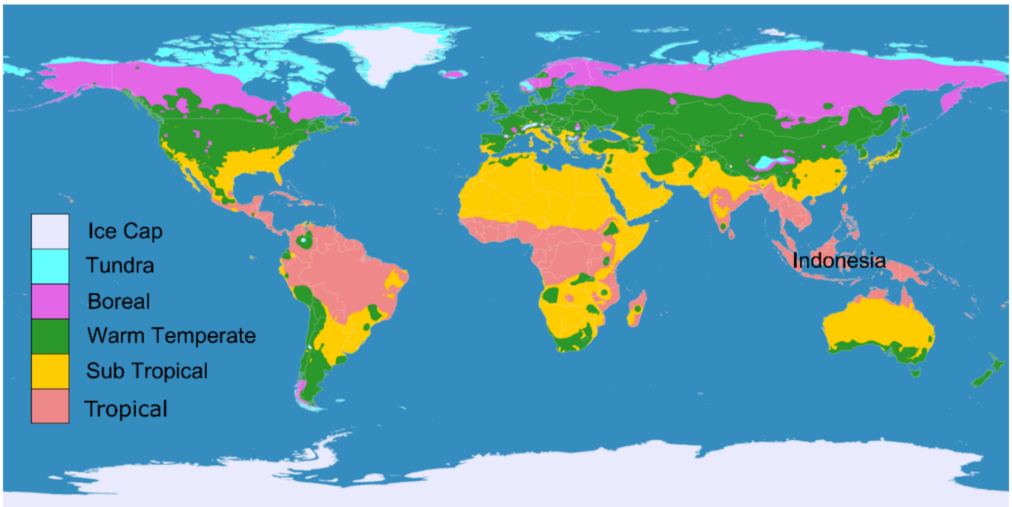


Figure 1.6 *Earth climatic zone. Besides Brazil, Indonesia is the largest country located in the tropical region (https://en.wikipedia.org/wiki/Geographical_zone)*

1.5.1 The biogeochemistry of tropical lakes

Traditionally, the study of limnology has focused on temperate regions. Numerous studies have shown that tropical lake systems are fundamentally different from temperate ones (Escobar et al., 2020; Giesen, 1994). Warm climate, higher solar radiation and precipitation rates have crucial consequences for biogeochemical processes in tropical waters (Lewis, 1987). Besides, rapid population and economic growth in many tropical countries have resulted in high levels of anthropogenic pressures on these systems in recent times. Such pressures have resulted in a reduction in the adequate supply of water of acceptable quality in many tropical countries and provide challenges to limnologists regarding societal concerns and climate change impacts (Santoso & Toruan, 2020). Therefore, understanding the connection between processes in terrestrial and aquatic systems in tropical regions will be critical for addressing environmental problems associated with locally, regionally, and globally altered biogeochemical cycles.

Overall metabolic activity in tropical lakes is regulated primarily by temperature, irradiance, and substrate availability (Lewis, 2010). Solar irradiance is of direct relevance to photosynthesis; it also induces gradients in water temperature and thereby fosters stratification and/or mixing of the water column (Lewis, 1987). The trends in air temperature are extremely different between tropical and temperate regions (Fig. 1.7). Continuously high solar irradiation levels in tropical regions and a lack of seasonal temperature fluctuations, lead to a stable temperature gradient in the water column that is not disturbed by changing surface water temperatures (Lehmusluoto et al., 1997). Unlike in temperate regions, where the annual climatic variation is mainly controlled by air temperature fluctuations, the main annual climatic variation in tropical regions is precipitation with a wet and a dry season and no more than 5ºC temperature differences (Boehrer and Schultze 2008; Katsev et al., 2017). Consequently, the higher temperature in tropical lakes will lead to an doubling of total metabolic (anabolic and catabolic) activity compared to mid-latitude lake (Lewis, 1987; Talling, 2001).

Many larger and deep tropical lakes are meromictic (Katsev et al., 2017; Lehmusluoto et al., 1997); i.e., the water column is permanently stratified with a well-mixed oxic surface layer (also called mixolimnion or epilimnion) and a denser anoxic deep layer (hypolimnion) (Hutchinson, 1957). Lakes are called meromictic if a chemically different bottom layer, has continuously been present for at least one annual cycle (Boehrer & Schultze, 2008). The stratification leads to a permanent distinct in the geochemical composition in the hypolimnion, called monimolimnion (Fig. 1.8.B).

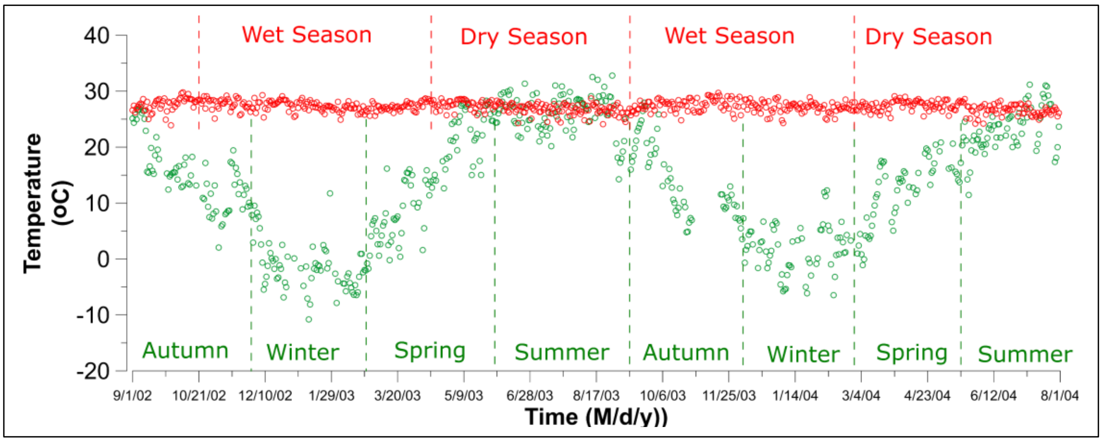


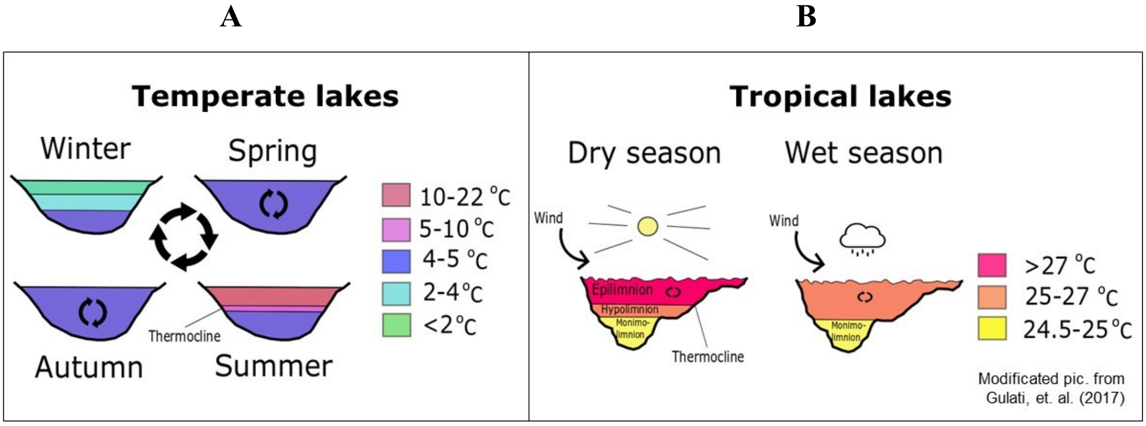
Figure 1.7 *Air temperature variations at Lake Sentani (red) and Germany (green) as representatives of tropical and temperate climates, respectively. The temperature profile from Germany shows up to 30°C difference between seasons. For comparison, the air temperature profile from Lake Sentani shows a relatively flat pattern. The data was mined from TRMM_3B43, Giovanni Earth Data for Germany amd from BMKG's (Indonesian Meteorological, Climatological, and Geophysical Agency) meteorological station in the Sentani area.*

The annual climatic variation impacts only the epilimnion but not the hypolimnion (Fig. 1. 8). Consequently, persistent stratification will occur throughout the year (Santoso et al., 2018). Even though the upper and the lower layer differ by only ~ 2ºC (Lewis, 2010), another example in Lake Matanao (Crowe et al., 2008) and Lake Toba (Nomosatryo & Lukman), this difference is sufficient to maintain a stable density stratification which has profound implications on the biogeochemistry of tropical lakes (Katsev et al., 2017).

The same temperature differences in tropical lakes therefore produces stronger density stratification than in temperate lakes because it is not disturbed by annual overturning (Katsev et al., 2017). Nutrients and other elements will be accumulated in the hypolimnion and can act as nutrient supply for the mixed layer thus providing nutrient feedstock for primary production (Crowe et al., 2008; Göltenboth & Lehmusluoto, 2006). The boundary layer between the hypolimnion and monimolimnion (chemocline) in the water column is an important layer which is acts as a bridge of the redox processes in regulating the cycling of the nutrients. Therefore, the chemocline forms a boundary between the oxic environment in the epilimnion and the anoxic environment in monimolimnion.

In tropical deep lakes, most oxidation processes take place in the epilimnion whereas reduction processes take place in the hypolimnion. Oxygen solubility decreases with increasing temperature thus, tropical lakes tend to have a lower oxygen concentration than temperate lakes even in the surface water. Because the oxygen in tropical lake tends to be consumed faster with depth, microbial respiration below the mixing depth produces the depletion of oxygen in the monimolimnion. The respiration in the oxic surface water is dominated by aerobic metabolism, whereas microbial respiration in the anoxic water column take sulfate, iron, and manganese oxide, or CO_2 (methanogenesis) as electron acceptors (Katsev et al., 2017). The oxic-anoxic layer is found in large tropical lakes, like Lake Tanganyika and Lake Malawi (East Africa), and also in the ferruginous lake in Indonesia, Lake Matano (Jones et al., 2011), eutrophic lake, Lake Maninjau (Henny & Nomosatryo, 2012; Arianto Budi Santoso et al., 2018) and lake Toba (Nomosatryo & Lukman, 2011; Lukman et al., 2021). In those lakes the oxygen may penetrate hundreds of meters below the wind-mixed layer and become exhausted within several meters of the permanent oxycline. Furthermore, the persistent oxic-anoxic layer in tropical lakes will have distinctive effects on geochemical and ecological features in the water column; i.e., Chemical stratification (Oxygen and nutrients) and biological stratification (Microbial community in the redoxclines) (Katsev et al., 2017). The different chemical setting in the tropical meromictic lakes supports diverse microbial processes concerning carbon fixation and oxidation.

Apart from the oxycline in the water column, biogeochemical processes at the Sediment Water Interface (SWI) are also crucial. These processes can be mainly linked to redox differences between the bottom water and the pore water and are fueled by the supply of labile organic matter from the water column to the SWI (Vuillemin et al., 2016). In the deeper parts of stratified lakes (i.e., in the monimolimnion), processes at the SWI will take place without interference from the mixing of the water column or bioturbation. The stable stratified water column and the anoxic monimolimnion provide optimal conditions for undisturbed sedimentation. Consequently, lake sediment from tropical meromictic lakes provide some of the best climate records, which range from a few hundred years to millions of years (Zadereev, Boehrer, & Gulati, 2017).



Modificated pic. from Gulati, et. al. (2017)

Figure 1.8 *Different physical characteristics of the water column in temperate (A) and tropical lakes (B). In temperate lakes, a thermocline forms in winter and summer, but will disappear due to the overturn of the water column in spring and autumn caused by fluctuations in the density of the surface water. In tropical lakes, even strong winds and heavy rain will mix only the upper layer, the water column will remain persistently stratified throughout the year.*

1.5.2 Lakes in Indonesia

Indonesia is an archipelago country, also known as the “Island Continent", with about 17,508 islands. It lies in the Indo-pacific region between two major continents (Asia and Australia), and has a unique and strategic position and role in the global socio-economy and in sciences. It is also one of the world's largest maritime nations and has many natural resources. Traditionally 840 lakes of various sizes were known in Indonesia, covering an area of more than 685,700 ha (Giesen, 1994; Haryani, 2016) but recently, by using the integrated GIS method, Research Center for Limnology (BRIN) identified 5808 lakes of which 1022 were classified as natural lakes and 1341 as artificial lakes (Man-made lake), the rest still being under investigation (Research Centre for Limnology-LIPI, 2020). Interestingly, 64% of the lakes are still unnamed. The number of lakes in each province can be seen in Figure 1.10. About 0.25% of Indonesia’s land surface is covered by lakes, holding about 500 km^3 of freshwater. Lake Toba is the largest lake with a volume of 240 km^3 (National Committee for Wetland Ecosystem Management, 2004, Haryani & Hehanussa, 1999, 2009). The volume of several lakes in Indonesia is presented in Table 1.

Lakes are essential for human life in Indonesia. Apart from being a source of drinking water and a source of water for daily needs, lakes are also used as a source of raw water for both domestic and industrial use, as a means of water transportation, irrigation, and tourism, as well as a source of protein from both fishing and aquaculture (Lukman et al., 2017). The rapidly increasing anthropogenic activities around the lakes cause heavy degradation of lake ecosystems in many areas (Haryani, 2016; Kementerian Lingkungan Hidup Republik Indonesia, 2011).

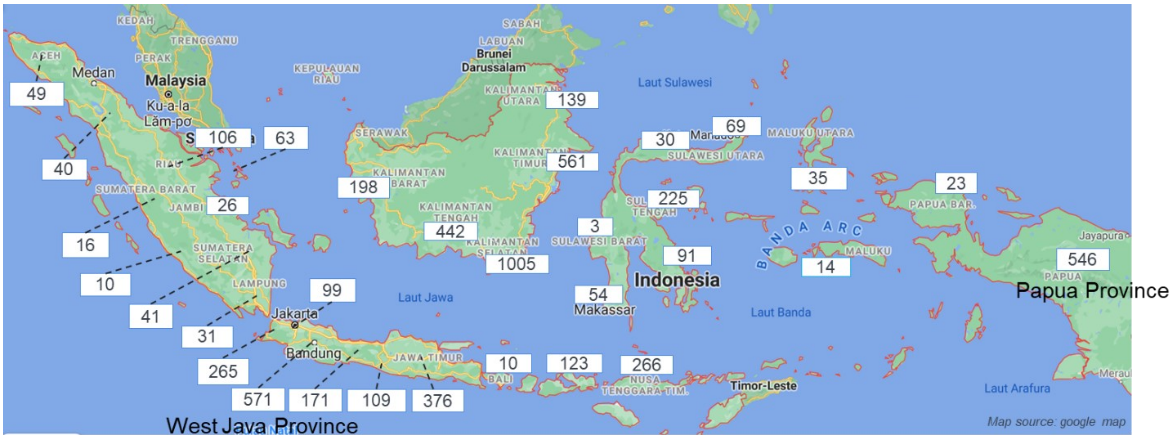


Figure 1.9 Distribution map of the identified lakes and reservoirs in the Indonesian archipelago (modified after Research Center for Limnology, 2020). The number in the white box is a total number of the identified lakes for each Province. The total area of identified lakes is 586.871,64 Ha (Research Center for Limnology, 2020).

Apart from the functions of the lakes mentioned above, the function of the lakes from a scientific perspective is not less interesting. Indonesian lakes can be grouped based on the origin of the lake formation (Table 1.2). The depth of lakes in Indonesia varies widely, from the deepest ones with over half a kilometer water depth (Lake Matano and Toba) to shallow lakes (Lake Tempe and flood-exposed lakes in Kalimantan) with less than 10 m water depth. The chemical composition of the water and biodiversity of the lakes is highly different from one lake to another.

1.5.3 Biogeochemical studies of lakes in Indonesia

Few biogeochemical studies in Indonesian lakes were carried out as part of limnological studies of Indonesian lakes and reservoirs. There are only some historical water quality studies from Java, Sumatra and Bali from 1928-1929 (Ruttner, 1931). Lehmusluoto et al., (1997) complemented the data with the Indodanau project which covered 38 major lakes and reservoirs in Sumatra, Java, Bali, Lombok, Flores, Sulawesi and Irian Jaya. The study showed that the lakes in Indonesia have different physical, chemical and biological characteristics. Even though the study was conducted with very limited infrastructure and lacks detailed information on many datasets, it found that the hypolimnion in the deep lake is anoxic and it was proposed as a reference condition for lake management.

Nowadays, the massive anthropogenic input of nutrients into most of Indonesian lakes leads to eutrophication, which has become a big issue. Consequently, the biogeochemical processes in the lake water system change from natural to artificially perturbed. Traditionally, most (bio)geochemical studies in Indonesian lakes were conducted to characterize the trophic status of the lakes (Nomosatryo & Lukman, 2011; Suryono & Sadi, 2014), to answer the factors triggering mass fish killings in eutrophic lake Maninjau (Henny & Nomosatryo, 2012), pollution in the big lake, Lake Toba (Lukman, et al., 2021), and also acting as a trigger for modeling studies helping to solve lake management problems (Rustini, et al., 2018, 2020; Arianto Budi Santoso et al., 2018). These studies were also used to support fisheries and aquatic biological studies (Sulastri, et al., 2019).

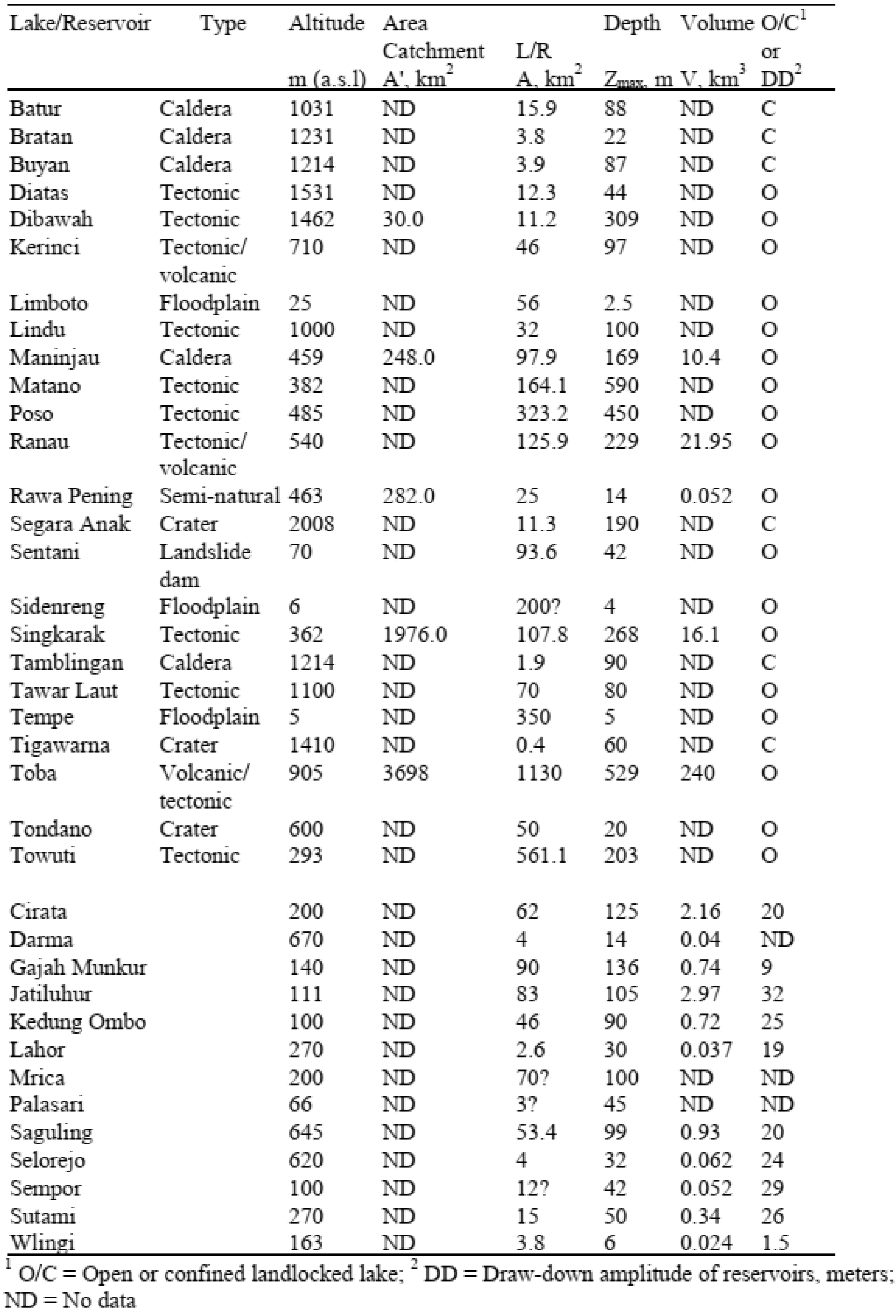
The collaborative biogeochemical research between Indonesian and foreign scientists helped top carry out more basic research and to develop a much deeper understanding of the fundamental processes controlling the biogeochemistry of these lakes. Crowe et al. (2008 and 2014), investigated one of the deepest lakes in Indonesia, ultraoligotrophic and ferruginous Lake Matano. This lake has oxic surface water and anoxic bottom water separated by a persistent chemocline in several hundred-meter water depth (Katsev et al., 2017). Lake Matano is categorized as a ferruginous lake because the lithology in the catchment area is dominated by laterites originating from ultramafic rocks, leading to high dissolved iron concentrations in the anoxic bottom waters. The results of their studies showed that Fe plays an important role in biogeochemical processes in this lake. Of particular interest were anoxygenic photoferrotrophs that use sunlight and Fe(II) to fix CO_2 into biomass and produce Fe(III) as a metabolic by-product suggesting that the processes that occur in Lake Matano can be used as a model of the ferruginous oceans that prevailed during most of Archaean Eon (Crowe et al., 2008, 2014).

Table 1.1 *Physical properties of lakes in Indonesia (Kementerian Negara Lingkungan Hidup (2008))*

Lake		Area (Km^2)	Max.Depth (m)	Volume (million.m^3)	Lake Volume Category
1.	Batur	15,9	88	820	Medium
2.	Bratan	3,85	22	49	Small
3.	Buyan	3,9	87	160	Medium
4.	Diatas	12,3	44	–	
5.	Dibawah	11,2	309	–	
6.	Kerinci	46	97	1600	Big
7.	Limboto	56	2,5	159.566	Big
8.	Maninjau	97,9	169	10.400	Big
9.	Matano	164,1	590	55.015	Big
10.	Poso	323,2	450	–	
11.	Ranau	125,9	229	21.950	Big
12.	Rawa	25	14	52	Small
13.	Sentani	93,6	42	–	
14.	Singkarak	107,8	268 16.	100	Big
15.	Tamblinga	1,9	90	27	Small
16.	Tempe	350	5	–	
17.	Toba	1.130	529	240.000	Very Big
18.	Tondano	50	20	–	
19.	Towuti	561,1	203	–	

–= No data

***Table 1.2** Morphometry of the natural lakes and reservoirs in Indonesia (Lehmusluoto et al., 1997).*



Lake/Reservoir	Type	Altitude m (a.s.l)	Area Catchment A', km^2	L/R A, km^2	Depth Z_{max}, m	Volume V, km^3	O/C^1 or DD^2
Batur	Caldera	1031	ND	15.9	88	ND	C
Bratan	Caldera	1231	ND	3.8	22	ND	C
Buyan	Caldera	1214	ND	3.9	87	ND	C
Diatas	Tectonic	1531	ND	12.3	44	ND	O
Dibawah	Tectonic	1462	30.0	11.2	309	ND	O
Kerinci	Tectonic/ volcanic	710	ND	46	97	ND	O
Limboto	Floodplain	25	ND	56	2.5	ND	O
Lindu	Tectonic	1000	ND	32	100	ND	O
Maninjau	Caldera	459	248.0	97.9	169	10.4	O
Matano	Tectonic	382	ND	164.1	590	ND	O
Poso	Tectonic	485	ND	323.2	450	ND	O
Ranau	Tectonic/ volcanic	540	ND	125.9	229	21.95	O
Rawa Pening	Semi-natural	463	282.0	25	14	0.052	O
Segara Anak	Crater	2008	ND	11.3	190	ND	C
Sentani	Landslide dam	70	ND	93.6	42	ND	O
Sidenreng	Floodplain	6	ND	200?	4	ND	O
Singkarak	Tectonic	362	1976.0	107.8	268	16.1	O
Tamblingan	Caldera	1214	ND	1.9	90	ND	C
Tawar Laut	Tectonic	1100	ND	70	80	ND	O
Tempe	Floodplain	5	ND	350	5	ND	O
Tigawarna	Crater	1410	ND	0.4	60	ND	C
Toba	Volcanic/ tectonic	905	3698	1130	529	240	O
Tondano	Crater	600	ND	50	20	ND	O
Towuti	Tectonic	293	ND	561.1	203	ND	O
Cirata		200	ND	62	125	2.16	20
Darma		670	ND	4	14	0.04	ND
Gajah Munkur		140	ND	90	136	0.74	9
Jatiluhur		111	ND	83	105	2.97	32
Kedung Ombo		100	ND	46	90	0.72	25
Lahor		270	ND	2.6	30	0.037	19
Mrica		200	ND	70?	100	ND	ND
Palasari		66	ND	3?	45	ND	ND
Saguling		645	ND	53.4	99	0.93	20
Selorejo		620	ND	4	32	0.062	24
Sempor		100	ND	12?	42	0.052	29
Sutami		270	ND	15	50	0.34	26
Wlingi		163	ND	3.8	6	0.024	1.5

[1] O/C = Open or confined landlocked lake; [2] DD = Draw-down amplitude of reservoirs, meters; ND = No data

Recently, the Towuti Drilling Project (TDP) was carried out in Lake Towuti (James M. Russell et al., 2016). This lake is located close to Lake Matano and both lakes are part of the Malili lake system that encompasses five interconnected ferruginous lakes. The main goals of the project are paleoclimatology and biogeochemistry. The biogeochemical studies in this project focused mainly on the influence of extremely iron-rich sediments on the microbial community.

1.5.4 Lake Sentani

Indonesia has many other lakes with different characteristics, one of them is Lake Sentani. Lake Sentani is located in Papua Province at the eastern edge of Indonesia (2° S, 140° E). It was formed by minor tectonic movements causing a landslide that formed a dam on the Jafuri River, nowadays the only outlet of the lake (Lehmusluoto et al., 1997). The lake is classified as moderately deep (<50m) open water, has a low altitude (70 m asl) and is relatively close to the ocean. The Cycloop mountains form a barrier between the lake and the ocean. The lake has a unique shape, as it is divided into four basins of which three separated by shallow sills and one by a narrow natural canal, (Simboro passage) (Sadi, 2014; Indrayani *et.al.*, 2015a). The catchment geology is highly diverse, ranging from carbonates over clastic sediments to igneous and metamorphic rocks, some with ultramafic composition (Suwarna & Noya, 1995). The northern side of the lake is bounded by the Cycloops mountain range, the southern side has a relatively flat topography. There are eight sub-districts located in the catchment area of Lake Sentani. Heram sub-district, located in the western part of the lake, is under the territory of Jayapura municipality, whereas the others are under Jayapura districts. Most of the sub-districts located in the northern part of the lake have a higher population than the southern part of the lake. Heram and Sentani sub-district are central settlements in the lake Sentani catchment area.

Lukman & Fauzi (1991) collect the available literature about Lake Sentani and reported that the research had already started in 1904. They also pointed out that until 1972, most studies on Lake Sentani were focused on biological diversity. This is obvious since Lake Sentani is home to several endemic species of fish, mainly rainbow fish and sawfish *(Pristis microdont)* (Ohee, 2013), *Oxyeleotris, Ophiocara sp* (Boeseman, 1956) and

Zooplankton organism (Decapoda Machura) and Mollusca (Surbakti, 2011). Through a donation from the United Nations for Irian Jaya (the former name of Papua), the FUNDWI project in 1970-1971 conducted the first physical study in Lake Sentani and continued with a water quality study for drinking water and a hydropower scheme project in 1981 (Lukman & Fauzi, 1991). A paleolimnological study on a high altitude small lake in the Cycloop mountains was done by Hope (2007) and several studies were on the different drainage basins and their influence on the lake (Handoko, et al., 2014; Sartimbul et al., 2015; Thirnbeck, 2018) revealed that processes in the drainage basin have a potentially strong impact on the lake system.

The biogeochemistry of Lake Sentani has not been studied in greater detail so far. The studies of the Indodanau project (Lehmusluoto et al., 1997) and the limnology studies (Lukman & Fauzi, 1991; Sadi, 2014) can be a good reference for starting (bio)geochemical studies in this lake. Lehmusluoto et al., (1997) reported that the lake was stratified (RTR 51.5), with an anoxic hypolimnion, containing traces of hydrogen sulfide and carbon dioxide concentrations of 2.2 to 3.0 mg/l.

Over the last decade annual population growth in Jayapura Regency is 2.5% (BPS Kabupaten Jayapura, 2020), especially in the sub-districts located in the northern part of the lake. Even though the population density and the population rate in the Lake Sentani area are relatively still lower than the average value of the other areas in Indonesia, the lake shows some signs of eutrophication (Lehmusluoto et al., 1997; Sadi, 2014; Indrayani et al., 2015). There are different data regarding the water quality results but the indicators of decreasing water quality are described by Pattiselanno (2013). Erosion, sedimentation, flooding, and alien fish introduction are the major problems of Lake Sentani. Therefore, based on the consortium on National Conference of lakes in Indonesia (*Konferensi Nasional Danau Indonesia I* (KNDI I)) in 2009, the government of Republic Indonesia determined Lake Sentani as one of 15 lakes as a national priority to be purified, rehabilitated and conserved (Kementerian Lingkungan Hidup Republik Indonesia, 2011; Perpres No. 60, 2021).

1.6 Objectives

This study aims to develop a fundamental understanding of Lake Sentani's sedimentary geochemistry and geomicrobiology with a special focus on the effects of different lithologies in the catchment. We hope that our result can be used to compare the different basins of Lake Sentani to other tropical lakes as a contribution to a better understanding and as a reference of biogeochemical processes of tropical lakes and help stakeholders manage the lake holistically.

To achieve the main objective, the research in Lake Sentani focused on the following three specific questions:

1. How does catchment lithology affect the sedimentary characteristics of surface sediment in the different basins of Lake Sentani?
2. Are there differences in water column structure and chemistry in each basin and how do they influence sediment and pore water chemistry and vice versa?
3. What microorganisms (bacteria and archaea) live in these sediments and what are their potential metabolic capabilities?

To achieve these aims and answer the research questions, we conducted an integrated limnological, geochemical and geomicrobial study in Lake Sentani in the surface sediment, the water column and porewater of four tropical lacustrine sub-basin system with different catchment lithologies and water column structure, but with a common surface water chemistry. The data obtained during this study will provide crucial information to understand and predict the further development of the lake system under changing climate conditions and increasing anthropogenic pressure.

1.7 Outline of thesis

This cumulative thesis is based on three manuscripts that have been published or are in the process of being published as original research articles. Since I was involved in the Towuti Drilling Project and another collaborative research with UBC in Lake Matano and produced several published manuscripts, I also put it as a supporting manuscript. Even though they are not the main manuscript in the thesis, they can be essential references to the biogeochemical characteristic of the ferruginous tropical lake.

1.8 Summary of the main manuscripts and contribution of the co-authors as the additional manuscript

1.8.1 Main Publications

Manuscript 1 (Published in Frontiers in Earth Sciences, 2021)

Title: **Geochemical Characteristics of Lake Sentani, Papua Province, Indonesia**

Authors: ***Sulung Nomosatryo****, Rik Tjallingii, Anja Maria Schleicher, Cynthia Henny, Dirk Wagner, Jens Kallmeyer*

This publication is our first publication on lake Sentani. We used sediment cores and water samples and measured physicochemical water column profiles to reveal the geochemical characteristics of the water column, the sediment and pore water for all four sub-basins of Lake Sentani. The chemical composition of the sediment reveals differentiation among the sub-basins according to their sediment input and water column structure. Catchment lithology mainly affects overall sediment composition, whereas pore water chemistry is also affected by water column structure, which is related to basin morphology and water depth. In the meromictic sub-basins the bottom water and sediment pore water appear to form a single continuous system, whereas in those sub-basins with oxygenated bottom water the sediment-water interface forms a pronounced chemical barrier.

As a geochemist, Jens Kallmeyer gave me a lot of input in the study design and the geochemical characteristics of the water column and porewater. Valuable input on various issues was also provided by Dirk Wagner. Cynthia Henny and Paulus Boli (UNIPA) were involved in the field sampling and provided input from a limnological perspective and field condition. Rik Tjalinggii and Anja M. Schelter are involved in the mineralogical and elemental analyses and their interpretation.

Manuscript 2 (Published in Journal of Paleolimnology, 2022)

Title: **Surface sediment compositions and depositional environments in tropical Lake Sentani, Papua Province, Indonesia**

Authors: ***Sulung Nomosatryo****, Rik Tjallingii, Cynthia Henny, Iwan Ridwansyah, Dirk Wagner, Sara Tomás, Jens Kallmeyer*

This publication characterizes surface sediment samples based on their geochemical composition. Major element distribution, smear slide identification, particle distribution, and sulfide speciation are presented to show that the geologically diverse catchment will lead to distinctly different sediment input into each sub-basin of Lake Sentani. Our study reveals a large spatial heterogeneity within lake basins related to the great variability of individual elements on a relatively small spatial scale, mainly caused by catchment geology and topography, river runoff, and water depth of the oxycline.

Jens Kallmeyer and I designed the study and sampled in the field, I processed the samples and carried out the analyses except XRF, which was done by Rik Tjalinggii. Jens Kallmeyer, Rik Tjallingii, Cynthia Henny, and Dirk Wagner helped in the preparation of the manuscript. Iwan Ridwansyah provided input for the morphological interpretation and Cynthia Henny was responsible for logistics and permitting.

Manuscript 3 (In preparation, 2023)

Title: **Investigation of Microbial Communities highlights anthropogenic influences across Lake Sentani, River, and Lake sediments**

Authors: Sulung Nomosatryo, Cynthia Henny, Puguh Surjanto, Daniel Lipus, Sizhong Yang, Alexander Bartholomäus, Dirk Wagner, Jens Kallmeyer

The geomicrobiology data will be presented in this chapter. The Next-Generation

Sequencing (NGS) method was chosen to identify microbial communities in surface sediment between habitats. The sampling location was similar to the sampling location in our first publication. Surface sediment samples were collected from 30 locations within lake, nine samples from the river mouth, and nine samples from the main rivers that drain into the lake. The investigation reveals that the multivariate separation of microbial community is identical to the geochemical composition separation. Yet, the distinct microbial community between sub-basins was not different. One of the primary observations of this study was the large degree of variation in the freshwater bacterial community in taxonomic composition between the different habitats across Lake Sentani. Differences in microbial communities suggest the different environmental and anthropogenic pressure at each location likely influence the microbial and diversity composition patterns. Overall, microbial communities in river sediments were different from those found in lake sediments.

Jens Kallmeyer, Daniel Lipus, Dirk Wagner and I designed the topic and formulated the publication method. Sizhong Yang and Alexander Bartholomäus helped in the bioinformatic analysis. Cynthia Henny gave the input from the limnology perspective and sampling strategy. Puguh Surjanto facilitated me in the accommodation in the fieldwork.

1.8.2 Additional Publications

Due to my continuing involvement in the research around the Malili Lakes, particularly the ICDP Lake Towuti Drilling Project (TDP), I also co-authored several papers, which are not directly connected to my PhD. I was involved in the sampling, processing of samples and analysis of transient parameters in the field. Therefore, only the abstracts are provided in this thesis.

Additional Manuscript 1 (Frontiers in Microbiology, 2016)

Title: Geomicrobiological Features of Ferruginous Sediments from Lake Towuti, Indonesia.

Authors: *Aurèle Vuillemin, André Friese, Mashal Alawi, Cynthia Henny,* ***Sulung Nomosatryo****, Dirk Wagner, Sean A. Crowe and Jens Kallmeyer*

Abstract: Lake Towuti is a tectonic basin, surrounded by ultramafic rocks. Lateritic soils form through weathering and deliver abundant iron (oxy)hydroxides but very little sulfate to the lake and its sediment. To characterize the sediment biogeochemistry, we collected cores at three sites with increasing water depth and decreasing bottom water oxygen concentrations. Microbial cell densities were highest at the shallow site—a feature we attribute to the availability of labile organic matter (OM) and the higher abundance of electron acceptors due to oxic bottom water conditions. At the two other sites, OM degradation and reduction processes below the oxycline led to partial electron acceptor depletion. Genetic information preserved in the sediment as extracellular DNA (eDNA) provided information on aerobic and anaerobic heterotrophs related to Nitrospirae, Chloroflexi, and Thermoplasmatales. These taxa apparently played a significant role in the degradation of sinking OM. However, eDNA concentrations rapidly decreased with core depth. Despite very low sulfate concentrations, sulfate-reducing bacteria were present and viable in sediments at all three sites, as confirmed by measurement of potential sulfate reduction rates. Microbial community fingerprinting supported the presence of taxa related to Deltaproteobacteria and Firmicutes with demonstrated capacity for iron and sulfate reduction. Concomitantly, sequences of Ruminococcaceae, Clostridiales, and Methanomicrobiales indicated potential for fermentative hydrogen and methane production. Such first insights into ferruginous sediments showed that microbial populations perform successive metabolisms related to sulfur, iron, and methane. In theory, iron reduction could reoxidize reduced sulfur compounds and desorb OM from iron minerals to allow remineralization to methane. Overall, we found that biogeochemical processes in the sediments can be linked to redox differences in the bottom waters of the three sites, like oxidant concentrations and the supply of labile OM. At the scale of the lacustrine record, our geomicrobiological study should provide a means to link the extant subsurface biosphere to past environments.

Additional Manuscript 2 (Scientific Drilling: reports on deep earth sampling and monitoring, 2016)

Title: The Towuti Drilling Project: paleoenvironments, biological evolution, and geomicrobiology of a tropical pacific lake.

Authors: *Russell, J. M., Bijaksana, S., Vogel, H., Melles, M., Kallmeyer, J., Ariztegui, D., Crowe, S., Fajar, S., Hafidz, A., Haffner, D., Hasberg, A., Ivory, S., Kelly, C., King, J., Kirana, K., Morlock, M., Noren, A., O'Grady, R., Ordonez, L., Stevenson, J., von Rintelen, T., Vuillemin, A., Watkinson, I., Wattrus, N., Wicaksono, S., Wonik, T., Bauer, K., Deino, A., Friese, A., Henny, C., Imran, Marwoto, R., Ngkoimani, L. O.,* ***Nomosatryo, S****., Safiuddin, L. O., Simister, R., Tamuntuan, G.*

Abstract: The Towuti Drilling Project (TDP) is an international research program, whose goal is to understand long-term environmental and climatic change in the tropical western Pacific, the impacts of geological and environmental changes on the biological evolution of aquatic taxa, and the geomicrobiology and biogeochemistry of metal-rich, ultramafic-hosted lake sediments through the scientific drilling of Lake Towuti, southern Sulawesi, Indonesia. Lake Towuti is a large tectonic lake at the downstream end of the Malili lake system, a chain of five highly biodiverse lakes that are among the oldest lakes in Southeast Asia. In 2015 we carried out a scientific drilling program on Lake Towuti using the International Continental Scientific Drilling Program (ICDP) Deep Lakes Drilling System (DLDS). We recovered a total of ∼1018m of core from 11 drilling sites with water depths ranging from 156 to 200 m. Recovery averaged 91.7 %, and the maximum drilling depth was 175m below the lake floor, penetrating the entire sedimentary infill of the basin. Initial data from core and borehole logging indicate that these cores record the evolution of a highly dynamic tectonic and limnological system, with clear indications of orbital-scale climate variability during the mid- to late Pleistocene.

Additional Manuscript 3 (Nature Communications, 2019**)**

Title: Mesophilic microorganisms build terrestrial mats analogous to Precambrian microbial jungles

Authors: *N. Finke, R.L. Simister, A.H. O'Neil,* ***Sulung Nomosatryo****, C. Henny, L.C. MacLean, D.E. Canfield, K. Konhauser, S.V. Lalonde, D.A. Fowle & S.A. Crowe*

Abstract: Development of Archean paleosols and patterns of Precambrian rock weathering suggest colonization of continents by subaerial microbial mats long before evolution of land plants in the Phanerozoic Eon. Modern analogues for such mats, however, have not been reported, and possible biogeochemical roles of these mats in the past remain largely conceptual. We show that photosynthetic, subaerial microbial mats from Indonesia grow on mafic bedrocks at ambient temperatures and form distinct layers with features similar to Precambrian mats and paleosols. Such subaerial mats could have supported a substantial aerobic biosphere, including nitrification and methanotrophy, and promoted methane emissions and oxidative weathering under ostensibly anoxic Precambrian atmospheres. High C-turnover rates and cell abundances would have made these mats prime locations for early microbial diversification. Growth of landmass in the late Archean to early Proterozoic Eons could have reorganized biogeochemical cycles between land and sea impacting atmospheric chemistry and climate.

Additional Manuscript 4 (Geology, 2019**)**

Title: Formation of diagenetic siderite in modern ferruginous sediments

Authors: *Aurèle Vuillemin, Richard Wirth, Helga Kemnitz, Anja M. Schleicher, André Friese, Kohen W. Bauer, Rachel Simister,* ***Sulung Nomosatryo****, Luis Ordoñez, Daniel Ariztegui, Cynthia Henny, Sean A. Crowe, Liane G. Benning, Jens Kallmeyer, James M. Russell, Satria Bijaksana, Hendrik Vogel, the Towuti Drilling Project Science Team*

Abstract. Ferruginous conditions prevailed in the world's deep oceans during the Archean and Proterozoic Eons. Sedimentary iron formations deposited at that time may provide an important record of environmental conditions, yet linking the chemistry and mineralogy of these sedimentary rocks to depositional conditions remains a challenge due to a dearth of information about the processes by which minerals form in analogous modern environments. We identified siderites in ferruginous Lake Towuti, Indonesia, which we characterized using high-resolution microscopic and spectroscopic imaging combined with microchemical and geochemical analyses. We infer early diagenetic growth of siderite crystals as a response to sedimentary organic carbon degradation and the accumulation of dissolved inorganic carbon in pore waters. We suggest that siderite formation proceeds through syntaxial growth on preexisting siderite crystals, or possibly through aging of precursor carbonate green rust. Crystal growth ultimately leads to spar-sized (>50 µm) mosaic single siderite crystals that form twins, bundles, and spheroidal aggregates during burial. Early-formed carbonate was detectable through microchemical zonation and the possible presence of residual phases trapped in siderite interstices. This suggests that such microchemical zonation and mineral inclusions may be used to infer siderite growth histories in ancient sedimentary rocks including sedimentary iron formations.

Additional Manuscript 5 (Biogeosciences, 2020**)**

Title: Vivianite formation in ferruginous sediments from Lake Towuti, Indonesia

Authors: *Aurèle Vuillemin, André Friese, Richard Wirth, Jan A. Schuessler, Anja M. Schleicher, Helga Kemnitz, Andreas Lücke, Kohen W. Bauer, Sulung Nomosatryo, Friedhelm von Blanckenburg, Rachel Simister, Luis G. Ordoñez, Daniel Ariztegui, Cynthia Henny, James M. Russell, Satria Bijaksana, Hendrik Vogel, Sean A. Crowe, Jens Kallmeyer, and the Towuti Drilling Project Science team.*

Abstract. Ferruginous lacustrine systems, such as Lake Towuti, Indonesia, are characterized by a specific type of phosphorus cycling in which hydrous ferric iron (oxy-hydr)oxides trap and precipitate phosphorus to the sediment, which reduces its bioavailability in the water column and thereby restricts primary production. The oceans were also ferruginous during the Archean, thus understanding the dynamics of phosphorus in modern-day ferruginous analogues may shed light on the marine biogeochemical cycling that dominated much of Earth's history. Here we report the presence of large crystals (> 5mm) and nodules (> 5 cm) of vivianite – a ferrous iron phosphate – in sediment cores from Lake Towuti and address the processes of vivianite formation, phosphorus retention by iron and the related mineral transformations during early diagenesis in ferruginous sediments. Core scan imaging, together with analyses of bulk sediment and pore water geochemistry, document a 30m long interval consisting of sideritic and non-sideritic clayey beds and diatomaceous oozes containing vivianites. High- resolution imaging of vivianite revealed continuous growth of crystals from tabular to rosette habits that eventually form large (up to 7 cm) vivianite nodules in the sediment. Mineral inclusions like millerite and siderite reflect diagenetic mineral formation antecedent to the one of vivianite that is re- related to microbial reduction of iron and sulfate. Together with the pore water profiles, these data suggest that the precipitation of millerite, siderite and vivianite in soft ferruginous sediments stems from the progressive consumption of dis- solved terminal electron acceptors and the typical evolution of pore water geochemistry during diagenesis. Based on solute concentrations and modeled mineral saturation indices, we inferred vivianite formation to initiate around 20m depth in the sediment. Negative δ^{56}Fe values of vivianite indicated incorporation of kinetically fractionated light Fe^{2+} into the crystals, likely derived from active reduction and dissolution of ferric oxides and transient ferrous phases during early diagenesis. The size and growth history of the nodules indicate that, after formation, continued growth of vivianite crystals constitutes a sink for P during burial, resulting in long-term P sequestration in ferruginous sediment.

2 Geochemical Characteristics of Sediment in Tropical Lake Sentani, Indonesia, Are Influenced by Spatial Differences in Catchment Geology and Water Column Stratification

2.1 Abstract

Physical and (bio)chemical processes in the catchment, as well as internal lake processes, influence the composition of lacustrine sediments. Lake internal processes are a consequence of reactions and fluxes between sediment, porewater and the water column. Due to its separation into four interconnected sub-basins, Lake Sentani, West Papua Province, Indonesia, is a unique tropical lake that reveals a wide range of geochemical conditions. The highly diverse geological catchment causes mineralogical and chemical differentiation of the sediment input into each sub-basin. Also, strong morphological differences between the sub-basins result in a unique water column structure for each sub-basin, ranging from fully mixed to meromictic. Given the strong differences in sediment composition and bottom water chemistry among the four sub-basins, Lake Sentani offers a unique chance to study multiple lacustrine systems under identical climate conditions and with a common surface water chemistry. We used sediment cores and water samples and measured physicochemical water column profiles to reveal the geochemical characteristics of the water column, the sediment and pore water for all four sub-basins of Lake Sentani. The chemical composition of the sediment reveals differentiation among the sub-basins according to their sediment input and water column structure. Catchment lithology mainly affects overall sediment composition, whereas pore water chemistry is also affected by water column structure, which is related to basin morphology and water depth. In the meromictic sub-basins the bottom water and sediment pore water appear to form a single continuous system, whereas in those sub-basins with oxygenated bottom water the sediment-water interface forms a pronounced chemical barrier.

Keywords: Tropical lakes, limnology, sediment geochemistry

2.2 Introduction

Lake sediments are sinks for terrestrially derived material from the catchment. The composition of lacustrine sediment is altered by physical and (bio)chemical processes in the catchment, such as weathering and erosion of bedrock and soils, as well as processing of the eroded material during transport. Additional material is produced in the water column, e.g., phyto- and zooplankton, as well as mineral precipitates (Ryves et al., 2003; review in Volkman, 1986). After deposition on the lake floor, diagenetic processes modify the deposited material. For the aforementioned reasons, lacustrine sediment is a mixture of materials from different sources and records many different processes and conditions (Schnurrenberger et al., 2003).

The various components that make up the sediment tend towards chemical equilibrium with the surrounding pore water, leading to mineral dissolution, formation, and transformation (Burdige & Gieskes, 1983; Santschi et al., 1990). Differences in concentrations of dissolved compounds between the sediment pore water and water column lead to fluxes between these two pools. The sediment-water interface (SWI) is the site where gradients in physical, chemical and biological properties are steepest because it is the interface between two vastly different systems: (i) The open water column in which water moves freely at comparably high velocities, despite often being referred to as stagnant in the case of well stratified water bodies, thereby compensating and flattening most chemical gradients, and where solid material accounts for only a very small fraction of the total volume, and (ii) the sediment, where water movement is restricted by tortuous flow paths in the pore space, diffusion is the dominant transport process and solid material makes up the majority of the volume. Also, due to the much greater available surface area in sediments, microbial abundance is usually much higher than in the water column, with most microbes attached to particles, forming biofilms (Flemming, 1995). Due to the high microbial biomass, the metabolic activity in sediment leads to enhanced chemical exchange with their aqueous environment, involving metal sorption and precipitation (Konhauser et al., 1993).

The elemental and mineralogical composition of the sediment at the SWI provides the most accurate estimate of the composition and quantity of material that was transferred from the catchment and the water column to the sediment (Martin-Puertas et.al., 2017). In deeper sediment layers this record might have been overprinted by diagenetic mineral transformations (Rothwell & Croudace, 2015). So, the processes at the SWI are perhaps the most crucial step in the transfer of material from the terrestrial to the lacustrine environment (Sun et.al., 2016). Therefore, knowledge of the geochemical processes at this interface is imperative to understand biogeochemical cycling in a lake system.

Limnological studies have been carried out for a long time, but most were conducted in temperate lakes, which are controlled by entirely different physical conditions than lakes in tropical climates (Crowe et al., 2008; Katsev et al., 2017). Other than tropical climates being on average warmer (>18°C, Feeley & Stroud, 2018) than temperate ones, the most important difference between temperate and tropical lakes is the muted intra-annual (seasonal) temperature fluctuations in the latter, leading to stable temperature gradient in the water column that is not disturbed by changing surface water temperatures. Therefore, many larger tropical lakes like Lake Tanganyika and Lake Matano are meromictic, i.e the water column is permanently stratified with a well-mixed oxic surface layer (epilimnion or mixolimnion) and a denser anoxic deep layer (hypolimnion) and in some cases an even denser monimolimion below, which has fully reducing and often sulfidic conditions (Katsev et al., 2017). The stable stratification despite the small temperature differences between top and bottom waters is facilitated by the comparatively large density difference per unit temperature at high temperatures. Such a stable stratification has profound implications on the biogeochemistry of these lakes (Crowe et al., 2008).

As tropical areas usually have an annual wet and a dry season, but only minimal seasonal temperature fluctuations, the only parameter with annual variation is precipitation (Boehrer & Schultze, 2008; Katsev et al., 2017). High temperatures and, at least during some parts of the year, high precipitation rates, lead to strong weathering in the catchment, creating a high flux of suspended sediment and dissolved compounds from the catchment to the lake (Crowe et al., 2008). Most studies on tropical lakes focus on biodiversity of flora and fauna (review in Lohmann et al., 2011), only a few focus on the biogeochemistry of these systems (review in Escobar et al., 2020).

Lake Sentani is located in Papua Province, Indonesia. Although the population around Lake Sentani is growing and the lake faces increasing anthropogenic nutrient input (Walukow et al., 2008; Indrayani et al., 2015), the area still has a relatively low level of urbanization despite its proximity to Jayapura, the capital of the province. A unique feature is the lake's shape, as it is divided into four sub-basins of which three are separated by shallow sills and one by a narrow natural canal (Sadi, 2014; Indrayani et.al., 2015a). The catchment is geologically highly diverse, ranging from carbonates over clastic sediments to igneous and metamorphic rocks (Suwarna & Noya, 1995). The basins share a common surface water chemistry, but each basin receives different sediment inputs (Sadi, 2014).

Our previous work found that the surface sediment in each of Lake Sentani's basins has a distinct geochemical composition, reflecting the lithology in the respective catchments (Nomosatryo et al., 2022). Therefore, Lake Sentani offers a unique opportunity to study the influence of catchment geology and water column stratification caused by variations in lake basin geometry in four basins that share a common surface water chemistry and overall climate conditions. As a result of the differences in catchment lithology, we hypothesized that each sub-basin not only has different sediment characteristics that set it apart from the others but that bottom water and pore water chemistry also reflect sediment composition.

To address our hypothesis, we conducted an integrated limnological and geochemical study in Lake Sentani to reveal the geochemical characteristics of the water column and porewater of the four sub-basins, which reveal considerable differences due to different catchment lithologies and water column structure, but share a common surface water chemistry. The data obtained during this study will provide crucial information to understand and predict the further development of the lake system under changing climate conditions and increasing anthropogenic pressure.

2.3 Site Description

Lake Sentani (2º36'S, 140º30'E) is located near Jayapura, the capital city of Papua Province and lies at an elevation of 74 m asl. The lake is irregularly shaped with approximate dimensions of 28 km (East to West) by 19 km (North to South) and a surface area of 9,360 ha (Kementerian Lingkungan Hidup Republik Indonesia, 2011). Lake Sentani consists of four separate sub-basins. The three eastern sub-basins are connected by shallow sills, the westernmost sub-basin is connected via the Simboro passage (Lukman & Fauzi, 1991), a natural canal with a maximum depth of just 6 m (Fig. 2.1). The volume of the lake is 4821.5×10^6 m^3 (Sartimbul, 2015). The sub-basins have different maximum water depths. We tried to collect our samples at or close to the deepest parts of each basin. Our depth soundings at the sampling locations revealed depths between 11 and 43 m. Previous studies provided considerably different values with maximum depths ranging from 30 m (Sadi, 2014) to 70 m (Indrayani et. al., 2015a).

The lake has a catchment area of about 600 km^2 and is bounded by the Cyclops Mountains (also called Cycloop Mountains) to the north (Tappin 2007) and lowlands to the south. The north side of the lake is dominated by volcanic breccia, mafic and ultramafic rocks as well as alluvial deposits, whereas the southern part of the lake is dominated by coralline-algal limestone, calcirudite, calcarenite of the Jayapura formation; sandstone and claystone, intercalation of limestone, siltstone and marl of the Aurimi formation; alluvial and basaltic deposits; alternating greywacke, siltstone and claystone intercalated with marl and conglomerate of the Makat formation; and finally Unk formation, consisting of alternating greywacke, claystone, siltstone, marl, conglomerate, and sandstone with lignite intercalations (Fig. 2.1, Suwarna and Noya 1995).

At least sixteen rivers drain into the lake. Yahim, the largest sub-catchment located on the north side of the lake, covers almost 38% of the total catchment (Table SI 2.1). Twelve rivers come from the Cyclops Mountains on the northern side of the lake, and four rivers originate from the lowlands in the south (Fig. 2.1). The Doyo River in the Yahim sub-catchment is the biggest single source of water to the lake with an average discharge of 18.98 m^3s^{-1} (Table SI 2.1, Handoko et al., 2014). The other rivers have discharge rates of

<1 m^3s^{-1}; many are ephemeral and only have water during the wet season. The Jayafuri (Jayefuri) River, located in the southeastern tip of the easternmost basin, is the only outlet, having a discharge rate of 15.66 m^3s^{-1} (Handoko et al., 2014; Kementerian Lingkungan Hidup Republik Indonesia 2011).

The average annual precipitation around Lake Sentani is 1691 mm/year (Sartimbul et al., 2015). The highest precipitation occurs in March, with an average of 206 mm; July has the lowest precipitation with 95 mm. Air temperature around Lake Sentani ranges between 23.6 and 33.2°C, with July being the coldest month. Water temperature ranges from 29.3 to 30.5°C (Sadi, 2014). Lake Sentani shows significant heterogeneity with respect to spatial distribution of major elements in its surface sediment (Nomosatryo et al., 2020, submitted). The geochemical composition in the eastern basin of the lake is dominated by siliciclastic minerals, whereas the western part is strongly influenced by mafic and ultramafic catchment lithology.

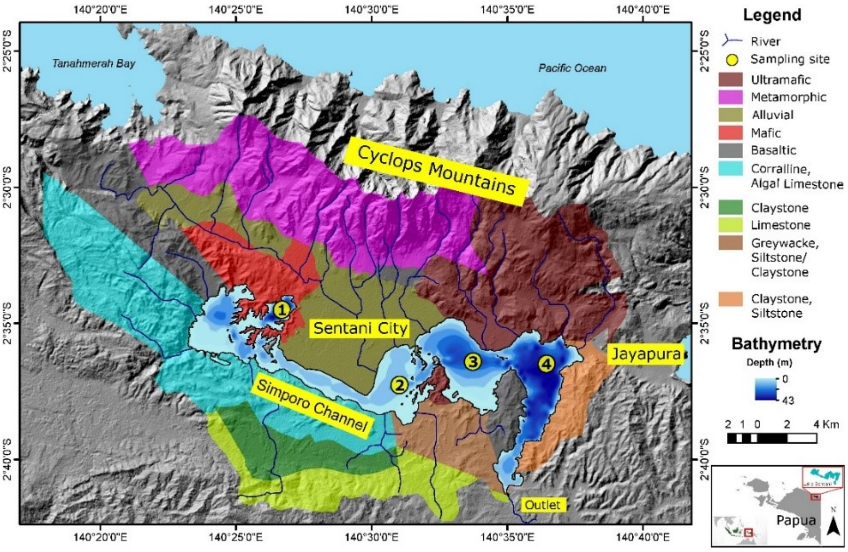


__Figure 2.1__ Map of Lake Sentani and its surrounding watershed. Catchment lithology is indicated by different colours. The lake is bounded by the Cyclops Mountains to the north and lowlands to the south. Sampling locations 1 to 4 are indicated by yellow circles. Locations 1 and 4 are located in the deepest sub-basins, whereas location 2 is in the shallowest sub-basin. The bathymetric map is modified after Sadi (2014), the lithology of Lake Sentani's catchment is modified after Suwarna and Noya (1995) and the catchment boundary is modified after Sartimbul et al. (2015).

2.4 Materials and Methods

2.4.1 Field Campaigns

Three expeditions were carried out in April-May 2016, November 2016, and January 2018. Small local fishing boats were used as platforms. During the first campaign, we took measurements and samples at all four locations described in Fig. 2.1. We sampled one location in the center and/or the deepest part of each sub-basin, locations were labeled 1 to 4 from west to east. Locations 1 and 4 have the greatest water depth and meromictic conditions. We measured the water depths at our sampling locations by echsounder, as well as by wireline. During the second campaign, we re-visited locations 2, 3 and 4, and on the third campaign, we focused on the two sites with the deepest water and re-sampled location 1 in the westernmost sub-basin and measured profiles for water temperature, Dissolved Oxygen (DO), and conductivity at location 4 in the easternmost sub-basin.

2.4.2 Limnological characterization and water column sampling

During the first and third expeditions, we measured profiles for water temperature, DO and conductivity, using a conductivity-temperature-depth probe (CTD; Rinko-Profiler ASTD 102). During the second campaign in November 2016 we measured the same variables with a Water Quality data logger (YSI 6920, Yellow Springs Instruments, Ohio, USA). On all expeditions, measurements were also conducted on discrete water samples at 5- or 10-meter depth resolution using a 5-L Niskin water sampler (General Oceanics, Miami, Florida). Water temperature, pH and conductivity were determined with a multi-parameter instrument (WTW, Multi 3420, Xylem Analytics, Germany); Dissolved Oxygen was measured with an optical Dissolved Oxygen Meter (YSI Pro ODO, Yellow Spring Instruments, Ohio, USA). Density of the water column was calculated from temperature profiles using R-package rLakeAnalyzer (Read et al., 2011).

2.4.3 Sediment and pore water sampling

Sampling was conducted using a gravity corer (90 cm long, Ø 7 cm) and great care was taken to retrieve cores with an undisturbed sediment-water interface (SWI). We usually recovered duplicate sediment cores of at least 50 cm in length from each sampling site. The cores were sectioned at 2 cm resolution from 0 to 20 cm depth, 5 cm resolution from 20 to 50 cm depth and 10 cm intervals below 50 cm. At least 16 depth intervals were collected from each core.

One entire core was sampled for pore water, another one for sediment analyses. Pore water sampling was conducted on-site by squeezing with a small air-powered pore water press (Pore-water pressing bench, KC Denmark a/s). For each depth interval, at least 10 mL of pore water was collected in syringes, filtered through 0.2-µm pore size cellulose acetate membrane syringe filters to remove all particles and most microorganisms, transferred into 2-mL twist-top vials and stored at +4°C until analysis. Hydrogen Sulfide (HS^-) in pore water was preserved by adding 0.4 ml of saturated $ZnCl_2$ solution to 2 mL of sample.

Each sediment sample was packed into a gas-tight Aluminium foil bag and heat-sealed. Due to the unavailability of nitrogen gas, we tried to squeeze out as much air as possible, but some oxidation during storage and transport cannot be ruled out.

2.4.4 Water analyses

2.4.4.1 Anion analysis

Major inorganic anions (NO_2^-, PO_4^{3-}, NO_3^-, and SO_4^{2-}) were analyzed by using suppressed ion chromatography (IC). The system consisted of a SeQuant SAMS anion IC suppressor (EMD Millipore, Billerica, Massachusetts), a S5200 sample injector, a 3.0 × 250 mm lithocholic acid column (LCA 14) and a S3115 conductivity detector (all Sykam, Fürstenfeldbruck, Germany). The eluent was 5 mM Na_2CO_3 with 20 mg L^{-1} 4-hydroxybenzonitrile and 0.2% methanol. Flow rate was set to 1 mL min^{-1} and column oven temperature to 50°C. A multi-element anion standard (Sykam, Lot 20150220) containing NO_2^- (434.7 µM), PO_4^{3-} (210.6 µM), NO_3^- (806.4 µM), and SO_4^{2-} (520.5 µM) was diluted 10 times and measured every 10 samples along with with a blank. Respective minimum detection (S/N = 3) and quantification limits (S/N = 10) were as follows: NO_2^- (4.1 µM; 14.14 µM), NO_3^- (2.8 µM; 9.3 µM), PO_4^{3-} (4.3 µM; 14.3 µM) and SO_4^{2-} (2 µM; 8.4 µM).

2.4.4.2 Cation analysis

Major cations (Mg^{2+}, Ca^{2+}, and NH_4^+) were analyzed by using non-suppressed ion chromatography (IC). The IC system consisted of an S5300 sample injector (Sykam), a 4.6 × 200 mm Reprosil CAT column (Dr Maisch HPLC, Ammerbuch-Entringen, Germany) and an S3115 conductivity detector (Sykam). The eluent was 175 mg L^{-1} 18-Crown-6 and 120 µL L^{-1} methanesulfonic acid. The flow rate was set at 1.2 mL min^{-1} and column oven temperature at 30°C. A Cation Multi-Element Standard (Carl Roth) was diluted five times for calibration. Based on a respective signal-to-noise (S/N) ratio of 3 and 10 the detection and quantification limits were calculated for each ion and are as follows: Mg^{2+} (9.6 µM; 31.7 µM), Ca^{2+} (8.3 µM; 26.5 µM) and NH_4^+ (11.3 µM; 67.6 µM).

We also measured iron speciation on samples collected during the third expedition at location 1. The samples were kept in glass vials without headspace and measured photometrically (Viollier et a., 2000) within 6 hours after sampling.

2.4.4.3 Phosphate analysis

In most samples, phosphate concentrations were below the detection limit of ion chromatography and were thus measured by spectrophotometry (Murphy & Riley, 1962). 0.5 mL sample was transferred to 1.5 mL disposable cuvettes (Brand Gmbh, Germany) and 80 µL reagent. The reagent was prepared by mixing 125 ml of 5 N sulphuric acid and 37.5 ml of 0.032 M ammonium molybdate, 75 ml of 0.1 M ascorbic acid solution and 12.5 ml of 4 mM potassium antimonyl tartrate solution. The absorbance was measured at 882 nm with a DR 3900 spectrophotometer (Hach, Düsseldorf, Germany). The detection limit of the method is 0.005 µM.

2.4.4.4 Sulfide analysis

Hydrogen sulfide was preserved by adding 0.4 ml of saturated $ZnCl_2$ solution to 2 mL of sample almost immediately after collection. The concentration of HS^- was quantified spectrophotometrically using the methylene blue technique (Cline, 1969). Samples were measured by adding 40 µL diamine reagent to 0.5 mL homogenized $ZnCl_2$-preserved samples. Absorption was measured at 668 nm using a DR 3900 spectrophotometer (Hach, Düsseldorf, Germany). The detection limit is 0.25 µM with a 1 cm cuvette. Samples were measured in duplicate. For all spectrophotometric analyses, the concentrations are given as average values; error bars are one standard deviation. Reproducibility was always better than 5%.

Total Alkalinity determination and Dissolved Inorganic Carbon (DIC) calculation

Total Alkalinity (TA) was determined immediately after pore water squeezing by colorimetric titration, pH was measured using a Horiba pH-22 Twin Compact pH Meter. These two variables were used to calculate DIC from the carbonate speciation ($DIC=CO_2+ HCO_3^-+CO_3^{2-}$) using the LLNL method in PHREEQC (Parkhurst & Appelo, 1999).

2.4.5 Sediment analyses

The sediment samples were freeze-dried and the large material such as rock, shells, twigs and leaves, was removed using tweezers. Grinding was done manually in a porcelain mortar and the entire sediment sample was passed through a 63-µm-mesh sieve.

2.4.5.1 TC, TOC and TN analyses

For quantification of TC and TN, about 5 mg of material was combusted in tin foil at 950°C in a Vario EL III analyzer (Elementar Analysensysteme GmbH). For TOC quantification, about 15-100 mg of material was combusted at 580°C using a Vario Max C analyzer (Elementar Analysensysteme GmbH), after pretreatment with HCl. The detection limit of these methods was 0.1 wt.% for TOC and TN and 0.05% for TC.

2.4.5.2 Mineralogical analyses

Mineralogical data were collected with a PANalytical Empyrean X-ray diffractometer operating with Bragg-Brentano geometry at 40 mA, 40 kV and Cu-K_α radiation. A random distribution of the powdered sample was prepared for bulk-rock mineralogy analysis. The identification of the mineralogy was performed using the EVA 11.rev.0 Software (Bruker).

2.4.5.3 X-Ray Fluorescence (XRF) Scanning

About 4 g of freeze-dried sediment powder was loosely packed in sampling cups (~ 2 cm high, Ø 2 cm) and covered with X-Ray-transparent foil. Analysis of elemental sediment composition was performed on these samples using an ITRAX XRF core scanner with a Cr X-ray source (30 kv, 55 mA, 10 s). Element intensities of all samples (N=55) obtained by XRF core scanning were calibrated using quantitative results of 11 discrete reference samples. Reference analyses were performed on glass beads using a PANalytical AXIOS Advanced XRF. International and internal reference samples were used for calibration. Coefficients of determination (R^2) of the XRF scanning calibration are in Table SI 2.1. Sediment characterization based on geochemical results was conducted using principal component analyses (PCA) and hierarchical clustering of the calibrated and log-ratio-transformed XRF core scanning data (Weltje et al., 2015). Element correlations and compositional grouping by means of hierarchical clustering were visualized using a biplot of the first two principal components.

2.4.6 Reaction rate and flux calculations

Using the MatLab routine of Wang et al. (2008) we quantified net rates of production and consumption of several dissolved pore water compounds that play a quantitatively significant role in carbon remineralization processes. The model requires several data *a priori*. We used sediment porosity data from location 1 to calculate the reaction rates at all locations (Table SI 2.3). Diffusion coefficients (assuming 25°C) of the respective compounds were $1.85\text{x}10^{-9}$ m^2 s^{-1} for NH_4^+, and $1.11 \text{ x } 10^{-9}$ m^2 s^{-1} for HCO_3^- (Schulz, 2000). We used the latter as the dominant species of dissolved inorganic carbon (DIC).

Because we did not have values for sedimentation rates at Lake Sentani, we used a typical value for tropical oligotrophic lakes (1.9×10^{-4} m yr^{-1}, Russell et al., 2014) and assumed steady-state conditions. A minimum of five measured concentration data points was used to determine each reaction zone. Uncertainties in the rate estimates were quantified using a Monte Carlo technique (Wang et al., 2008).

2.5 Results

2.5.1 Water Column Characteristics

There were differences in the vertical structure of the water column among the locations and sampling times (Fig. 2.2). At all four locations, temperatures ranged from 31.0-32.5°C at the lake surface to 29.0-30.0°C at the bottom, but each location exhibited a distinct temperature profile.

Both the temperature and density profiles show small but measurable fluctuations between seasons. Except for the measurements from the Nov 2016 campaign, when temperatures decreased rather steadily with depth, profiles from all other sites show a relatively distinct thermocline. The temperature profiles are mirrored by the density profiles, with lower values of 0.995 g cm^{-3} at the surface and 0.996 g cm^{-3} at the bottom. Temperature and density fluctuations have little effect on the depth of the oxycline, which appears to remain fairly stable throughout the year.

The two deepest locations, 1 and 4, show relatively steep oxyclines, with oxygen concentrations decreasing rapidly below 10 m water depth. The shallowest location (2) exhibits features similar to locations 1 and 4, although oxygen is never fully depleted because of the shallow water depth. At location 3, the decline in DO is much more gradual than at the other locations and only reaches full depletion at 25 to 30 m, similar to location 1. The depth of DO depletion marks the change of the Oxidation Reduction Potential (ORP) value from positive to negative.

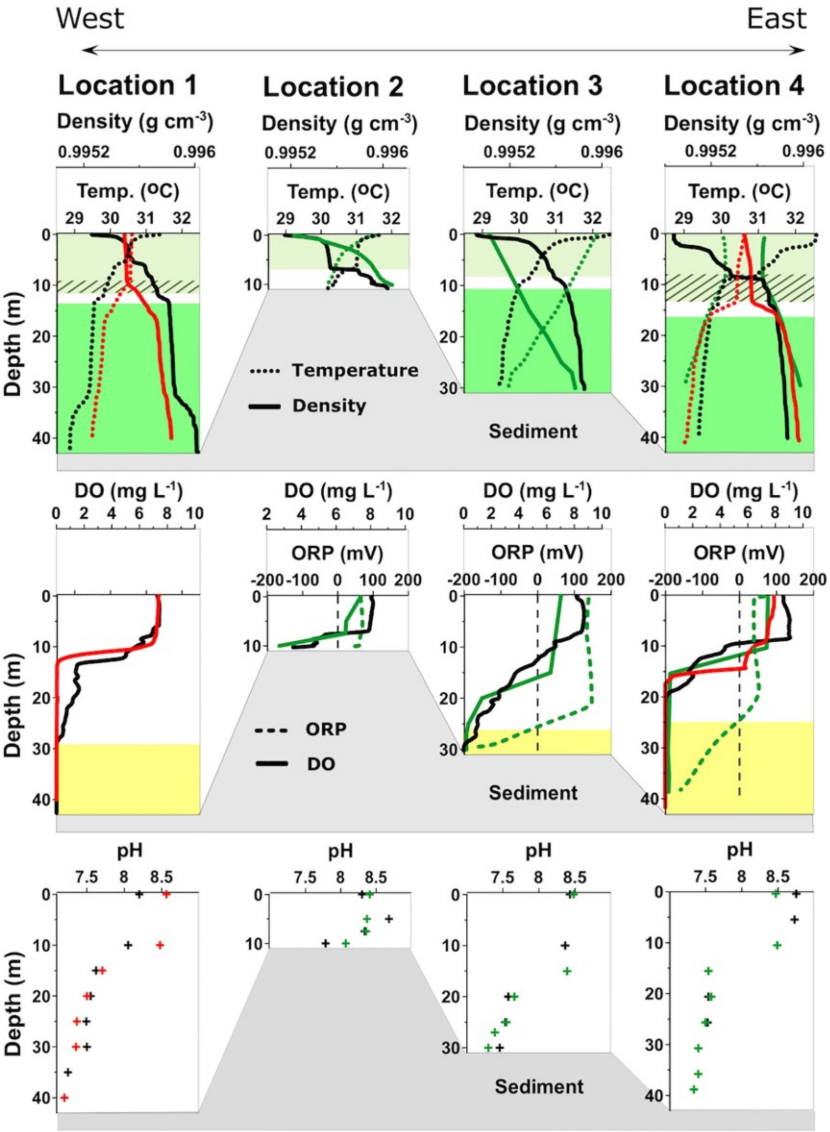


Figure 2.2 *Water column profiles of density, temperature, dissolved oxygen (DO), oxidation-reduction potential (ORP), and pH of the four sampling locations in Lake Sentani. Measurements were taken in April (black) and November (green) 2016, and January 2018 (red). The profiles show clear thermal stratification with a well-mixed epilimnion extending to about 10 m water depth (light green shading) and a denser hypolimnion below about 15 to 20 m (dark green shading), depending on the basin and time of measurement. The diagonal line pattern indicates the fluctuations of the epilimnion boundary. Negative ORP values characterize the monimolimnion (yellow shading) with reducing conditions.*

At all locations, the surface water is slightly alkaline, with pH values around 8.5, dropping with depth by about 1 unit. The depth profiles are similar to the oxygen profile with a rapid decrease at the oxycline and a more gradual drop below. One notable feature of location 1 is that pH varies by about half a pH unit between April and November in the upper 10 m but remains stable at the other sites.

2.5.2 Anion and cation distributions in the water column and porewater

The concentration profiles of dissolved anions and cations such as phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), sulfide (HS^-), ammonium (NH_4^+), Calcium (Ca) and Magnesium (Mg) in the water column and porewater are presented in Fig. 2.3. Concentrations of NO_3 and NO_2 were below the detection limit in both the water column and pore water.

At all four locations, phosphate concentrations in the oxic surface water were around our detection limit and only increased below the oxycline. At location 1, the depth of oxygen depletion had shifted from 15 to 30 m between the two sampling campaigns, but the phosphate profiles from both campaigns are identical. Despite some scatter in the data from locations 2 and 4, there appears to be a flux of dissolved phosphate out of the sediment into the water column at all locations.

Sulfate concentrations are 28-31 µM in the oxic surface water of all locations. Above the oxycline, values remain rather stable, but decrease in the anoxic part with concentrations between 10 and 15 µM at the SWI. Pore water sulfate concentrations decrease even further and fall below our detection limit (~2 µM) in the upper few cm. Values remain around the detection limit throughout the rest of the core at all locations.

Hydrogen sulfide (HS^-) concentrations in the oxic surface waters are below our detection limit at all locations, but increase with depth below the oxycline. There is a distinct difference between the concentration profiles below the oxycline at locations 1 and 4. Whereas the concave upward profile at location 1 indicates hydrogen sulfide production in the water column, the linear to the slightly concave downward profile at location 4 indicates no production in the water column but either a purely diffusive flux or consumption of hydrogen sulfide. Location 2 has a fully oxygenated water column and therefore no hydrogen sulfide. At location 3 the sample resolution below the oxycline is too low to assess whether any production or consumption takes place in the bottom water.

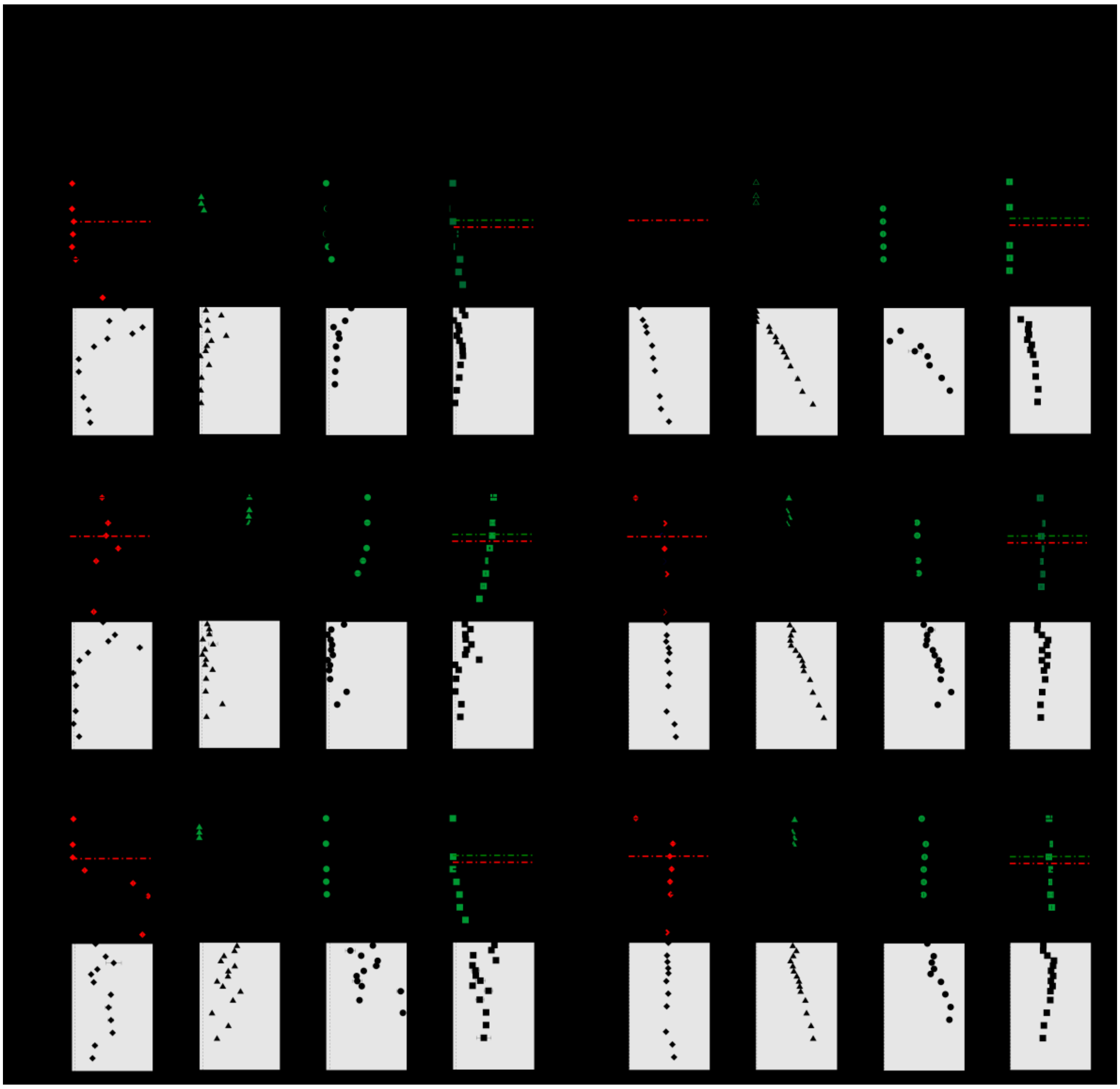


Figure 2.3 *Vertical distribution of anions and cations in the Lake Sentani water column and sediment pore water. The horizontal dashed-dotted black lines indicate the oxycline on the different sampling dates, black indicates April 2016, green November 2016, and red January 2018. Pore water profiles are indicated by the grey shaded area. Reproducibility was always better than 5%. See main text for details.*

At location 1 the ammonium (NH_4^+) concentration profile in the water column shows low concentrations and a slight increase close to the SWI. However, it displays a different trend in the porewater. Generally, the concentration of NH_4^+ in the pore water increases with depth. Locations 2 and 3 have steeper pore water gradients than the other locations. Location 4 shows the lowest gradient.

Calcium and Magnesium concentrations in the water column reveal constant profiles from the surface to the bottom at all locations. In the porewater, there are two pairs of locations that display similar profiles; at locations 1 and 4 the relatively constant values from the water column continue, whereas at locations 2 and 3 the Ca^{2+} concentration profiles start to increase with depth below ~10 cm depth in the sediment.

2.5.3 Reaction rate of organic matter mineralization

Production and consumption of dissolved pore water constituents can provide crucial information about early diagenetic reactions, most of which are driven by microbial activity. As organic matter mineralization leads to CO_2 production, the DIC concentration can be used as a good proxy for microbial activity (Fig. 2.4). At all locations, DIC concentrations increase with depth, although with different slopes. Locations 1 and 2 have almost linear gradients and only show curvature, i.e., production, in the upper 12 cm, whereas locations 3 and 4 show stronger curvature and higher DIC production rates.

Mineralization of organic matter also releases NH_4^+ to the porewater. As for DIC, concentrations increase with depth, but the respective profiles show somewhat different curvatures and hence zones of production. Locations 1 to 4 all show almost linear gradients, reflecting low production rates. Location 4 reveals a steeper slope in the NH_4^+ concentration profile, especially in the upper 15 cm, and consequently several times higher production rates.

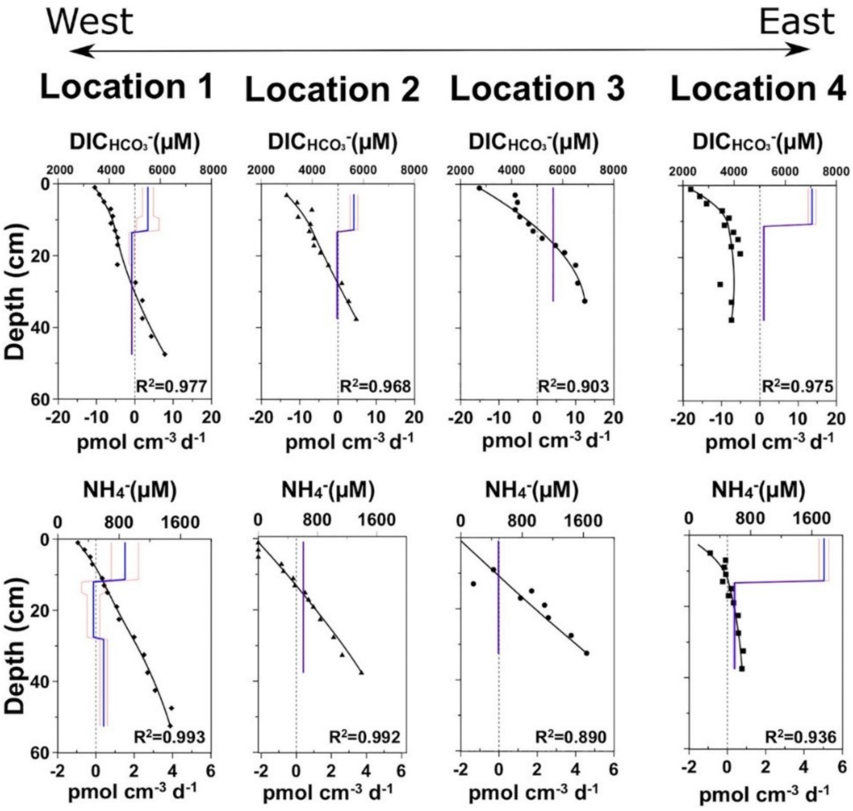


Figure 2.4 *Calculated reaction rates based on measured pore water concentrations and physical properties. The symbols represent measured concentrations, the black line shows the modeled concentration. Production and consumption rates of the respective compound are shown by positive or negative values of the blue line, respectively. The red lines indicate error ranges. See main text for details.*

2.5.4 Sediment characteristics

2.5.4.1 Sediment Carbon and Nitrogen

With values between 8 and 16 dry wt% Total Carbon (TC), concentrations are dominated by organic carbon, which constitutes at least 80% of the TC (Fig. 2.5). Surprisingly, the concentrations of TOC do not decrease with depth as a consequence of microbial degradation taking place continuously throughout the sediment column, but rather increase at all locations except location 1, which shows considerable scatter in the profile.

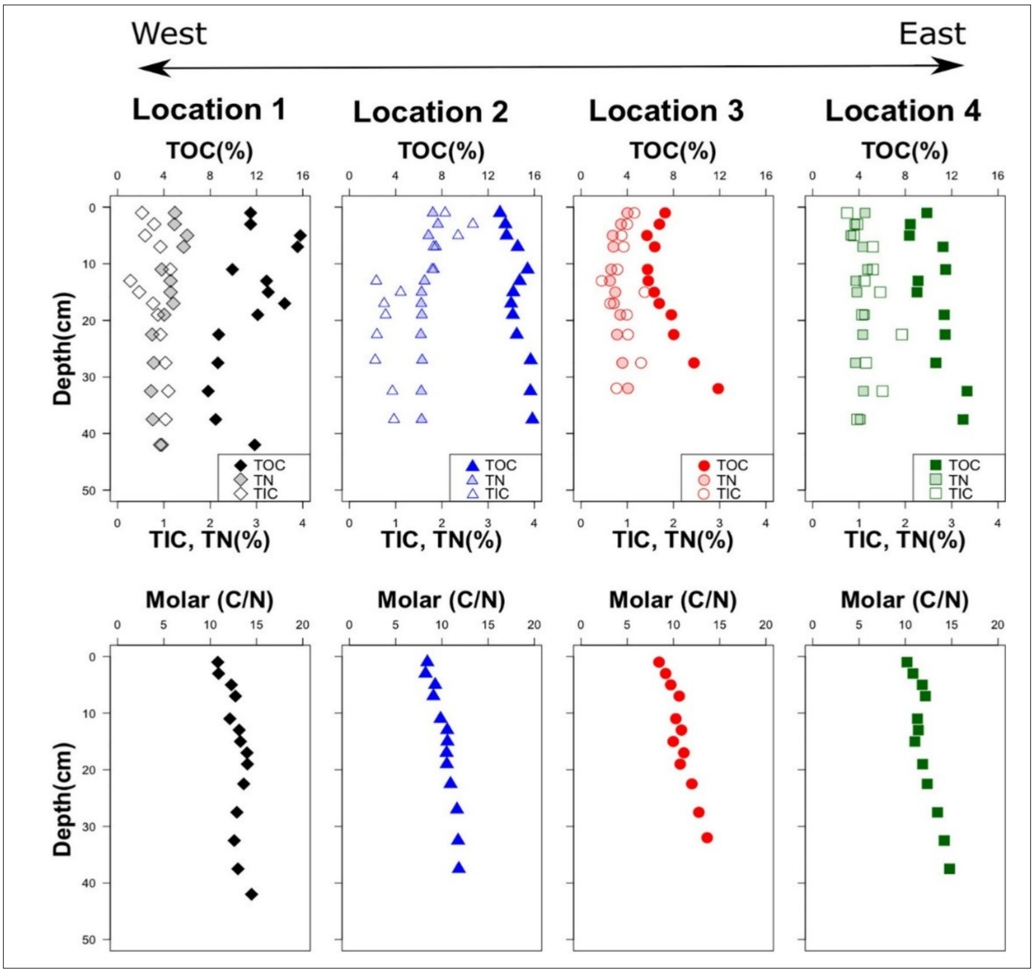


__Figure 2.5__ Down-core variation of Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), Total Nitrogen (TN) and molar C/N ratio.

Total Nitrogen (TN) concentrations are between 0.33 and 1.91%. With the exception of location 3, the concentration profiles are more or less constant with depth. The C/N ratios are very similar at all sites and depths, starting at the SWI with values around 8 to 10 and increasing more or less linearly to values close to 15 deeper in the profiles.

2.5.4.2 Mineralogy

The overall mineralogy in the samples is quartz, chlorite, kaolinite, plagioclase, pyrite, illite, and amphibole (Fig. 2.6.A). Based on the peak shape, chlorite-smectite interlayers were detected at locations 1 and 2, whereas dolomite was observed solely at location 1. Calcite is absent in all samples. Pyrite is more dominant in locations 1 and 2. These two locations also have higher sulfur and TOC values. Locations 3 and 4 contain a higher amount of ultramafic minerals such as amphibole and talc, originating from the Cyclops Mountains, whereas locations 1 and 2 contain material originating from catchment areas composed of alluvial, claystone, siltstone, sandstone and carbonate rocks.

2.5.4.3 Elemental composition

Calibration results of the XRF core scanning data for major elements detected in Lake Sentani sediment include Mg, Al, Si, S, K, Ca, Ti, Mn and Fe (Tables SI 2.2 and 2.4). The coefficients of determination (R^2) of the calibration results are between 0.68 and 0.93, except for Ca (R^2= 0.09). The poor correlation of Ca can be ascribed to the low and very limited variations of the Ca concentrations in the samples, which range from 1.4 to 2.1 % (Tables SI 2.2 and SI 2.4). Silica is the most abundant element and accounts for about 42-60 wt% at all locations. Location 1 shows higher Si concentrations than the others (Fig. 3.6.B). Ca is distributed almost evenly across all locations. Concentrations of Al and Mg show considerable differences between locations. With average concentrations of 18.37% and 16.67%, respectively, locations 1 and 2 have higher Al concentrations than locations 3 and 4. Magnesium shows the opposite pattern with average concentrations of 3.99% and 5.15% for locations 1 and 2, respectively, compared to 11.41% and 12.15% for locations 3 and 4. Iron concentration shows little variability within cores, but considerable differences between sites, with average concentrations of 4.1 %, 14.93%, 12.53% and 9.89% at locations 1 to 4, respectively. Although Mn only accounts for a few percent of the total sediment, it shows a clear bimodal distribution, with higher values at locations 1 and 4 and

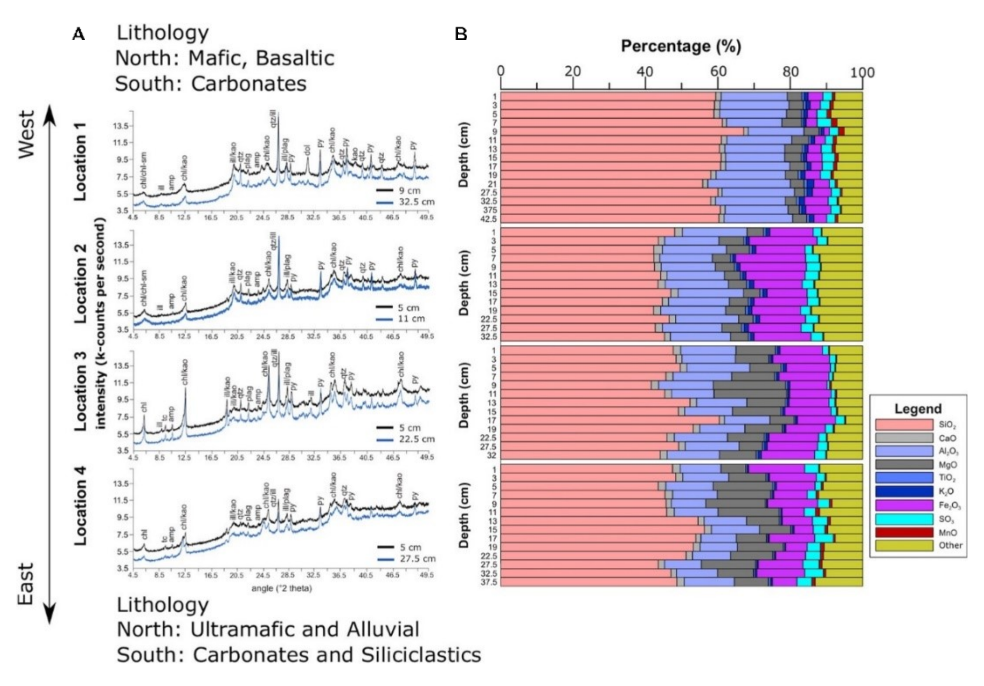


__Figure 2.6__ Mineralogy (A) and elemental composition (B) of Lake Sentani sediment. The term "Other" in panel B denotes other elements and organic matter.

lower ones at locations 2 and 3. Even though K and Ti only account for a maximum of one percent, K shows a gradual decrease from location 1 to location 4. The average concentration of Ti at location 1 is higher than at the other locations.

2.5.5 Sediment geochemical characteristics

The first two principal components PC1 and PC2 explain 47.1 and 29.1 % of the total variance, respectively. The lithogenic elements Al, K, Ti have a strong negative loading on PC1 and are oriented in the same direction indicating a positive correlation (Fig. 2.7). The element Si shows a negative loading on PC1, but a positive loading on PC2. The element Si has two main sources, one is silicate frustules of diatoms and the other is siliciclatic minerals of the lithogenic sediment fraction. The elements Mg, Ca and Fe all have a positive loading on PC1, but only Ca and Fe are oriented in the same direction indicating a positive correlation (Fig. 2.7). The opposite orientation of lithogenic elements Al, K, Ti and the elements Mg, Ca and Fe along PC 1 reveals that these elements represent different sediment fractions that are negatively correlated.

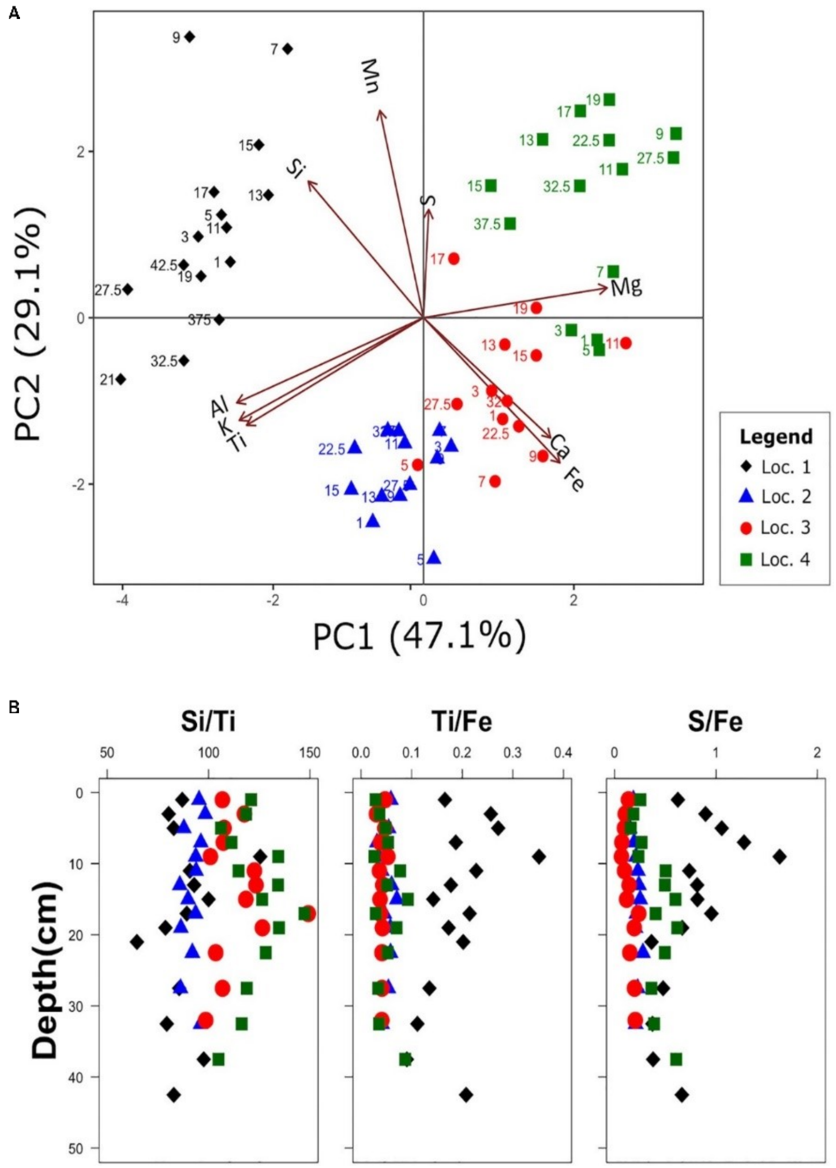


Figure 2.7 *Principal Component Analysis (PCA) of the elemental composition (A) and ratios of selected elements (B). Both the first and second Principal Component (PC) contribute to distinguishing sediment characteristics between locations. The selection of elements for the ratios was based on the fact that each pair is on opposite ends of one of the PCA axes. The numbers in panel A in dicate sediment depth (cm).*

The four sediment cores can be clearly distinguished based on their distribution in the PCA biplot (Fig. 2.7.a). Samples from location 1 all group on the left side of the biplot, whereas locations 2-4 group on the right and display a gradual and partly overlapping shift with respect to PC2. The distribution of the four locations suggests that lithogenic sediments are more dominant at locations 1 and 2, with a stronger influence of Si at location 1 and Al, K and Ti at location 2. The gradual change displayed by locations 2-4 suggests an increasing influence of the elements Mn and S, which is probably related with an increasing amount of organic matter.

PC2 has an opposite correlation of the two redox-sensitive elements Mn and Fe. In both locations 1 and 4, there is a weak correlation between PC2 and sediment depth. Although location 1 shows decreasing PC2 values with increasing depth, with the three deepest samples revealing negative numbers, location 4 shows the opposite trend, with the three shallowest samples having negative PC2 values.

Based on the PCA analysis, we found that Ti forms opposing pairs with Fe and Si on PC1 and PC2, respectively. A similar pair is formed by S and Fe on PC2. Therefore, these element ratios (Fig. 2.7.b) can be used as proxies for different sediment input and water column conditions.

2.6 Discussion

2.6.1 Physicochemical characteristics of the water column

The water column profiles show clear signs of stratification, which have profound effects on the overall structure of the water column and bottom water oxygenation in all four sub-basins of Lake Sentani. Although all sub-basins have a well-mixed epilimnion, basins 1 and 4 both have anoxic monimolimnia (Fig. 2.2), and in sub-basin 3, DO just reaches depletion at the SWI and basin 2 remains oxic, albeit at low concentrations (Fig. 2.2). These findings indicate that there is one location that is oxygenated (2), one intermediate (3) and two fully meromictic basins (1 and 4) in Lake Sentani, while all four sub-basins share the same surface water chemistry. We did not sample in the coldest month (June), when overturn would be most likely, but the water column profiles from the other three sampling campaigns show relatively little variation, so we are confident that the water column is stable throughout the year.

Different patterns of water column stratification are reflected in the pore water profiles. The vertical distribution patterns of anions differ considerably between the fully oxygenated (loc. 2), the intermediate basin (loc. 3) and the two meromictic basins (loc. 1 and 4). Even in highly oligotrophic lake systems with low sediment organic carbon concentrations and fully oxygenated bottom waters, oxygen penetrates at most only a few mm into the sediment (Corzo et al., 2018). Therefore, reducing conditions and hence anaerobic processes are prevalent in the sediment at all locations (Fig. 2.3).

In the absence of other electron acceptors with a higher energy yield (NO_3^{2-}, Fe^{3+}, Mn^{4+}), the anaerobic degradation of organic matter will proceed via sulfate reduction (Froelich et al., 1979). Sulfate concentrations in Lake Sentani are around 18-25 µM, which is about twice as high as in other oligotrophic lakes in Indonesia, e.g., Lake Matano or Lake Towuti, but less than one-thousandth that in the ocean (Jørgensen et al., 2001; Vuillemin et al., 2016). Sulfate concentrations are more or less constant throughout the water column of the oxic basin (loc. 2) and above the oxycline in the meromictic basins (loc. 1 and 4). The product of sulfate reduction, HS^-, is present in all sediment samples at all locations, but the considerable scatter within the profiles, possibly indicating some degree of sulfide oxidation during sample handling, prevents the identification of clear depth trends. Nevertheless, the presence of HS^- indicates that even such low sulfate concentrations are sufficient to enable microbial sulfate reduction (Crowe et al., 2014; Vuillemin et al., 2016).

Although it is not surprising that there is no HS^- in the oxic water column of location 2, even the low DO concentrations at the SWI of loc. 3 appear to be sufficient to facilitate oxidation of HS^-. At locations 1 and 4, HS^- is present throughout the monimolimnion and only becomes depleted at the oxycline. Unfortunately, the data show too much scatter (loc. 1) and have an insufficient resolution (loc. 4) to assess whether the HS^- concentration profile is purely diffusive and sulfide oxidation is limited to the oxycline or whether it indicates production or consumption throughout the monimolimnion. It is interesting to note that sulfate and sulfide coexist in the monimolimnia of locations 1 and 4. Given the thermodynamically constrained sequence of electron acceptor use (Froelich et al., 1979), there appear to be sufficient available electron donors that would yield greater energy than sulfate. In this case, nitrate and manganese oxides are not quantitatively important, and ferric iron is most probably the main electron donor (Fig. SI 2.1) thereby preventing sulfate reduction. We consider neither anoxygenic photosynthesis nor sulfide oxidation with another electron acceptor to be a significant source of sulfate in the monimolimnion. There are no suitable electron acceptors available and anoxygenic photosynthesis can be excluded due to water depth. Moreover, the concentration profiles of sulfate and sulfide provide no indication for sulfide oxidation.

Despite some variation in maximum concentration levels, the PO_4^{3-} profiles are quite similar at all locations. Similar to HS^-, the shape of the concentration profiles in the water column reflects redox conditions, with both ions only showing enrichment in the sediment pore water and anoxic parts of the water column, indicating that the oxic-anoxic interface represents an efficient barrier for both ions, although the mechanisms that govern their respective concentrations are quite different. Whereas HS^- can be oxidized both biologically and abiologically (Millero, 1991), PO_4^{3-} is usually bound in biomass or adsorbed to mineral surfaces, particularly Fe-oxy-hydroxides (Davison, 1993).

The increasing concentration of phosphorus in the anoxic bottom water is apparently caused by release of iron-oxide-bound phosphate. Although we only have iron speciation data from location 1 (Fig. SI 2.2), they indicate that phosphate and iron are tightly coupled. Below the oxycline, the concomitant increase in dissolved PO_4 and Fe (II) show that the reduction of solid Fe (III) to dissolved Fe (II) leads to a release of adsorbed PO_4. The same process has also been shown for tropical ferruginous and oligotrophic Lake Matano, South Sulawesi, Indonesia (Crowe et al., 2008).

The different patterns in ion distribution in relation to water column structure of each basin are clearly shown in the cation concentration profiles. The cation species analyzed in our study are not involved in redox processes, however the anaerobic mineralization of organic matter will liberate ammonium as a product (Beutel, 2006; Hansen & Blackburn, 1991). Different from HS^- and PO_4^{3-}, which diffuse out of the sediment and become enriched in the anoxic water column, NH_4^+ mainly remains below our detection limit in most water column samples, except the bottom two samples of location 1 (Fig. 2.3). Interestingly, the pore water NH_4^+ concentration profiles increase at a steeper rate in basins 2 and 3, which have oxygenated bottom waters, than in meromictic basins 1 and 4. We do not have an explanation for this observation, but one possibility could be the difference in N-incorporation efficiencies between aerobic and anaerobic bacteria (Canfield et al., 1993; Hansen & Blackburn, 1991).

As for ammonium, the concentration profiles of Ca and Mg, particularly the pore water profiles, can be divided into two groups, according to the stratification of the water column. Meromictic basins 1 and 4 reveal the same concentration throughout the water column and the sediment, indicating no net consumption (loss) or production (gain) of either compound on either side of the oxycline, although at location 4 there is a slight excursion to higher values in the upper 10 cm of the sediment. In basins 2 and 3 the water column profiles also do not show any concentration changes, but the sediment pore water concentration profiles continue the trend from the water column through the upper ~10 cm before starting to increase almost linearly with depth; at 30 cm depth they reach values that are higher by about 50% than in the water column. The depth at which the concentrations of Ca and Mg increase starts coincides with the depth at which ammonium also starts to become enriched in the pore water. A possible explanation could be oxidation of sulfide minerals (FeS and FeS_2, Fig. 2.6.A), which are present in the upper part of the sediment. Sulfide oxidation produces protons that could facilitate the dissolution of calcite and dolomite in the sediment (Smolders et al., 2006). However, the XRF analyses of the sediment do not indicate preferential dissolution of Ca and Mg at locations 2 and 3, and moreover we cannot identify potential oxidants that could drive this reaction.

Overall, the vertical concentration profiles indicate differences in biogeochemical processes between the basins. Although in meromictic basins 1 and 4, the bottom water and the sediment pore water are to some degree a single continuous system, even low DO concentrations are sufficient to form an effective barrier for reduced species.

2.6.2 Geochemical characteristics

The geochemical composition of Lake Sentani's surface sediment (Nomosatryo et al., 2021, submitted) and the short cores presented in this study is the result of equilibrium processes between the sediment, porewater and water column. The differences in sediment composition are representative of (i) the different processes and conditions in the water column of the basins, as well as (ii) the different sediment input caused by lithological variations in the catchment. The mafic and ultramafic lithology of the Cyclops Mountains deliver more Mg and Fe into basins 3 and 4 (Fig. 2.1, Fig. 2.7). Since Al and Ti are not redox sensitive, they are relatively conservative during diagenetic processes (Boës et al., 2011) and therefore rather immobile. Fe and Mn are both highly redox sensitive and therefore strongly involved in redox-driven element cycling, particular in those basins where conditions become anoxic in the water column.

Weathering in the catchment area leaches elements such as Mg, Ca, Fe from the bedrock and soils, which are eventually transported into the lake via rivers, streams or mass wasting and direct runoff from the slope. The less soluble elements Al, Si and Ti enter the lake as particulates rather than in dissolved form. Dissolved elements and particulates undergo biological and chemical transformation in the water column before deposition on the lake floor (Sheppard et al., 2019) where diagenetic processes further change the composition of the sediment (Davies et al., 2015; Rothwell & Croudace, 2015).

The distinct geochemical characteristics in sediment composition between the different locations are the result of several factors. The most important factor appears to be the lithology of the catchment. Lake Sentani is bounded to the north by the Cyclops Mountains, which are mainly composed of Fe- and Mg-rich mafic and ultramafic rocks. However, most of the runoff from these areas enters the two easternmost basins, 3 and 4, hence their correlation with Fe and Mg on PC1 (Fig. 2.7). Nomosatryo et al. (2022) showed that there is strong enrichment of Mn in the deepest part of basin 4, roughly coinciding with location 4 used in this study. In our present study we can show that the sediment cores from both deepest sub-basins (1,4) reveal higher Mn concentrations than shallower basins 2 and 3. Consequently, locations 1 and 4 plot positively on PC2, and so does Mn (Fig. 2.7). Although the ultimate reason for the enrichment could not be identified there are strong indications that the enrichment was caused by enhanced biogeochemical cycling of Mn, whereas the much more abundant Fe behaved more like a detrital element, which might also explain its correlation with Mg and Ca. At first glance, it appears counterintuitive that sediment from location 1, which is surrounded by basaltic and mafic rocks has the lowest Fe concentrations. However, most rivers that enter basin 1 come from the west and the south and drain catchments mainly composed of limestone (Fig. 2.1). Moreover, because these rivers are small and ephemeral (Table SI 2.1), plus the fact that they are flowing through very flat terrain, and location 1 being rather well isolated from these rivers, it is not too surprising that Ca and Mg are low at this location as well. So it is not just the geology of the immediate surrounding that shapes the elemental and mineralogical composition of a lake sediment, but also the pathways of the rivers draining into it and the topography of the terrain.

Location 1 is a good example of the shifting geochemical composition over different time scales. The relatively small basin is subdivided by two peninsulas with steep slopes that reach deep into the basin. Location 1 seems to be weakly stratified as shown by the DO profile data, where the depth of the oxycline changed from 30 to 15 m between April 2016 and December 2018 (Fig. 2.2). Water column dynamics also affect the concentration profiles of redox-sensitive anions like sulfate and sulfide. Compared to the other meromictic location 4, the profiles show more scatter, which we interpret as a result of non-steady-state conditions in response to a rapidly fluctuating oxycline depth. On longer timescales, we can also observe shifts in geochemical conditions caused by changes in sediment input. The PCA provides a weak indication for a change in sediment composition around a depth of 19 cm, and with one exception (42.5 cm) all samples below this depth have lower or even negative PC2 values. At this depth we can also observe a shift in TC, TN and C/N ratio (Fig. 2.5). As we do not have any age information from the sediment cores we can only speculate about the reason for this shift, but it clearly shows that each basin individually records local variations in sediment input or diagenesis, which might have multiple causes, e.g., changes in water column stratification, bottom water oxygenation, changes in land cover or runoff in the catchment. Identification of the reasons for these changes is beyond the scope of this study but our data show that these sediments offer the chance to study small-scale variations in the catchment and/or the water column.

Location 4 is also meromictic, but its stratification is much more stable than at location 1, given the little variation in oxycline depth over the different sampling campaigns. This results in more stable concentration gradients, showing less scatter and very little difference between the sampling campaigns. The sediment at this location also reveals compositional changes with depth. The three uppermost samples, from the SWI to 6 cm, are the only ones with a negative PC2 (Fig. 2.7). These three samples also show a markedly different trend in TC and TN (Fig. 2.5), indicating a shift in sedimentary input.

The differences in water column structure do not have a noticeable impact on the quality or the amount of sediment organic matter (OM). The fact that variations in sediment organic matter composition correlate with changes in element composition indicates that changes in environmental variables like erosion rates or land cover have a decisive influence on sediment composition. Although there are similarities in concentration profiles of individual elements and variables among basins, there is a sufficient number of differences that clearly show that each basin underwent its own evolution and its sediment provides a sensitive record of small-scale environmental variations.

The TOC concentration is influenced by both initial production and deposition of biomass and subsequent degradation (Philip A Meyers & Teranes, 2001). In all basins, TOC concentrations are sufficiently high to fuel abundant microbial respiration and therefore diagenetic processes. The concentrations lie between values typical for oligotrophic tropical lakes like Lake Towuti (2-3.5%) (Vuillemin et al., 2016) to eutrophic ones like Lake Maninjau (~22%) (Henny & Nomosatryo, 2012). The source of organic matter appears to be relatively similar between locations, although there are local variations in both concentration and composition of organic matter, the latter being indicated by variable quantities of diatom frustules, found in smear slides (data not shown).

Even though nutrient concentrations in the water column are currently low, shifts in productivity are recorded in the sediment record. Overall the C/N ratio increases with depth, which can be interpreted either as a gradual shift from a more terrestrial organic matter input (with relatively higher C/N ratio) towards a lacustrine (phytoplankton) source of organic matter (Meyers, 2003). Another possibility could be increasing degradation of the more reactive algal material over time (Kaushal & Binford, 1999). Without any detailed analyses of the sediment organic matter, we are not able to provide a definitive explanation for the trend. We suspect that the higher C/N ratio in deeper sediment relates to past climate change but without proper age information this remains speculative.

The quantitatively dominant element in Lake Sentani is Si (Fig. 2.6). Both biogenic (diatoms) and abiogenic Si (siliciclastics) are present in all samples although biogenic Si is never dominant. The opposite loading vector of Si and Ti on the PC2 (Fig. 2.7) can be used as an indicator of the source of Si. High Si and low Ti indicate a more biogenic source, and low Si and high Ti a more abiogenic one. Given the small size of the individual basins and the many factors that influence element distribution in the sediment it remains questionable whether the Si/Ti ratio could be used to reconstruct productivity in the lake. The fact that both meromictic basins correlate positively with Si indicates that water column structure appears to have an influence on this ratio as well. Still, the correlation between sediment depth and PC2 for locations 1 and 4, albeit weak, can be interpreted as an indication of changing productivity over time.

2.7 Conclusions

Despite sharing a common surface water chemistry, each of the four sub-basins of Lake Sentani has a distinct water column structure and sediment chemistry. The effects of water column stratification and shifts in oxygenation levels appear to be most pronounced in the deeper basins. Sediment composition is mostly controlled by catchment geology, but water column stratification and in particular bottom water oxygenation has a strong influence on the elemental composition of the sediment and pore water composition. Depth profiles of dissolved chemical species in the water column and the sediment pore water provide information on fluxes, rates and hot spots of mainly microbially driven organic matter degradation processes. Lake Sentani provides a unique chance to study the influence of different environmental factors on sediment composition under identical climate and hydrological conditions.

2.8 Acknowledgments

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3 Surface sediment composition and depositional environments in tropical Lake Sentani, Papua Province, Indonesia

3.1 Abstract

Tropical Lake Sentani in the Indonesian Province Papua consists of four separate basins and is surrounded by a catchment with a very diverse geology. We characterized the surface sediment (upper 5 cm) of the lake's four sub-basins based on multivariate statistical analyses (Principal Component Analysis, hierarchical clustering) of major element compositions obtained by X-ray Fluorescence (XRF) scanning. Three types of sediment are identified based on distinct compositional differences between rivers, shallow/proximal and deep/distal lake sediments. The different sediment types are mainly characterized by the correlation of elements associated with redox processes (S, Mn, Fe), carbonates (Ca), and detrital input (Ti, Al, Si, K) derived by river discharge. The relatively coarse-grained river sediments mainly derive form the mafic catchment geology and contribution of the limestone catchment geology is only limited. Correlation of redox sensitive and detrital elements are used to reveal oxidation conditions, and indicate oxic conditions in river samples and reducing conditions for lake sediments. Organic carbon (TOC) generally correlates with redox sensitive elements, although a correlation between TOC and individual elements change strongly between the three sediment types. Pyrite is the quantitatively dominant reduced sulfur mineral, monosulfides only reach appreciable concentrations in samples from rivers draining mafic and ultramafic catchments. Our study shows large spatial heterogeneity within the lake's sub-basins that is mainly caused by catchment geology and topography, river runoff as well as the bathymetry and the depth of the oxycline. We show that knowledge about lateral heterogeneity is crucial for understanding the geochemical and sedimentological variations recorded by these sediments. The highly variable conditions make Lake Sentani a natural laboratory, with its different sub-basins representing different depositional environments under identical tropical climate conditions.

Keywords: Tropical lake, lacustrine sediment, XRF analysis, multivariate statistics

3.2 Introduction

Chemical composition of lacustrine sediments is controlled by biological, chemical, and physical processes both within the lake and during sediment transport to the lake. In tropical regions with high precipitation, particulate and dissolved compounds are transported into the lake mostly by rivers ; Stallard and Edmond, 1983). In these regions, strong chemical weathering of bedrock material and rapid soil formation alters erosion products that are transported by streams and rivers and accumulate in lacustrine deposits. High temperatures and, at least during some parts of the year, high precipitation rates, lead to strong chemical weathering in the catchment, creating a high flux of suspended sediment and dissolved compounds from the catchment to the lake (Crowe et al., 2008; Liu et al., 2012). In aquatic environments, biological activity and the production of organic matter play a prominent role on the level of oxygenation in the water column and at the sediment-water interface (Santschi et al., 1990).

Degradation of organic matter by heterotrophic microorganisms is the main consumer of dissolved oxygen (Holmer and Storkholm, 2001). After oxygen has been depleted, compounds like metal (mostly Fe and Mn) oxides, nitrate or sulphate are being used as electron acceptors in the anaerobic degradation of organic matter (Froehlich et al., 1979). Heterotrophic degradation of organic matter, particularly with metals as electron acceptors, plays a dominant role on diagenetic alteration of lacustrine sediments (Capone and Kiene, 1988). For example, solid ferric (oxyhydr)oxides can enter the lake either as detrital minerals or are formed in the water column under oxidizing conditions (Zegeye et al., 2012; Vuillemin et al., 2019). Upon depletion of electron acceptors with a higher energy yield, i.e., oxygen, nitrate, Mn^{4+} (Froelich et al., 1979), these minerals can be reduced, producing dissolved Fe(II) (Davison, 1985) which might diffuse upward and become oxidized again, or form ferrous minerals (Fredrickson et al., 1998; Vuillemin et al., 2019 and 2020; Bauer et al., 2020). Even in highly oligotrophic systems with low organic carbon concentrations, anaerobic processes dominate sedimentary mineral transformation, as oxygen only penetrates a few mm into the sediment (Corzo et al., 2018). Hence, sediments in tropical lakes are influenced by chemical weathering of bedrock in the catchment, fluvial transport, and alteration in the water column as well as diagenesis after deposition (Hasberg et al., 2019).

Despite all the chemical variations caused by a number of conditions and processes both in the catchment and the water column, the “finger print” of the source rock, i.e. its primary chemical signature is still at least partly visible in surficial lacustrine sediment. Elemental and mineralogical compositions of near-surface sediment provide detailed information on the distribution of the dominant sediment sources and the main depositional environments in a lake system. In addition, detailed characterization of depositional environments can provide fundamental information for the interpretation of sediment cores that archive long time series of depositional changes (Last and Smol, 2001).

Most limnological studies are carried out in temperate lakes, whereas the special characteristics of lacustrine sediment in tropical lakes are still largely unknown (Escobar et al., 2020). The most important difference between temperate and tropical lakes are the small seasonal temperature fluctuations in the latter, leading to an often more stable temperature gradient in the water column that is not disturbed by changing surface water temperatures. However, even subtle temperature fluctuations in combination with increased evaporation during the dry season can lead to sufficient cooling to allow overturning of the water (Lewis, 1987).

The main annual climatic variation is precipitation with one or two wet and dry seasons. (Boehrer and Schultze, 2008; Katsev et al., 2017). Therefore, many large tropical lakes like Malawi, Tanganyika and Matano are meromictic (Katsev et al., 2017), i.e. the water column is permanently stratified with a well-mixed oxic surface layer (epilimnion) and a denser anoxic deep layer (monimolimnion) (Crowe et al., 2008; Roland et al., 2017; De Crop and Verschuren, 2019). Smaller lakes where the fetch across which the wind can blow and mix the water is small compared to the maximum water depth, can be meromictic as well. However, according to Schmid’s lake stability formula, deep but small lakes show only weak stratification (Hutchinson, 1957). Irrespective of the size and maximum depth of a lake, stable stratification and resulting meromixis has profound implications on the biogeochemistry of these lakes (Katsev et al., 2017).

Lacustrine sediments are often used for paleoclimate reconstructions, where long sediment cores are retrieved to obtain archives of past environmental conditions (Last & Smol, 2001). However, as coring is logistically challenging and expensive, normally only very few sites that promise the longest and least disturbed sedimentary sequence are being cored. Especially for deep drilling projects the characterization of spatial heterogeneity has become an important aspect. In recent years several studies showed the importance of riverine input on lacustrine sediment and the spatial variability of sediment distribution within a single basin in several tropical and temperate lakes, e.g., Lake Turkana (Yuretich, 1979), Lake Ohrid (Vogel et al., 2010), Lake Donggi Cona (Dietze et al., 2012), Lake El'gygytgyn (Wennrich et al., 2013), Laguna Medina (van 't Hoff et al., 2016), or Lake Towuti (Hasberg et al., 2018; Morlock et al., 2019). Many of them showed that lateral heterogeneity can severely complicate reconstructions of paleoenvironmental conditions based on long sediment cores. In Lake Sentani, Nomosatryo et al. (2021) sampled the water column and took sediment cores in the deepest part of each sub-basin. Their results showed that climatic and hydrological changes are recorded in sedimentary sequence. However, as this study only used one sampling location per basin, a differentiation between lateral variability and temporal climatic or hydrological changes was not possible.

In order to contribute to a better general understanding of the relationship between catchment geology and lacustrine sediment composition we studied the spatial distribution of sediment types in Lake Sentani in Papua Province, Indonesia (2° S, 140° E). A unique feature is the lake's shape, as it is divided into four sub-basins of which three are separated by shallow sills and one by a narrow natural channel (Fig. 3.1.A) (Sadi, 2014; Indrayani et al., 2015a). The catchment geology is highly diverse, ranging from carbonates over clastic sediments to igneous and metamorphic rocks, some with ultramafic composition (Suwarna and Noya, 1995). The northern side of the lake is bounded by the Cyclops Mountains, the southern side has a relatively flat topography (Fig. 3.1.B).

While the four basins share a common surface water chemistry, the basins differ in water column structure and bottom water chemistry. Moreover, each sub-basin receives a distinct sediment input (Sadi, 2014). Thus, this lake offers the chance to study the effects of different catchment lithologies and water column processes on lacustrine surface sediment under otherwise identical environmental conditions. Although the population around Lake Sentani is growing, and the lake faces increasing anthropogenic nutrient input (Kementerian Lingkungan Hidup Republik Indonesia 2011; Indrayani et al., 2015b), the area still has a relatively low level of urbanization despite its proximity to Jayapura, the capital of the province.

3.3 Study Site

Lake Sentani is located near the capital city of Papua Province, Jayapura, at an elevation of 73 m asl (Fig. 3.1.B). The lake is approximately 28 km long (East to West), 19 km wide (North to South), has a total surface area of 96.3 km^2 (Kementrian Lingkungan Hidup Republik Indonesia, 2011) and a storage capacity of 4821.5×10^6 m^3 (Sartimbul et al., 2015). Lake Sentani consists of four sub-basins of which one is connected by a shallow natural channel (Simboro Channel), the other three are separated by shallow sills with a maximum depth of just 6 m (Fig. 3.1.B). There are considerable differences in the maximum water depths of the four sub-basins, literature values range from 30 m (Sadi 2014) to 70 m (Indrayani et al., 2015a). Our own depth soundings at every sampling location revealed maximum depths of 42, 12, 30 and 43 m, for sub-basins 1 to 4, respectively. In a recent study, Nomosatryo et al. (2021) presented physicochemical properties of the water column, measured at or close to the deepest parts of each basin. In short, the upper 10 m of the water column in all four basins is well mixed, below this depth dissolved oxygen (DO) decreases more or less rapidly and becomes fully depleted in sub-basins 1 and 4, in sub-basin 3 DO just reaches depletion at the sediment-water interface, and shallow sub-basin 2 remains fully oxygenated. Surface water temperatures in all four sub-basins are between 31 and 32°C, bottom temperatures are around 29° C except for sub-basin 2, where temperatures remain above 30° C (Fig. 3.2).

The lake has a catchment area of about 600 km^2 and is bounded by the Cyclops Mountains to the north (Tappin, 2007) and lowlands to the south. The highest peak of the Cyclops

Mountains is Merahriboh, reaching an elevation of 3200 m asl (Husein et al., 2018). The north side of the lake is dominated by volcanic breccia, mafic, ultramafic rocks and alluvial deposits, whereas the southern part of the lake is mainly characterized by a wide range of mainly sedimentary rocks comprised of various types of carbonates, siliciclastic sediments with some basaltic areas (Fig. 3.1.B) (Suwarna and Noya, 1995). At least sixteen rivers drain into the lake (Bungkang et al., 2014; Handoko et al., 2014). Yahim, the lake's largest sub-catchment is located on its northern side and covers almost 38% of the total catchment (Table 3.1). Twelve rivers come from the Cyclops Mountains in the north and four rivers originate from the lowlands in the south (Fig. 3.1). The Doyo River in the Yahim sub-catchment is the biggest single source of water to the lake with an average discharge of 19 $m^3 s^{-1}$ (Table 3.1 , Handoko et al., 2014). With the exception of the Warno River (discharge rate 5.5 $m^3 s^{-1}$), which drains the Kuruwaka catchment immediately east of the Yahim catchment, all other rivers have discharge rates of <1 $m^3 s^{-1}$. The Jayafuri (Jayefuri) River, located in the southeastern tip of the easternmost basin, is the only outlet (Handoko et al., 2014; Kementerian Lingkungan Hidup Republik Indonesia, 2011). Discharge rate of the outflow at Jayafuri river is 15 $m^3 s^{-1}$ (Handoko et al., 2014). The retention time of water in the lake is 510 days (Sadi 2014). Many catchment areas and rivers are known under different names (Table 3.1), but we will refer to the names of the sub-catchments (Fig. 3.1.A, Sartimbul et al., 2015).

The average annual precipitation at Lake Sentani is 1691 mm $year^{-1}$ (Sartimbul et al., 2015). Highest precipitation occurs in March with an average of 206 mm $month^{-1}$; July has the lowest precipitation with 95 mm $month^{-1}$. Air temperature around Lake Sentani ranges between 23.6°C and 32.2°C, the water temperature ranges between 29.3°C and 30.4°C (Sadi, 2014).

Most of the catchment of Lake Sentani is dominated by natural vegetation (forests, grasslands) and agricultural areas with mainly sago plants (Kementerian Lingkungan Hidup Republik Indonesia, 2011). Due to the mostly dense plant cover and the high precipitation, aeolian transport of sediment is negligible and we assume the sediments in and around the lake to be mostly fluvial or lacustrine, as in many tropical settings

(Stallard, 1998), however we cannot fully exclude other processes like mass wasting or slumping, potentially triggered by the frequent earthquakes in the area (Mantiri, 2016).

Table 3.1 *Names and main characteristics of the rivers in Lake Sentani's catchment*

Sartimbul (2015); Bungkang et al. (2014); Fauzi et al. (2014)				Handoko et al. (2014)	
Sub Catchments	Area (km^2)	Length of the river (m)	Slope (s)	Name of rivers	Discharge rate (m^{3}s^{-1})
1 (Dogefu)	17	5010	0.0581	Dogefu/Kanda	0.24
2	25	6281	0.0718		n/a
3	29	6822	0.0475		n/a
4	64	14099	0.053	Benali	0.14
Yahim	236	33670	0.0424	Doyo Kemiri	19 0.36
Kuruwaka	23	12165	0.1277	Belo Warno	0.62 5.47
Netar	25	12243	0.1034	Flavouw	0.36
Yakembeng	33	13061	0.0715	Yabawi	0.84
Harapan	19	9070	0.1072	Telaga maya	0.09
Expo	35	14877	0.0664	Espo	0.23
Tiaga Ria	24	7769	0.0667		n/a
Hendo	40	5815	0.0253		n/a
Belo	24	6733	0.0148	Jembatan 2	0.55
Waisyake	25	10598	0.0139		n/a

3.4 Materials and Methods

3.4.1 Sediment sampling

We collected surface sediment samples from 32 stations in the lake from water depths between 4 and 43 m, eight samples from river mouths from water depths less than 4 m and nine samples from rivers (Fig. 3.1.A, Fig. SI 3.1). Sampling positions were determined by a hand-held Global Position system (Garmin eTrex 10), and water depths were determined by an echosounder (Garmin 42DV). Sampling was conducted using a short gravity corer, retrieving cores of up to 20 cm in length, a diameter of 7 cm. Great care was taken to retrieve cores with an undisturbed sediment-water interface (SWI).

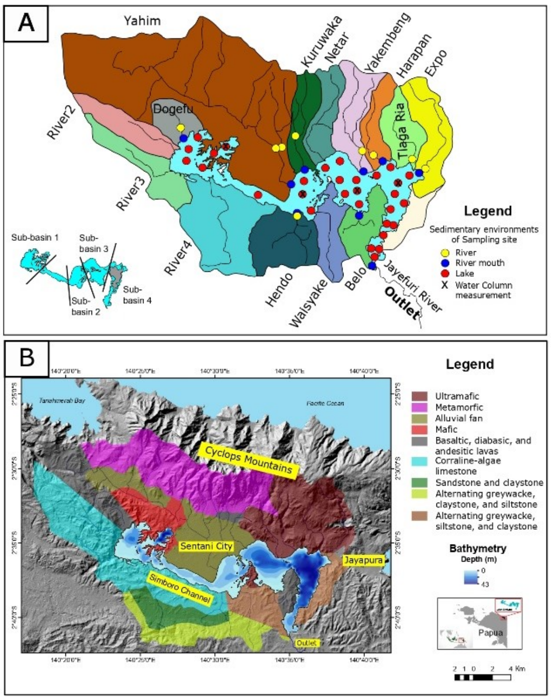

Figure 3.1 *Lake location and Setting. (A) Sampling sites and the Sub-catchments in Lake Sentani (digitized and modified after Sartimbul et al. (2015)). The circles indicate sampling sites in rivers (yellow), river mouths (blue) and lake (red). (B) Map of Lake Sentani and its surrounding watershed. Catchment lithology is indicated by different colours. The lithology of Lake Sentani's catchment is modified after Suwarna and Noya (1995). The low-resolution bathymetric map is modified after Sadi (2014).*

The material was sampled from the upper 5 cm, and each sediment sample was packed into a gas-tight aluminium foil bag and heat-sealed. Due to the unavailability of nitrogen gas, we tried to squeeze out as much air as possible, but some oxidation during storage and transport cannot be ruled out. Upon arrival in the home lab, the sediment samples were freeze-dried and ground to pass a 63 µm-mesh sieve before analysis completely.

3.4.2 X-Ray Fluorescence (XRF) scanning and data analysis

About 4 g of freeze-dried sediment powder was loosely packed in sampling cups (ca 2 cm high, Ø 2 cm) and covered with an XRF transparent foil. Analysis of elemental sediment compositions was performed on these samples using an ITRAX XRF core scanner with a Cr X-ray source (operated at 30kv, 55 mA, 10s).

XRF scanning analysis does not provide quantitative results but element intensities in counts per second. Relative element concentrations are provided by log-ratios of element intensities, which are free of physical and matrix effects (Weltje and Tjallingii, 2008; Weltje et al., 2015). In addition, log-ratio-transformed intensities allow the meaningful application of multivariate statistical analysis to characterize sediment compositions (Weltje et al., 2015). Normalized relative concentrations are expressed by standardizing (Z-score) the log-transformed data.

3.4.3 TOC Analysis

The concentration of TOC was determined by combusting between 15-100 mg of samples at 580°C in a Vario Max C analyzer (Elementar Analysensysteme GmbH). The limit of detection was 0.1 wt.%. The TOC data were also transformed and standardised to allow comparison of these quantitative data with the semiquantitative XRF data.

3.4.4 Pyrite quantification

For quantification of pyrite (FeS_2) and other sulfide minerals like FeS or MnS we performed a sequential cold chromium extraction (Kallmeyer et al., 2004). In short, 0.5 to 1 g of freeze-dried and finely ground sediment is placed in a distillation flask that is constantly flushed with nitrogen gas. Upon addition of 8 mL of 6N HCl and constant stirring, the acid volatile sulfur (AVS), mainly FeS and other monosulfides, are dissolved, and the liberated H_2S is transported by the flow of nitrogen into a trap filled with 7 ml of 5 wt% zinc acetate solution (ZnAc) where the H_2S precipitates as ZnS. After two hours the extraction is complete, the ZnAc trap is replaced by a fresh one and 16 ml of 1M $CrCl_2$ solution is added to the flask through a valve to maintain strictly anoxic conditions in the distillation flask. The chromous chloride acts as a strong reductant and will promote breakdown of more crystalline reduced sulfur species like disulfides (Canfield et al., 1986; Luther, 1987), of which pyrite is quantitatively most important. The H_2S that is liberated from the chromium reducible sulfur (CRS) is then also transported to the trap and precipitated as ZnS. The precipitates are centrifuged and the ZnAc-containing supernatant discarded as it interferes with downstream analyses. The ZnS pellet is resuspended in deionized water and sulfide is quantified photometrically using the methylene blue method (Cline, 1969). Data are presented as the percentage of total reduced inorganic sulfur (TRIS) on total dry sediment, and the fraction of AVS on TRIS.

3.4.5 Smear Slide analysis

Smear-slide analyses were conducted on 24 selected samples, covering all four sub-basins and all sedimentary environments. A small amount of sediment (1-2 mm^3) was picked from bulk wet sediment and dispersed in two drops of deionized water by swirling on a microscope slide to get a good particle separation and even distribution on the slide. The suspension was spread thinly to reach a just barely visible layer of sediment. The slide was dried on a hot plate at ~60° C. Once dry, the slide was covered by a cover slip mounted with two drops of low viscosity UV-glue (Ber-Fix 50-100, Ber-Fix Klebstoffprodukte Berlin, Germany). The glue was cured by exposing the slide to sunlight at room temperature until dry.

The 24 selected smear slides were studied for compositional characterization under a transmitted light microscope (Olympus BX 51). All components were characterized, and their relative abundance was visually estimated, with special emphasis on carbonate and mafic minerals, biogenic (diatoms and sponge spicules) and detrital silica content.

3.4.6 Grain-size analysis

Prior to analysis, organic matter was removed by adding 2.5 ml of 10 vol% H_2O_2 to bulk dry sediment aliquots of 0.5-0.7 g, followed by shaking for at least one week. If the reaction was still incomplete after one week, the treatment was repeated. Most samples were organic-free after one treatment, some organic-rich samples required a second round. The sediment residue was rinsed three times with 2.5 ml of de-ionized water followed by centrifugation and decantation of the supernatant. The sediment residue was then resuspended in 2.5 ml dispersion solution (35.7 g L^{-1} tetra-sodium diphosphate decahydrate, $Na_4P_2O_7 \cdot 10\ H_2O$) and placed in an overhead shaker for 24 hours at 25 rpm. After complete dispersion, the entire volume of suspended sediment was measured with a Horiba LA-950 laser diffraction particle size distribution analyzer, providing 92 grain-size classes between 0.011 and 2500 µm. Each sample was measured 10 times with ultrasonic excitation.

3.5 Results

3.5.1 Sediment composition

3.5.1.1 Chemical analyses

The relative distribution maps were produced with the QGIS 2.18.11 free software, using the IDW spatial interpolation method. Relative distributions of TOC and 8 major elements (Al, Si, S, K, Ca, Ti, Mn, Fe) in Lake Sentani as well as its main tributary rivers reveal compositional differences within the lake sediment and its main sediment contributors. Highest TOC concentrations of up to 27.9 $\%_{dwt}$ (percent dry weight) are found in Simboro Channel between sub-basins 1 and 2 and at the lake's only outlet at the southern end of sub-basin 4. Generally, TOC concentrations are slightly higher in the southern parts of sub-basins 2 to 4. River samples have much lower TOC concentrations (average around 1.5$\%_{dwt}$) compared to lake sediment samples (average ca 11.5$\%_{dwt}$).

Although relative concentrations differ, the distribution patterns of Al, Ti and K, all commonly associated with detrital minerals and known to be enriched in tropical soils, are generally similar (Fig. 3.2). Relative concentrations are highest in westernmost sub-basin 1 and decrease towards the east. River samples also reveal relatively high concentrations of the three elements with the exception of the Dogefu sub-catchment area at the north-western side of sub-basin 1, which shows low K and high Ti values. This pattern is surprising, given that the lake sediments of sub-basin 1 reveal an opposite pattern for these two elements (Fig. 3.2).

The distribution patterns of Mn and Fe are broadly similar with highest relative concentrations in the deep eastern sub-basin 4 and lower values in the three western sub-basins. However, there are subtle differences in the distribution pattern of these two elements within sub-basins 1 and 4. Throughout sub-basin 1 Fe shows low relative concentrations, whereas in the northeastern arm there is a strong enrichment in Mn. Iron values are high in the northern part of sub-basin 4, where the Tiaga Ria and Harapan sub-catchments drain into Lake Sentani. Sediment from the rivers draining these two catchments also reveal high relative Fe concentrations. Manganese concentrations rather follow bathymetry, with highest relative concentrations at the deepest part of sub-basin 4.

The distribution patterns of Si and S show that relative concentrations are evenly distributed throughout the lake (Fig. 3.2) whereas in river samples relative concentrations are much higher for Si and lower for S. Relative concentrations of Ca are highest in central sub-basin 2, where runoff from the sub-catchments Hendo and Waisyake enter the lake, both dominated by limestone of the Jayapura Formation, intercalated silt- & claystone and shale of the Makat Formation, and alluvial deposits. However, river samples reveal high relative Ca distribution in the Dogefu and Kuruwaka sub-catchments as well (Fig. 3.1.A, Fig. 3.2) but the lake samples closest to these rivers are apparently not affected. Silica shows a relatively even distribution with only minor positive or negative relative distribution peaks (Fig. 3.2), however, the smear slide analyses show that the sources of silica vary considerably (Fig. 3.3.A).

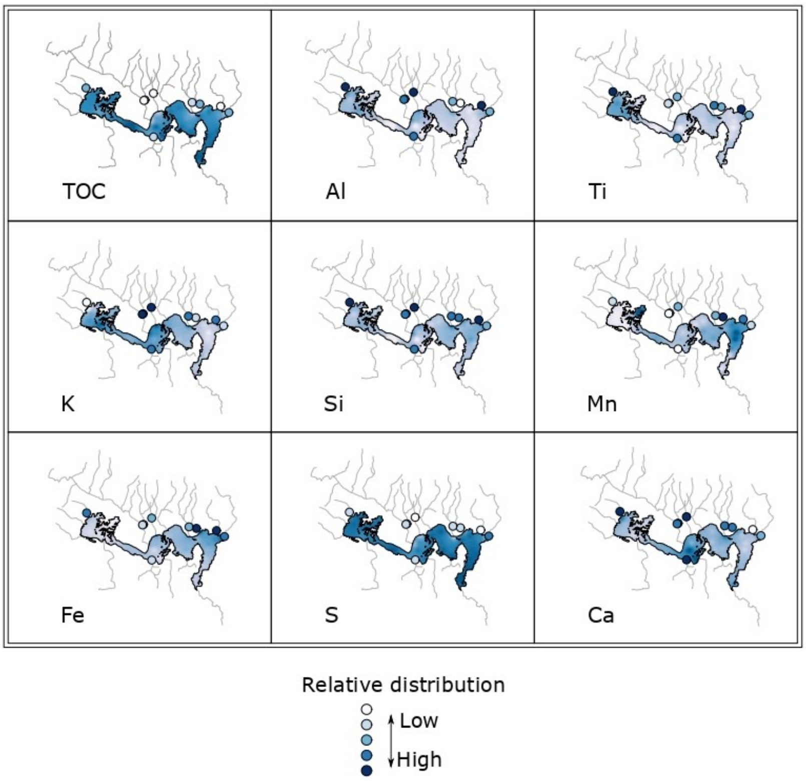

Figure 3.2 *Relative distribution of major elements in the surface sediment of Lake Sentani and its rivers. Sampling sites in rivers are marked by blue circles. Graduated colors indicate relative element distribution (Z-score, see text for details). The same scale was used for river and lake samples.*

3.5.1.2 Smear slide analyses

Smear slide analyses reveal the presence of diatoms and sponge spicules in almost all samples, together with detrital quartz grains (Fig. 3.3.A). Other siliceous compounds like phytoliths are only found in some lake samples but never play a quantitatively significant role. Biogenic compounds are much more abundant in the two deepest sub-basins 1 and 4 and in the deeper parts of sub-basin 3, whereas detrital silica dominates the shallow sub-basins 2, the southern part of sub-basin 3, as well as the river samples. The only notable exception is the single sample in the Simboro channel that has the highest relative abundance of spicules of all samples, and only about 50% detrital silica (Fig. 3.3.A, Table SI 3.1).

The smear slide analyses also confirm the dominance of the mafic and ultramafic geology on the sediment composition of the lake (Fig. 3.3.B). With the exception of the single sample at Simboro channel where mafics were rare, they were present in all other samples. Highest abundances were found in samples from rivers and river mouths, mostly at the northern end of sub-basins 2 and 4, an area that is predominantly characterized by mafic and ultramafic catchment geology. In samples from sub-basin 1 mafic minerals are present but less abundant than in the other sub-basins. The distribution of carbonates reveals the close relationship between catchment geology and sediment composition (Fig. 3.3.C). Samples closest to the limestone-dominated catchment located south west of the lake contain carbonates, whereas they were absent in all other samples. A notable exception is the presence of carbonate in a sample from the northeastern arm of sub-basin 1, which is entirely surrounded by mafic rocks.

3.5.1.3 Pyrite quantification

Pyrite and other reduced inorganic sulfur components could be detected in all samples with maximum concentrations of 5.4 $\%_{\text{dwt}}$ (percent dry weight), although some had TRIS (Total Reduced Inorganic Sulfur) concentrations as low as 0.01 $\%_{\text{dwt}}$ (Fig. 3.4.A). Overall, chromium reducible sulfur (CRS) is the quantitatively dominant reduced inorganic sulfur species. As pyrite is the only CRS species detectable by X-Ray Diffraction in these samples (Fig. 3.4.B), we assume that pyrite is in fact the dominant reduced inorganic sulfur species. Acid Volatile Sulfur (AVS, mostly monosulfides) accounts for less than 1 % of TRIS in most samples. Concentrations of AVS exceeding 10% TRIS were found only in samples from rivers that drain the ultramafic catchment north of the lake as well as in samples from the corresponding river mouths.

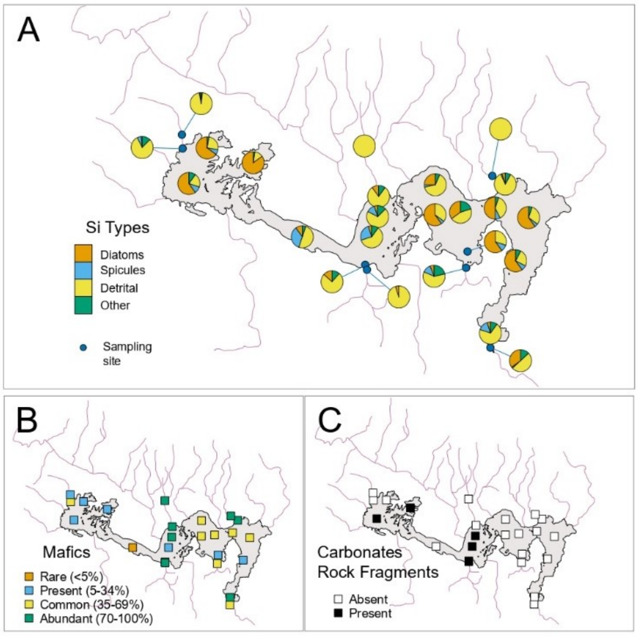

Figure 3.3 *Results of Si-speciation and proportions of mafic and carbonate rock fragments obtained from smear-slide analysis.*

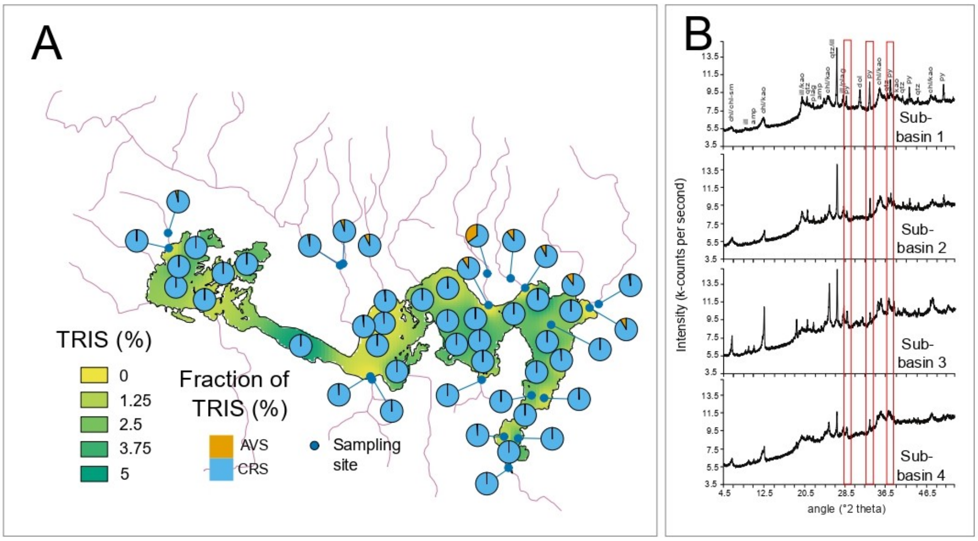

Figure 3.4 *Distribution of Total Reduced Inorganic Sulfur in Lake Sentani. Pie diagrams indicate in red the fraction of AVS (acid volatile sulfur, i.e. monosulfides) and in green CRS (chromium reducible sulfur, i.e. pyrite) among the Total Reduced Inorganic Sulfur (TRIS) pool at each sampling site. Total TRIS concentration is provided by graduated colors. (B) X-Ray Diffractograms of representative samples from each sub-basin. Pyrite is the only identifiable mineral that contains reduced sulfur.*

3.5.1.4 Grain size distribution

There are clear geographic differences in the distribution of the different grain size classes (Fig. 3.5). Clay (1-4 µm particle size) accounts for up to 34% of the sediment in the southern parts of sub-basins 1 and 2 and the connecting Simboro channel. In the northern parts of these two sub-basins and elsewhere concentrations are much lower and usually below 10 %. River samples show even lower clay contents in the low single-digit percent range. Silt (4-63µm particle size) makes up the bulk of Lake Sentani's sediment, accounting for up to 86% and shows an almost opposite distribution pattern to clay. Silt concentrations are lower in the southern parts of sub-basins 1 and 2 and the Simboro Channel, but with lowest concentrations still exceeding 35%. Silt content in river sediment varies over almost the entire concentration range with no visible pattern. Sand only makes up a comparatively small fraction of the lake sediment, concentrations are usually below 10%, higher values are only found around river mouths. Two samples from rivers draining the Yahim and Kuruwaka sub-catchments show high sand content of up to 52 %.

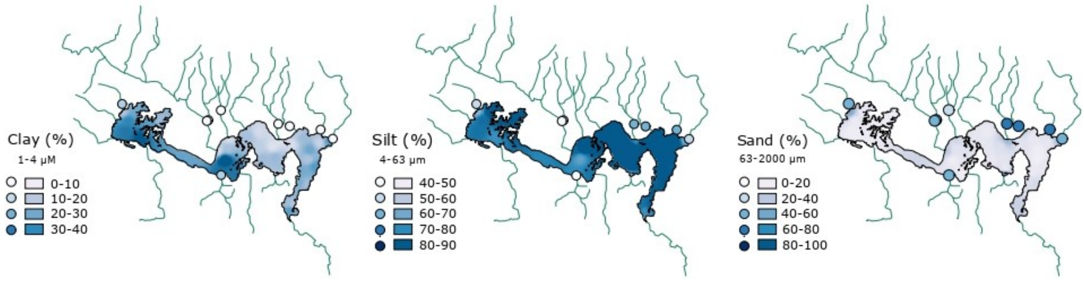

***Figure 3.5** Grain size distribution of Lake Sentani's surface sediment. For river samples the values are presented in circles.*

Multivariate analysis of the chemical composition of the sediment

Statistical clustering allows identification of sediment samples with similar geochemical compositions. Here we use Ward's hierarchical clustering after z-scoring of the clr-transformed data of the major elements obtained by XRF scanning and TOC. Ward's hierarchical clustering of the geochemical composition was analyzed by using PAST3

(Hammer et al., 2001) and principal component analyses (PCA) was carried out with prcomp in the R statistical package ‘composition’. A three-cluster-solution with an Euclidian linking distance of > 2.5 was chosen as it explains the largest differences in the dataset for the minimal number of clusters (Fig. SI 3.1).

Element correlations of each cluster are explored using PCA biplots of PC 1 and 2 (Fig. 3.6.A) that explain about 70% of the variance for all three clusters (C1 = 68.9%; C2 = 71.6%; C2 = 71.9%;). The clusters mainly comprise river and river mouth samples (cluster C1), lake samples from mostly shallow and near-shore (proximal) locations (C2), and deeper or more distal lake locations (C3). The river cluster (C1) show a clear separation between Ca and most of the detrital elements (Fig. 3.6.A) associated with the southern limestones and northern mafic catchment geologies, respectively. Although TOC concentrations are only low in river samples, TOC and S are orientated in the same direction along PC1 indicating the positive correlation. However, the positive correlation between redox sensitive elements (Mn, Fe) and the inert element Ti indicated by the same direction along PC2 (Fig. 3.6.A), suggest that degradation of organic matter and redox alteration of these sediments is neglectable.

Redox condition seems to intensify for samples of the shallow/proximal lake cluster C2, as show a positive correlation between TOC and the elements S, Mn and to a lesser extend Fe that all point in the same direction with respect to PC1. The deeper/distal lake samples of cluster C3 reveal a similar orientation of the both elements Mn and Fe along PC1 suggesting that reduced conditions prevail in these sediments (Fig. 3.6.A). Data distribution of cluster C3 reveals that the strongest redox conditions occur in the deepest part of the lake. The distribution of Ca (Fig. 3.2) is similar to the carbonate rock fragments (Fig. 3.3.C) and but deviates from the detrital elements Ti and K (Fig. 3.2), which is also apparent by the different directions/correlation of these elements (Fig. 3.6.A) The similar direction of the detrital elements Ti, K and Al indicates positive correlation of these elements in clusters C2 and C3 and association with sediments receiving input from catchments composed of siliciclastic rocks. In addition, river samples of C1 and lake samples of C2 and C3 reveal a different correlation between Si and detrital element Ti, K and Al, which is due to the abundance of diatoms and spicules in lake sediments (Fig.

3.3).

Most samples of cluster C2 are located above the oxycline and a few samples of sub-basin 3 are located around or the just below the, which is probably related to the less pronounced oxycline and stratification of this sub-basin (Fig. 2.2). The wide depth range of C3 shows that this cluster is more representative for lake sediments in general, ranging from oxic to anoxic. Within C1, highest PC1 factor scores are found in rivers in the north (Fig. 3.6.B), lowest values in the south. For the PC1 values of C2 there is no apparent geographic distribution pattern or visible correlation with water depth. Cluster C3 encompasses lake samples from shallow to maximum depth, with most of the deep lake sediment samples located below the oxycline. The PC1 values decrease with water depth and indicate stronger reducing conditions with increasing the water depth.

3.6 Discussion

Distinct geochemical differences between rivers and lake sediments are found using statistical clustering that can identify samples with similar elemental compositions and provides a more detailed look into the different geochemical characteristics of the sediment (Fig. 3.6, SI 3.2). The three clusters reveal a clear compositional differentiation between river and river mouth samples (cluster C1), lake samples from mostly shallow and near-shore (proximal) locations (C2), and deeper and more distal lake locations (C3).

Rivers and river mouths represented by cluster C1 reveal a clear separation between Ca and most other elements that matches finding of carbonate rock fragments (Fig. 3.3.C) and the special element distributions (Fig. 3.2). These distributions are associated with the contributions of different catchment geologies (Fig. 3.1). Moreover, the negative correlation between Ca and the elements Ti, Mn and Fe in cluster C1 (Fig. 3.6.A) can be associated to the limestone catchment located south of the basin and the iron- and manganese-rich mafic and ultramafic rocks in the Cycloop mountains in the north (Fig. 3.1.A). The influence of diagenetic transformations (Raiswell and Canfield, 2012) in the sediments of C1 is highly unlikely due to the low amounts of TOC (Fig. 3.2) and the positive correlation of Mn and Fe with the inert element Ti (Fig. 3.6.A). However, diagenetic transformation of Mn and Fe due to changes in redox chemistry does influence the sediments of clusters C2 and C3, which is probably caused by anaerobic organic matter degradation processes in the anoxic sediment, even under conditions with oxygenated bottom waters. Under oxygen-limited or anoxic conditions anaerobic reduction process can take place not just in the sediment but also in the water column and at the sediment-water interface and no re-oxidation of reduced species through diffusion of oxygen from the water column or burial of oxidized minerals into the sediment can take place.

Multiple processes influence distribution patterns of individual elements and organic carbon (TOC). The TOC concentrations of Lake Sentani sediment are highly variable (3-22% dwt) and range from values typical for oligotrophic tropical lakes like Lake Towuti (2-3,5%) to eutrophic ones like Lake Maninjau (~22%) (Henny and Nomosatryo 2012; Vuillemin et al., 2016). Despite this high variability, organic matter concentrations are sufficiently high to fuel abundant microbial respiration and therefore diagenetic processes in all samples.

Calcium-bearing sediments are delivered to the lake from limestone in the catchment areas located to the southwest of the lake, bordering sub-basins 1 and 2. Production of biogenic Ca-containing minerals by calcareous plankton does not seem to play a major role as carbonates are only found in five smear slide samples (Fig. 3.3.C). The distribution of Ca in the sediment (Fig. 3.2) correlates well with the smear slide data (Fig. 3.3.C) and catchment lithology (Fig. 3.1.B). The strong influence of catchment geology on Ca distribution is also corroborated by the distribution map of the Ca/Ti ratio (Fig. 3.7) showing highest values in sub-basin 2 around the Hendo sub-catchment, which is mainly composed of carbonate rocks. Slightly higher amounts of Ca and Ti in the northwestern corner of sub-basin 1 (Fig. 3.2) seems to originate from the basalts that make up most of the Dogefu catchment (Fig. 3.1.A). River samples have relatively high amounts of Si (Fig. 3.2), whereas lake samples show some minor variations in Si but no distinct distribution pattern. The Si/Ti ratio (Fig. 3.7) does show a strong enrichment towards the deepest part of sub-basin 4 (Fig. 3.7), which broadly correlates with a higher percentage of diatoms among the siliceous sediment constituents. However, in sub-basin 1 the silica fraction is also dominated by diatoms (Fig. 3.3), but the Si/Ti element ratio shows the opposite pattern of sub-basin 4. The very low Si/Ti ratios in sub-basin 1 are most probably caused by higher amounts of Ti in these sediments, which are higher than anywhere else in the lake.

Generally, the distribution of Si/Ti (Fig. 3.7) matches the distribution of diatoms in lake Sentani (Fig. 3.4.A). Near-shore samples contain up to ~60% detrital Si, it appears that the input of Si-bearing minerals from rivers is equal to or even dwarfed by higher biogenic Si concentrations in the deeper basins. Although no data are available on the hydrodynamics in Lake Sentani, we speculate that sediment focusing can increase diatom frustule concntrations in the deepest parts of sub-basin 4, and perhaps 1 as well.

The delivery of Ca, which is almost exclusively derived from the catchment, the rivers do not seem to have much influence on sediment composition, which matches the occurrence of carbonate rock fragments. There is also no increase in the percentage of sand at the river mouths, despite all river samples having a higher sand content (Fig. 3.5).

Particularly in lake sediments with ultramafic catchment geology, iron concentrations are generally high and play an important role in biogeochemical processes (Costa et al., 2015; Morlock et al., 2018; Sheppard et al., 2019). An interesting observation are the elevated concentrations of monosufide minerals (AVS fraction) in samples from rivers that drain ultramafic catchment areas (Fig. 3.4.A). In all other samples from both rivers and the lake itself, AVS was present only in trace amounts and the CRS fraction, containing mostly pyrite, dominates the reduced inorganic sulfur species. With the exception of sub-basin 1, overall pyrite distribution showed a weak correlation with water depth. This follows the general observation that microbial sulfate reduction, the main producer of hydrogen sulfide, only occurs under reducing conditions (Widdel, 1988) and therefore preferentially below the oxycline. However, oxygen penetration into the sediment is expected to be in the range of only a few mm, allowing for sulfate reduction throughout the lake's sediment. Depending on the availability of suitable metal ions, the produced hydrogen sulfide precipitates as metal sulfides. Given that iron is the most abundant metal ion in most sedimentary systems, pyrite is the most likely end product (Berner, 1984), which is also the case in Lake Sentani, as pyrite is the only reduced sulfur species detected by XRD (Fig. 3.4.B). Sulfate concentrations in Lake Sentani are around 2 mg L^{-1} (data not shown), which is less than one thousandth as concentrated as in seawater. But even in freshwater lakes with lower sulfate concentrations, e.g., ferruginous lakes like Lake Matano or Towuti (Crowe et al., 2014; Vuillemin et al., 2016), production of hydrogen sulfide and therefore pyritization takes place, albeit on a very low level (Vuillemin et al., 2016, Friese et al., 2021). The distribution maps of TOC, Fe and S (Fig. 3.2) do not show a uniform pattern and in the PCA of the three clusters the vectors for these three elements show a different orientation in each cluster (Fig. 3.6.A). The sample from the Simboro channel reveals highest sedimentary pyrite concentrations (Fig. 3.4.A) as well as elevated concentrations of TOC and S, (Fig. 3.2) which we interpret as a strong indication for elevated rates of sulfate reduction in this area. However, the low concentration of sulfate in the lake water limits the overall rate of sulfate reduction, which severely reduces the quantitative importance of sulfide minerals as a sink for iron and manganese.

3.6.1 Geochemical characteristics of each basin

Due to the lake’s peculiar shape and the highly diverse catchment, it is necessary to not simply consider the overall characteristics of the sediments but also on the level of the individual sub-basins. The daily strong winds keep the epilimnion well mixed and the basins share a common surface water chemistry (data not shown), but due to the highly diverse catchment geology each sub-basin receives a different sedimentary input. Given the steep slopes of the deep basins we argue that the water columns of at least sub-basins 1 and 4 remain well stratified throughout the year with little chances of complete overturn, although it cannot be completely ruled out, given the lake’s relatively small size.

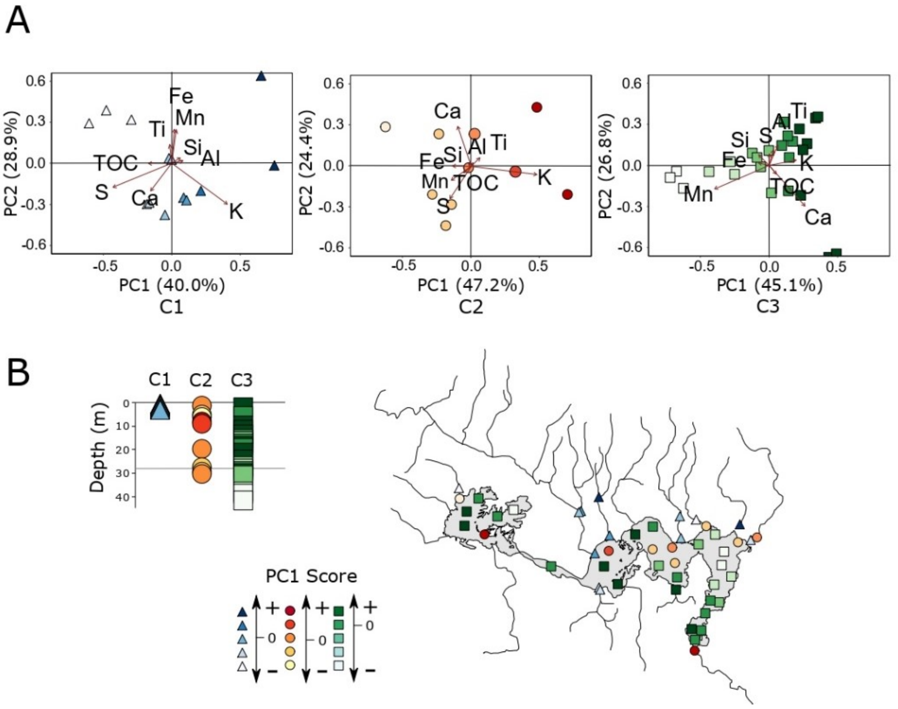

Figure 3.6 *Multivariate analyses including clustering of the relative elemental concentrations of the bulk sediment. A) Ward's hierarchical clustering of relative elemental concentrations results in three main clusters with distinctly different correlations. B) Distribution of samples of the three different clusters, colors indicate their respective PC1 factor score. The inset shows the depth distribution of the samples of each cluster.*

In westernmost sub-basin 1 there are two peninsulas with steep slopes on the north-eastern shore that reach far into the sub-basin (Fig. 3.1.A). Mass wasting and direct runoff from the slope could be a possible supply mechanism for significant amounts of terrestrial material to the lake (Trescases, 1973; Hasberg et al., 2019), and in this case almost to the center of the basin. Input through rivers seems to be small and only seasonal in this sub-basin (Table 3.1). However, given the relatively high clay content in the southern part of the sub-basin and the dominance of silt in the north, particularly around the two peninsulas, plus very low sand content throughout sub-basin 1, and the very dense vegetation cover that provides effective protection against erosion, mass wasting also does not seem to be quantitatively important, but cannot be ruled out. Moreover, the two peninsulas have a mafic bedrock geology, but the sediments around them do not show elevated amounts of Fe, which also argues against a significant sediment input from the peninsulas. Instead, the sediment composition with higher amounts of Al, K, and Ti could rather be the result of the deposition of clays and silt that originate from chemical weathering of limestone and argillaceous sedimentary rocks from the southern part of catchment.

Due its significant water depth of 42 m, sub-basin1 has a geochemical signature similar to the other deep sub-basin 4, despite all sites being relatively close to land. The rivers that drain into this sub-basin have relatively small discharge rates (Table 3.1) and some might only have water during rainy season (Handoko et al., 2014). The steep morphology in the north of the sub-basin suggests that eroded material could easily be mobilized and transported quickly by rivers, mass wasting or direct runoff from the slope. However, our data show that this is in fact not the case, as the sediments in sub-basin1 has a more siliciclastic signature whereas the catchment in the north has a mafic composition. Literature data about the rivers are sparse and do not cover all rivers, access to the area is difficult and we were not able to sample all rivers draining into this basin, so there might be a slight mismatch between river input and sediment chemistry in our study.

The long and shallow Simboro channel between sub-basins 1 and 2 is a very efficient sediment trap that effectively isolates sub-basin 1 from the rest of the lake. The channel has a depth of about 4 m and is suspected to become even shallower in the future due to sediment deposition caused by the abundant water plants that act as efficient sediment traps (Kementerian Lingkungan Hidup Republik Indonesia, 2011). A peculiar phenomenon is the strong enrichment of TOC and S in the middle of the channel (Fig. 3.2). The high TOC concentration in the channel is most probably caused by an accumulation of decaying aquatic plants and the elevated S concentrations indicate enhanced sulfate reduction fueled by organic matter degradation, which is further corroborated by the high pyrite concentrations (Fig. 3.4).

The relatively flat topography around sub-basin 2 continues inside the lake. Sub-basin 2 is the shallowest of the four basins with a maximum depth of about 12 m. It is the only sub-basin with a fully oxygenated water column and hence, aerobic processes at the sediment-water interface. We did not measure how far oxygen penetrates into the sediment but based on our experiences from other oligotrophic lakes in Indonesia and literature data (Corzo et al., 2018), we assume that penetration depth is much less than 5 mm. Still, even with such a thin oxygenated surface layer, a significant part of the sedimentary organic matter will be degraded aerobically because aerobic degradation is much faster (Kristensen et al., 1995), decreasing the overall concentration of organic matter in deeper anoxic layers and increasing the fraction of more recalcitrant material (Westrich and Berner, 1984). The diverse lithology of the different catchments is partially reflected in the element composition (Fig. 3.2) and the clustering results (Fig. 3.6). Calcium shows a very strong enrichment along the southern end of the basin (Fig. 3.2) and so does the Ca/Ti ratio (Fig. 3.7), reflecting the carbonate-rich geology of the catchment.

The geochemical characteristics of the sediment in sub-basin 3 lead to rather peculiar results of the clustering analysis. While samples from the deep lake cluster C3 are found in shallow water, the shallow lake cluster C2 occupies the deep center of the basin. This might be caused by the fact that oxygen concentrations in sub-basin 3 barely reach depletion at the SWI, providing the potential for repeated oxygenation-reduction cycles that can promote mineral precipitation. Those samples from sub-basin 3 that fall in cluster C2 show negative PC1 values (Fig. 3.6.B), indicating a positive correlation with Fe and Mn and partially S. Those samples that fall into cluster C3 have a positive PC1 score, revealing a positive correlation with elements indicative of detrital input from siliciclastic rocks. Elemental distributions (Fig. 3.2) and element ratios (Fig. 3.7) do not show any particular enrichments in this basin, with the exception of a decreasing north-south gradient of the Fe/Ti ratio, most probably caused by the greater input of Fe from the Cycloops Mountains in the north.

Samples from sub-basin 4 fall almost entirely into Cluster C3, most probably due to greater water depth and the strong riverine input of Fe and Mn from the mafic and ultramafic catchment on the northern shore. There are 3 rivers with a total discharge of 0.9 $m^3 s^{-1}$ draining into sub-basin 4, but only one river with 0.36 $m^3 s^{-1}$ into sub-basin 3 (Table 3.1). The Yabawi river, which drains the Yakembeng sub-catchment enters Lake

Sentani close to the sill between the two basins so we cannot assign it to either basin. A peculiar feature of sub-basin 4 are the enrichments of Fe and Mn (Fig. 3.2), although in different locations for each element. While highest amounts of Mn and Mn/Ti ratios are found in the deepest part of the sub-basin, Fe show a general decrease from north to south and no correlation with water depth. The Fe/Ti ratio (Fig. 3.7) however, reveals a distinct minimum at the deepest part of the sub-basin and a gradual increase towards the southern end of the sub-basin where the only outlet is located. We interpret this pattern as a combination of different processes. A strong riverine input of Fe from the ultramafic catchments in the north of the lake leads to higher amounts of Fe and Fe/Ti ratios right along the river mouths of the northern shoreline and in near-shore locations in deeper water, given the very steep slope in this area. It is surprising that only Fe shows such a distribution pattern and not Mn, considering that ultramafic rocks also contain considerable amounts of Mn. Here it seems that Fe behaves more like a detrital element, whereas Mn shows the behavior of a redox-sensitive element. We can only speculate about the reasons, detailed mineralogical studies that are beyond the scope of this study might be able to shed light into this phenomenon.

The deepest part of sub-basin 4 has fully reducing conditions, yet it reveals high amounts of Mn as well as highest Mn/Ti ratios. Under such conditions Mn should be reduced and highly soluble. At first glance the massive enrichment of Mn in the deepest part of sub-basin 4 suggests at least occasional complete overturning, as oxidation of the bottom water would lead to oxidation and precipitation of dissolved Mn. However, the lack of concomitant iron enrichments argues against overturning: Iron is also abundant in Lake Sentani and has similar redox behavior as Mn. It remains questionable whether the faster oxidation and dissolution kinetics of Fe in comparison to Mn (Martin 2005) could explain the specific enrichment of Mn but not Fe in the deepest part of sub-basin 4. Unfortunately, our XRD results (Fig. 3.4.B) do not reveal any Mn-rich mineral in sub-basin 4, so we do not know in which mineral the Mn is bound.

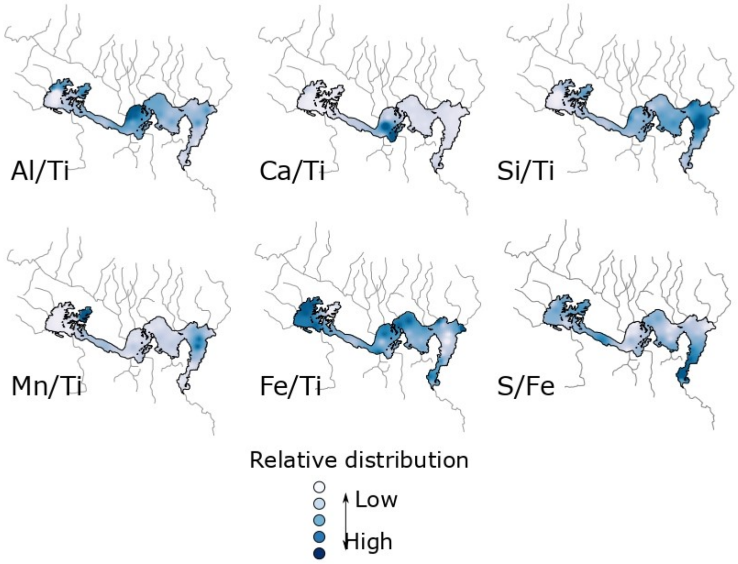

Figure 3.7 *Distribution of selected element ratios of sediment from river mouth and lake samples.*

Transport processes also do not seem to play a major role in sub-basin 4 as there are no obvious patterns in the distribution of the different size classes (Fig. 3.5). The PCA of Cluster C3 shows an almost perfect correlation between location and PC1, the most negative PC 1 values, strongly correlating with Mn, are found in the center of the basin, and steadily increase towards the south (Fig. 3.6.B), indicating a correlation with mainly Al and Ti. This is not surprising, given the fact that both the eastern and western shores of this narrow sub-basin are bounded by clay- and siltstones and alluvial fan deposit (Fig. 3.1.B). Although these rocks have a rather diverse geochemical signature, what they have in common is the different composition in comparison to ultramafic rocks in the north. Moreover, the narrow and shallow shape of the southern end of the sub-basin allows for complete mixing and resuspension of material during storm events at least in this this part. Such events probably remove most small-scale differences between the different sediment sources.

The recent study of Nomosatryo et al. (2021) presents geochemical depth profiles of sediment cores from each sub-basin, showing clear compositional differences between sites and with depth, and each sub-basin shows distinctly different trends. The present study focuses just on the sediment surface, albeit in higher spatial resolution. The geochemical data presented in both studies highlight the fact that studies addressing climate or hydrological variations based on lacustrine sediment records should use great care to distinguish between site-specific characteristics, which can be influenced by a great variety of processes, and variations caused by regional changes in climate or hydrology.

3.7 Conclusions

The overall patterns in geochemical composition between the different sub-basins and within each individual sub-basin are mainly caused by a combination of catchment geology and redox chemistry. Catchment geology seems to be the most important factor, the most obvious examples are the relative enrichment of iron, manganese and mafic minerals in those parts of the lake that are bounded by ultramafic catchment, as well as the presence of carbonates only in areas with a connection to catchments that are dominated by either carbonate rocks or basalts. The effects of transport processes appear to be only minor. The lake itself has an almost bimodal distribution of clay and silt that does not correlate with any other parameter, and sand only makes up a minor proportion of the total sediment and is very evenly distributed across the lake, despite having much higher concentrations in the rivers. Although we do see a clear influence of catchment geology on lake sediment composition, the rivers do not seem to leave a major imprint on the lake, neither with regard to grain size distribution nor chemistry. Mass wasting or direct runoff does have an influence on sediment chemistry, one example is the change in sediment composition in the southern part of sub-basin 4, where the compositional change correlates with the more siliciclastic catchment geology on both sides of this part of the sub-basin. However, the fact that there is no increase in grain size argues against mass wasting, so the final verdict about the influence on mass wasting on overall sediment composition is still out.

4 Investigation of Microbial Communities highlights anthropogenic influences across Lake Sentani, River, and Lake sediments

4.1 Abstract

Lake Sentani is a tropical lake in Indonesia consisting of four interconnected sub-basins of different water depths. While previous work has highlighted the impact of catchment composition on biogeochemical processes in Lake Sentani, little is currently known about the microbiological characteristics across this unique ecosystem. With the historically rural surrounding area facing continuous population growth, the anthropogenic impact on Lake Sentani and its microbial life is also increasing. Here we present a detailed microbiological evaluation of Lake Sentani, analyzing 49 different sites across the lake, its tributary rivers and their river mouths to assess diversity and community structure using 16S rRNA sequencing. Our results emphasize distinct communities in lake and river sediments, supporting differences in geochemical characteristics at these sites. Taxonomic assessment showed the potential impact of anthropogenic pressure along the northern, urbanized shore, as samples were characterized by Bacteroidota, Firmicutes and Cyanobacteria. In contrast, lake sediment communities were dominated by sulfate-reducing bacteria, *Methanomethylicia*, Bathyarchaeia and Thermoplasmata, supporting the role of thermophilic, acidophilic and methanogenic Archaea in tropical lake systems. This study provides novel insights into ecological functions of tropical lakes and contributes to the optimization of management strategies for Lake Sentani, ensuring its holistic preservation in the future.

Keywords: Microbial communities, tropical lake, limnology, surface sediment.

4.2 Introduction

Living microorganisms represent the most significant proportion of biodiversity on Earth and play an essential role in biogeochemical processes across aquatic ecosystems (Tranvik et al., 2009). Microbial communities especially contribute to the nutrient exchange between terrestrial and aquatic ecosystems. They are crucial players in the biogeochemical cycling of organic matter as well as the biodegradation and biotransformation of pollutants (Kirchman, 2002; Ruiz-González et al., 2015). Thus, microbial communities are shaped by their surrounding environment and represent major indicators for the state and fitness of a functioning ecosystem (Lau & Lennon, 2012; Zaghloul et al., 2020). Understanding the link between ecosystem functioning and distribution of microbial diversity is therefore crucial to predict the response of the ecosystem to a changing environment.

Lakes contribute disproportionately to global elemental cycles and support a wide suite of ecological functions (Anderson et al., 2020; Tranvik et al., 2009). They represent critical freshwater resources and especially in rural areas play an important part in providing economic and societal stability.

Climate and anthropogenic impacts are two of the most important factors impacting the health of aquatic ecosystems in general, and. Lakes specifically. Both factors can directly or indirectly drive the development of richness and diversity of a local microbiome and significantly affect how well an ecosystem functions. Human activities, including land-use changes as well as industrialization have been shown to seriously threaten the structure and function of aquatic lake ecosystems, resulting in increased nutrient load, algae blooms, and erosion events (Nwosu et al., 2023; Qi et al.,, 2020; Søndergaard & Jeppesen, 2007). Growing populations surrounding lake water systems can trigger a higher anthropogenic nutrient input to the lake, decreasing water quality and diminishing biological diversity (Gao et al., 2015; Zan et al., 2012). The Anthropocene and the global climate crisis pose new challenges to environmental health, particularly in freshwater systems. Evaluating the extent of anthropogenic stressors on lakes, their potential impact on ecosystem health and link to evolutionary changes is therefore pivotal.

About 40% of the lakes on Earth, representing almost one-third of global lake surface area, lie within tropical latitudes and within areas, that have seen rapid changes and increasing levels of urban development in the last decades. It is well-understood that tropical ecosystems are different in many ways from those of temperate regions. Warm climate (>18°C, Feeley & Stroud, 2018), higher solar radiation, and precipitation rates have essential consequences for biogeochemical processes in tropical ecosystems (Lewis, 1987). The lack of seasonal temperature fluctuations leads to a stable temperature gradient in the water column that is not disturbed by changing surface water temperatures. For instance, annual temperatures in Jakarta range from 32.5 to 37.7ºC (Maru & Ahmad, 2014). These temperature ranges represent optimum conditions for mesophilic growth over the entire year (Aragno, 1981), providing the basis for significant microbial turnover and large biomass production in tropical lake systems.

The water column in a tropical lake is often stratified with a well-mixed oxic surface water (epilimnion) and a denser, sometimes anoxic, deep layer (Hypolimnion) (Katsev et al., 2009). There is no turnover in the entire water column because of a lack of major seasonal changes. The stably stratified water column and the anoxic bottom water provide optimal conditions for undisturbed sedimentation due to a lack of resuspension and bioturbating organisms. These unique characteristics of tropical lake systems result in lacustrine surface sediments exhibiting great heterogeneity regarding their geochemical composition, resulting from geographical, hydrological and topographical variations in the catchment and are believed to harbor a distinct microbial community susceptible to changes in the physicochemical state of lake sediments (Ramsey et al., 2005; Vuillemin et al., 2017). Their unique characteristics make tropical lakes very sensitive to increases in nutrient supply and susceptible to changes in water quality and biotic communities in response to eutrophication (Molot et al., 2021). Tropical lakes are also more likely to lose deep-water oxygen, as they are permanently stratified. Thus, to maintain a functioning ecosystem, tropical lakes commonly underlie more stringent regulation of organic and nutrient loading than temperate lakes (Kilham & Kilham, 1990; Lewis, 2000; Muvundja et al., 2009; Sepulveda-Jauregui et al., 2018).

Despite the environmental and socio-economic importance of tropical aquatic ecosystems, the role of microbial communities and the interaction of microbes within complex aquatic networks in tropical regions remains limited, especially when compared to temperate regions (Amado & Roland, 2017; Humbert et al., 2009; Jørgensen, 2000; Meier et al., 2019; Ruiz-González et al., 2015). Limited work in this research area has focused on biochemical processes at the sediment-water interface (SWI) (Steger et al., 2011), and environmental changes (Han et al., 2020; Saarenheimo, 2015; Wang et al., 2018), however only a small number of studies have evaluated microbial distribution, diversity, or metabolism in tropical ecosystems and shown major differences to temperate regions (Humbert et al., 2009; Rochelle-Newall et al., 2015; Tripathi et al., 2012).

Although, bacterial communities in tropical lakes have been suggested to be generally similar to their counterparts found in temperate lakes, abundant in Actinobacteria, Proteobacteria, and to a lesser extent Bacteroidetes and Cyanobacteria (Humbert et al., 2009; Moguel et al., 2021), but certain differences, for example in the composition of Betaproteobacteria, have been observed (Humbert et al., 2009). Microbial communities in tropical lakes also depend on water column conditions and are influenced by the surrounding catchment. For example, in Lake Kivu, which contains high concentrations of naturally occurring methane gas (CH_4), Crenarchaeota are dominant and are believed to play an important role in methane production (Llirós et al., 2010). Analysis of sediments from Lake Towuti (Indonesia) revealed exogenous sources of eDNA related to soils reworked from the ferruginous catchment (i.e., Actinobacteria, Verrucomicrobia, Acidobacteria), while a very limited number of sequences from primary producers (i.e., Cyanobacteria) and high abundances of Chloroflexi and Planctomycetes suggests substantial degradation of sinking organic matter and planktonic microorganisms (Vuillemin et al., 2017).

Current lack of a solid understanding of tropical lake processes, especially on factors like biology, seasonality and water quality hinders efforts to manage and conserve lake ecosystems. As lakes located across temperate latitudes have been significantly affected by increases in population density and changes in land use and cover in the catchment (Lewis Jr, 2000), the role and impact of such human activities needs to be the focal point of ongoing and future research efforts targeting tropical lake systems.

To fill the gap in knowledge about microbial communities in tropical, lacustrine sediments and evaluate the effect of urban development and land use, we studied the microbial composition and diversity of surface sediments in Lake Sentani, located in Papua Province, Indonesia (2.6° S, 140.5° E). Lake Sentani is characterized by its unique shape, as it is divided into four sub-basins, of which three are separated by shallow sills and one by a narrow natural canal (Indrayani, 2015; Sadi, 2014). The catchment is geologically diverse, ranging from carbonates over clastic sediments to igneous and metamorphic rocks (Suwarna & Noya, 1995). While the southern shores of the lake are largely rural and only sparsely inhabited, the inhabited areas around Sentani City and Jayapura have constantly expanded. Over the last decade annual population growth in Jayapura Regency is 2.5% (BPS Kabupaten Jayapura, 2020), especially in the sub-districts located in the northern part of the lake (Figure 1), bringing along an increase in anthropogenic pressures, leading to increased nutrient fluxes to the lake (Walukow et al., 2008). Consequently, indicators for eutrophication have already been observed in lake Sentani over the last years (Indrayani, Nitimulyo, et al., 2015; Pattiselanno, 2013). In addition, land-use changes in lake Sentani's catchment have been suggested to cause erosion and flooding (Bungkang et al., 2014; Koyari & Asmaranto, 2018; Mujiati et al., 2021).

Some lakes in Indonesia are already facing a massive decline in water quality, indicated by frequent incidents of mass fish deaths. For instance, in Lake Maninjau, West Sumatera, mass fish kills occur frequently, especially affecting cage farming, due to the deterioration of lake water quality (Hafrijal, 2016; Makmur et al., 2020; Yuniarti et al., 2021). To anticipate further ecosystem decline, the government of the Republic of Indonesia has selected Lake Sentani as one of the fifteen national priority lakes for being managed and restored (Perpres No. 60, 2021)

While recent studies have characterized Lake Sentani's water column and sediments from a limnological and geochemical perspective (Nomosatryo et al., 2022, 2021), there is currently no data available on microbial diversity in the lake. As microbes play an important role in biogeochemical processes, are highly abundant in aquatic systems, from the bottom of the food web, and are usually very susceptible to environmental changes, they are useful indicators to assess ecosystem health and function.

We hypothesize that increases in anthropogenic activity over the last decade, particularly along certain areas of the catchment directly or indirectly influence microbial communities in lake Sentani's habitats and sub-basins. Consequently, microbial communities residing in areas closer to human development (e.g., draining rivers and shore adjacent) may be more impacted by these events and potentially enriched in coliforms, pathogens, and/or indicators for eutrophication, such as Cyanobacteria. Finally, geological and environmental factors, including water depth, proximity to and runoff from populated areas vs. unpopulated areas are also believed to be driving factors in shaping microbial composition. Although oxic water columns are present in certain lake locations, sediments are anoxic (due to low penetration depth) and therefore expected to be enriched in anaerobic microorganisms.

To address our hypothesis, we employed genomic, 16S rRNA based analyses to investigate microbial community structure and diversity in surface sediments across Lake Sentani and from ten river and river mouth locations along the shores of Lake Sentani. We also studied distribution patterns of the microbial populations to understand the niche differentiation potential for microorganisms across the different habitats of Lake Sentani. Using bioinformatic and statistical tools we were able to evaluate the environmental and anthropogenic impact on Lake Sentani microbial communities.

4.3 Site Description

Lake Sentani is located near Jayapura, the capital city of Papua Province and lies at an elevation of 73 m asl. The lake covers an area of about 600 km^2 and is bounded by Cyclops Mountains to the north (Tappin, 2007) and lowlands to the south. The north side of the lake is dominated by volcanic breccia, mafic, ultramafic rocks, and alluvial deposits. In contrast, the southern part of the lake is dominated by limestone of the Jayapura formation, siltstone & claystone of the Makat formation, and alluvial deposits (Fig. SI 4.1.A) (Suwarna & Noya, 1995).

There are eight administrative sub-districts located in the catchment area of Lake Sentani (Figure 4.1.A). Most of the sub-districts located in the northern part of the lake have a higher population than the southern part of the lake (Figure 4.1.B). Heram and Sentani sub-district are central settlements in the lake Sentani catchment area.

At least sixteen rivers drain into the lake (Kementrian Lingkungan Hidup Republik Indonesia, 2011; Handoko et al., 2014). The most significant sub-catchment area is the Yahim River, located on the north side of the lake. It covers five sub-districts (Depapre, Sentani Barat (West Sentani), Waibu, Sentani and a half of Ravenirara sub-district) and almost 38% of the total catchment area of Lake Sentani (Fauzi et al., 2014). Twelve rivers come from the Cyclops Mountains on the northern side of the lake, and four rivers originate from the lowlands in the south. Doyo River in the Yahim sub-catchment is the biggest single water source to the lake, with an average discharge of 18.98 m^3/s (Handoko et al., 2014). The only outflow of the lake is the Jayefuri River on the south-eastern tip of sub-basin 4.

The lake is irregularly shaped with approximate dimensions of 28 km (East to West) by 19 km (North to South) and a surface area of 9,630 ha (Kementrian Lingkungan Hidup Republik Indonesia, 2011). Lake Sentani consists of four separate basins which are characterized by maximum water depths ranging between 12 to 43 m at the center (own measurements). Literature values range from 30 m (Sadi, 2014) to 70 m (Indrayani et al., 2015). Shallow sills with a maximum depth of 6 m connect three sub-basins, the fourth sub-basin is connected via the Simboro Passage, a shallow natural canal (Fig. SI 4.1.A).

The geochemical composition of surface sediment and geochemical characteristics of water column and porewater sediment in the four different basins was described by Nomosatryo et al. (2021, 2022). There are differences in the vertical structure of the water column between the sub- basins. The oxycline depth ranges between 25 to 30 m.

4.4 Material and Method

4.4.1 Sample selection and collecting

Surface sediment samples were collected from the upper 3-5cm, using Ekman grabs from 30 locations within Lake Sentani. Nine samples were taken from the river mouth and ten samples from the main rivers that drain into the lake (Fig. 4.1.A). The samples were transferred into 2 mL screw cap microtubes by using an aseptic spatula. The river mouth and lake surface sediment samples were collected in the open air on the boat. Samples were stored at 4ºC during sampling and transportation and frozen at -20ºC until extraction was done at InaCC-LIPI (BRIN) laboratory, Cibinong, Indonesia.

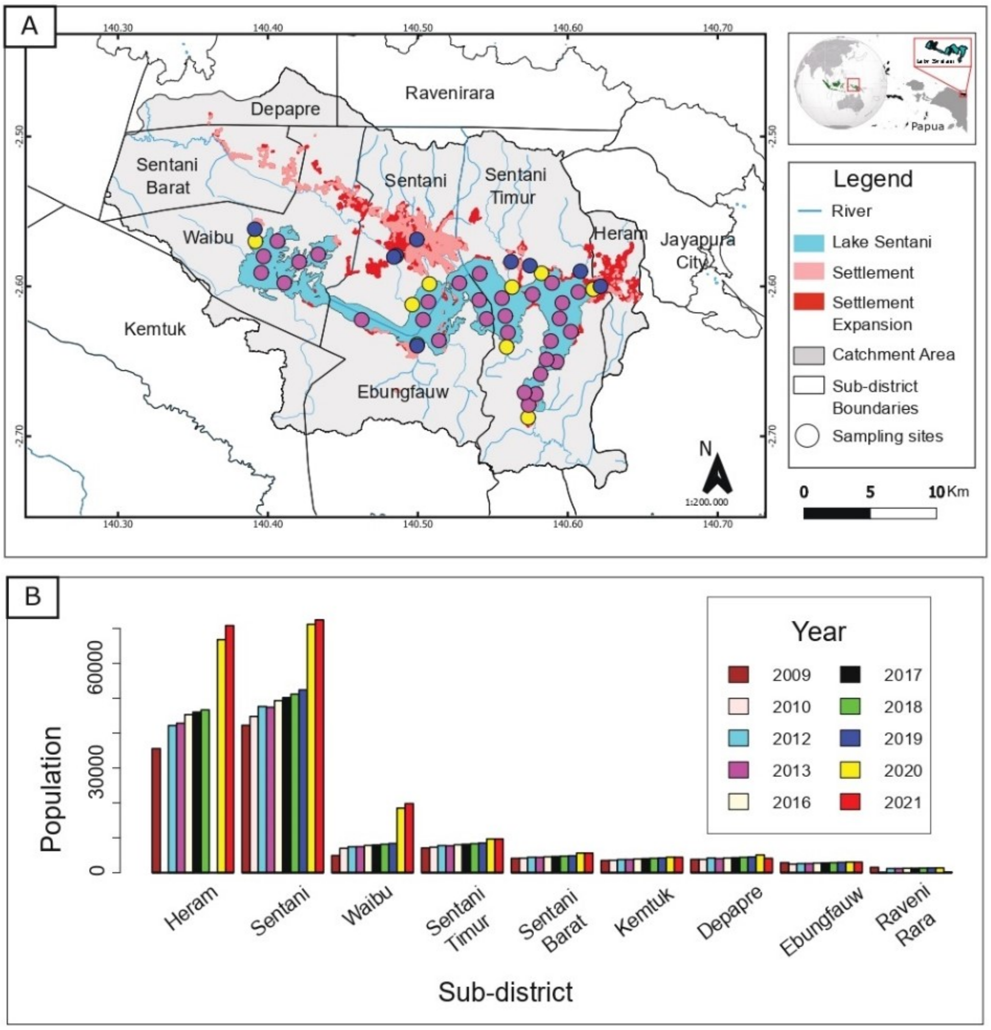

Figure 4.1 Lake location and setting. A) Sampling sites and sub-districts in Lake Sentani. A colored circle symbol indicated sampling sites. Blue, yellow, and purple colors for river, river mouth, and lake sampling sites, respectively. The red color indicates the settlement expansion from 2002 to 2017. B) The population by year in sub-districts surrounding Lake Sentani (BPS Kabupaten Jayapura, 2010-2022).

4.4.2 DNA extraction and purification

The total genomic DNA was isolated using the FastDNA TM SPIN Kit for soil (MP Biomedicals, Eschwege, Germany) following manufacturers' instructions. The homogenization was done by using a vortex. DNA was extracted from each sample in duplicates and two extraction blanks were included for each batch of extractions. The quality of the extracted genomic DNA was assessed visually via gel electrophoresis and DNA concentrations were quantified with the Qubit2 system (Invitrogen, HS-Quant DNA, Waltham, USA).

4.4.3 Illumina sequencing

Unique combinations of tagged 515F (5′-GTGTGYCAGCMGCCGCGGTAA -3′) and 806R (5′-CCGGACTACNVGGGTWTCTAAT -3′) primers targeting the V4 region of the 16S rRNA gene were assigned to each sample and the targeted region was amplified using Polymerase Chain Reactions (PCR) on a T100™ Thermal Cycler (Bio-Rad Laboratories Inc., CA, USA) in 25 µL reactions. Each reaction contained 0.125 µL OptiTaq DNA Polymerase and 2.5 µL 10× Pol Buffer C (Roboklon GmbH, Germany), 1 µL $MgCl_2$ (25 mM), 1 µL dNTP Mix (5 mM), 16.625 µL PCR water, each 0.625 µL of forward and reverse primer (20 µM), and 2.5 µL genomic DNA. The following cycler program was used: an initial denaturing step for 5 min at 95 °C followed by 35 cycles of 30 sec at 95 °C, 30 sec at 50 °C and 1 min at 72 °C, and followed by a final extension step for 7 min at 72 °C. PCR reactions were performed in duplicates for all sample extracts and extraction controls. Negative template controls were included for each PCR run. Resulting barcoded PCR products were purified using Agencourt AMPure XP – PCR purification beads (Beckman Coulter, Inc., CA, USA) and pooled into a single sequencing library to a final concentration of 30 nM. The final 16S rRNA library was sequenced on an Illumina MiSeq platform using 2x300bp chemistry by Eurofins Genomics Europe Sequencing GmbH (Konstanz, Germany).

4.4.4 Bioinformatic analysis

The sequencing library was demultiplexed using cutadapt v2.8 (Martin, 2011) using the following parameters: -e 0.2 -q 15,15 -m 150 --discard-untrimmed, identifying only read pairs with correct barcodes at both ends. The ASVs were generated using the trimmed reads and the DADA2 package v1.18 (Callahan et al., 2016) with R v4.0 using the pooled approach with the following parameters: truncLen=c(240,200), maxN=0, rm.phix=TRUE, minLen=200. Taxonomic assignment was done using DADA2 and the SILVA database v138 (Quast et al., 2013).

4.4.5 Data processing and statistical analysis

Absolute singletons, doubleton, and all ASV's with a read count below 3 were removed from the ASV table. Furthermore, ASVs, which were not classified as bacteria or classified as chloroplasts or mitochondria, were also removed from the ASV table. Finally, the ASV table was manually curated for potential contamination using the negative and positive control sequencing results. The ASV table was subsampled to a sequencing depth of 10,000 sequences for alpha diversity analysis. Species richness (S), Shannon index (H), Simpson and Pielou's evenness index (J) were calculated using the Vegan Package in R (Oksanen, 2015). To evaluate variations across the different sample communities (beta diversity) the ASV table was Hellinger transformed and a multivariate analysis was conducted. Principal coordinate analysis (PCoA) based on Bray-Curtis distance were used to visualize the dissimilarity of microbial communities between habitats (river, river mouth and lake). In addition, geochemical measurements (Nomosatryo et al., 2022) were z-score transformed and fitted onto the ordination plot of the PCoA as vectors. Differences in microbial community structure between habitats were assessed using analysis of similarity (ANOSIM). The taxonomic relative abundances across samples were visualized through bubble plots using the ggplot2 package. The Venn-diagram was created by using ggVenndiagram package (Gao et al., 2021) to merged ASVs reading in each habitat. Only total ASVs with an abundance above 0.01% were used for calculating the Venn-diagram.

4.5 Results

4.5.1 Microbial diversity

16S rRNA sequence libraries were prepared for all collected surface sediment samples to assess microbial distribution, diversity, and community composition across the different habitats in Lake Sentani. Overall, our analysis suggested microbial diversity parameters to be relatively similar across the evaluated habitats (Fig. SI 2); however, minor variations were observed. Microbial communities across the different river sediment samples were found to be least diverse (Fig. SI 4.2, Table SI 4.1). Richness of river communities ranged between 1,187 and 2,408 ASVs per 10,000 sequences, with a Shannon Index between 6.81-7.65 and an evenness range of 0.96-0.98, respectively. Microbial diversity measurements were moderately higher for river mouth samples, between 1,463 and 3,068 ASVs were identified per 10,000 sequences, resulting in a Shannon Index of 7.11-7.93. Microbial communities in the lake sediments were characterized by the largest range in diversity, with 536-2,501 ASVs reported per 10,000 sequences between and a Shannon Index of 6.06-7.93. Assessment of species evenness suggested microbial communities in rivers (0.96-0.98), river mouths (0.96-0.99) and lake sediments (0.96-0.99) to be very similar with respect to the distribution of microbial taxa. Geographically, microbial communities in sub-basin 1 were found to be more diverse than those across the other sub-basins (up to 2,501 ASV's per 10,000 sequences, Shannon up to 7.68). Detailed diversity measurements for all habitats, locations and samples are comprehensively summarized in the supplemental materials (Table SI 4.1).

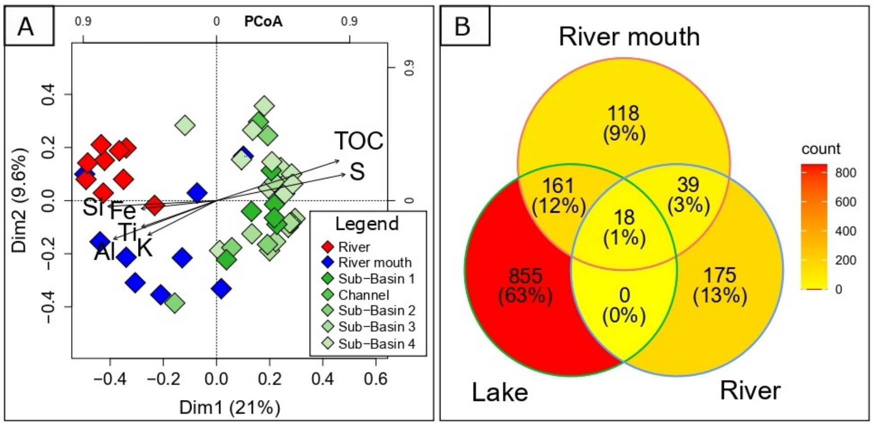

Figure 4.2 *Principal-coordinate analysis (PCoA) based on Bray-Curtis distances of microbial community structure (A) and Venn diagram (B). Different colors of the square symbol in PCoA indicate different habitats and solid arrows represent the environmental parameters as variables of geochemical characteristics. Venn diagram expressing the unique and potential shared methanogenic ASV's between the river, river mouth, and lake (the total ASV's of sub-basin 1, channel, 2, 3, and 4).*

4.5.2 Habitat specific microbial populations

Ordination analysis using Bray Curtis dissimilarity indices visualized on PCoA plot suggested microbial community composition to differ across the evaluated habitat types, as three distinct clusters representing the three sampling locations (river, river mouth, and lake) were observed (Fig. 4.2.A). Visual clustering was supported by statistical calculations using the analysis of similarity (ANOSIM) test, suggesting microbial communities from lake and river sediments to be significantly different (*p*=0.001, R=0.98, Fig. SI 4.3). Similarly, lake sediment communities were also found to differ significantly from microbial populations in river mouth samples (*p*=0.001, R=0.69, Fig. SI 4.3). Microbial communities in river and river mouth samples varied slightly (*p*=0.001, R= 0.45, Fig. SI 4.3). Visual inspection did not suggest any differences among microbial composition across the lake basins, as no obvious separation between samples could be observed in the ordination analysis (Fig. 4.2.A). However, ANOSIM calculations emphasized a moderate, but significant dissimilarity in microbial community structure between sub-basin 2 and sub-basin 3 (*p*=0.019, R=.65, Fig. SI 4.3) and small differences between sub-basin 1 and 3 (*p*=0.006, R=0.31, Fig. SI 4.3).

Analysis of shared and unique ASVs across the three main Lake Sentani Habitats (River, river mouth, lake) and the four different lake sub-basins, also emphasized differences in microbial richness among the evaluated sites and highlighted a gradual shift in microbial distribution from river, to river mouth, and lake samples. While 1034 ASVs were exclusively identified in lake sediments, only 18 ASVs were found to be shared across all three habitats (Fig. 4.2.B). River and river mouth shared 57 ASVs, while 179 ASVs were identified in both river mouth and lake sediments. 175 and 118 ASVs were exclusively found in River and River mouth sediments.

4.5.3 Oxygen availability does not significantly affect community structuring

Due to the water depths in the rivers and river mouths being less than 2 meters, we assume oxygen can reach the surface sediments. To assess the effect of oxygen on the microbial community composition, samples were clustered based on the oxic-anoxic conditions (oxygen concentration in bottom waters) in the surface sediment lake and light penetration (euphotic zone, 3 x of Secchi depth, 9 m) (Fig. SI 4.4). Neither visual separation nor statistical evaluation using ANOSIM suggested any significant dissimilarity between oxic and anoxic conditions. Nevertheless we observed a moderate, but insignificant dissimilarity between microbial communities in the euphotic zone (0-9 m depth) and the anoxic zone (*p*=0.015, R=0.48, Fig. SI 4.3).

4.5.4 Proteobacteria dominate, as Archaea, Bacteroidota and sulfate reducers shape habitat specific communities

Taxonomic evaluation of the collected sediment samples identified 23 phyla (18 phyla of bacteria and 5 phyla of Archaea) across Lake Sentani's surface sediment microbial communities, at a relative abundance of 2% or greater (Fig. 4.3). The majority of the samples were dominated by Bacteria (53.3-99.7%), however lake sediment samples were charachterized by high Archaea abundances (up to 46.7%). Proteobacteria (up to 54.1%), Chloroflexi (up to 19.1%) and Acidobacteria (up to 16.6%) were the most abundant bacterial phyla and were detected in all three habitats (Table SI 4.2). Bacteroidota (up to 20.2%) and Alphaproteobacteria (up to 41.6%) were especially abundant in the river and river mouth habitats, whereas sulfate reducing taxa Desulfobacterota (up to 9.5%) and Thermodesulfovibrionia (up to 4.5%) were particularly enriched in lake sediment samples. A closer investigation of microbial distribution patterns across the three habitats revealed distinct communities, especially at lower taxonomic levels.

4.5.5 Microbial community of the river sediments

River sediment samples were taken from eight different rivers, six of which are located across the more densely populated north-eastern shore areas of Sentani City and Jayapura. River sediment samples were especially characterized by high abundances of Alphaproteobacteria (up to 41.6%), Gammaproteobacteria (up to 38.8%), Bacteroidia (up to 20.2%), and Clostridia (up to 7.1%).

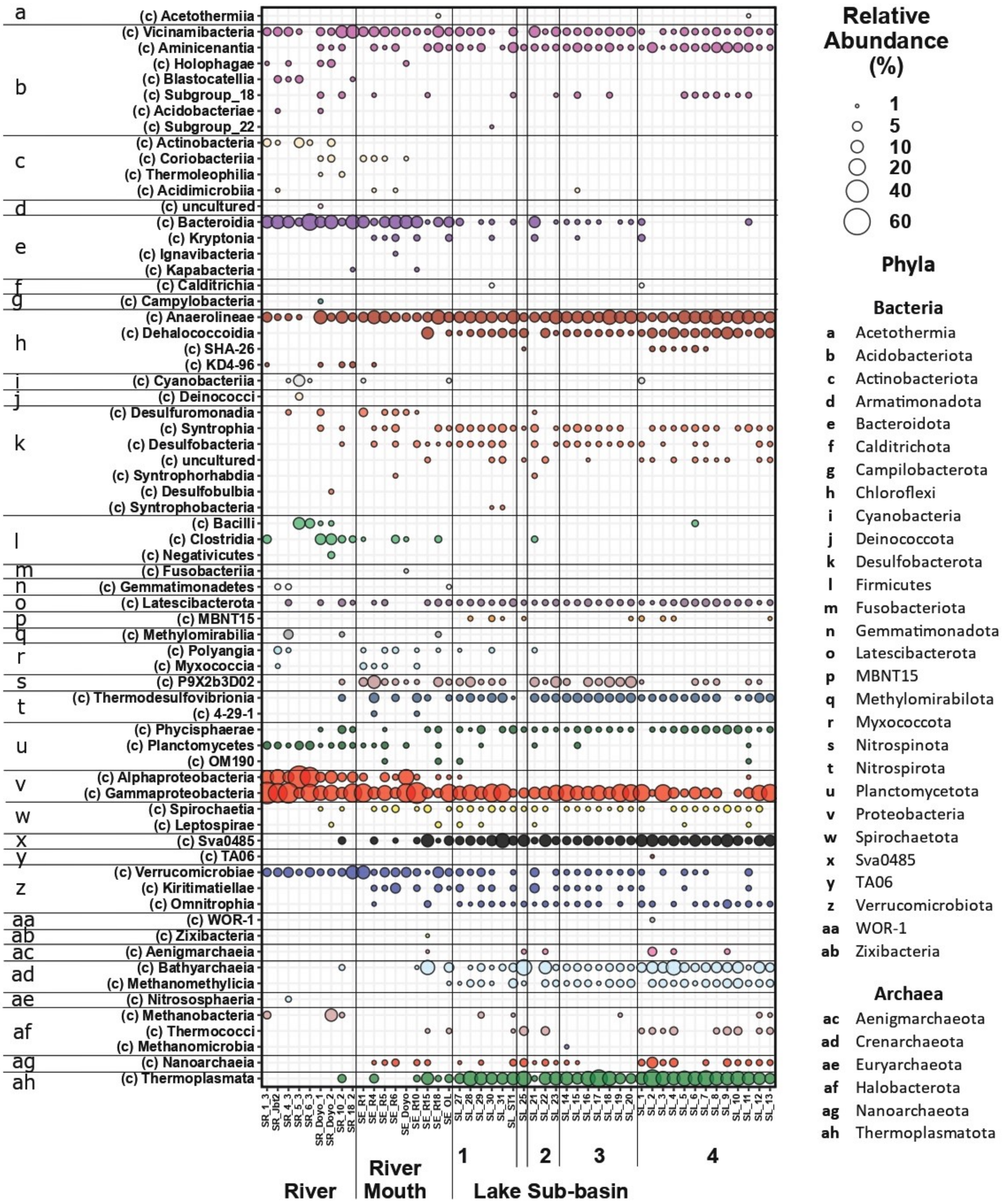

Figure 4.3 *Bubble plot depicting microbial community composition (> 1%) in analyzed surface sediment samples (right on the top) at class level based on 16 rRNA gene sequencing results.*

Closer examination of the taxonomic profiles suggested several Alphaproteobacteria sub-taxa to be especially enriched in river sediments and, with few exceptions, absent from lake samples (Table SI 4.3). Sphingomonadaceae (up to 33.9%), including the aromatic compound degrading genus *Novosphingobium*, Xanthobacteraceae (up to 1.4%), and nitrogen fixing Hyphomicrobiaceae (up to 1.8%) and Rhizobiaceae (up to 0.6%) were detected in all river sediments. Caulobacteraceae (up to 1.0%) were especially present in river sediments taken in Sentani City (Doyo and SR6, Fig. SI 4.1.B), while acidotolerant, nitrogen fixating methanotrophic Beijerinckiaceae (up to 0.7%) were identified in Sentani City river sediments and in sediments from southern shore rivers draining into sub-basin 2 (Fig. SI 4.5).

Gammaproteobacteria were detected throughout river sediments, with certain taxa specifically enriched. Uncultured Comamonadaceae (up to 12.7%) were detected in all river sediments, except those located on the southern shore. Within the Comamonadaceae, *Hydrogenophaga* and *Acidovorax* were most dominant genera in river sediments (Fig. SI 4.6.B).

Xanthomonadaceae (up to 6.5%) and Rhodanobacteraceae (up to 0.6%), including the genera *Lysobacter*, *Ahniella* and *Arenimonas*, were exclusively identified in sediments from rivers on the northern shore draining into basins two and three. In contrast, Nitrosomonadaceae (up to 3.5%) were detected in several river locations on the northeastern shore and the most eastern river draining into basin 1, while being completely absent from lake samples.

4.5.6 Bacteroidetes and Firmicutes are indicators for river sediments

Bacteroidia were specifically associated with river sediments, as Chitinophagaceae (up to 8.3%) and Saprospiraceae (up to 2.2%) were enriched in almost all river samples. Closer examination suggested these taxa to consist of ASVs classified as *Terrimonas* and *Lacibacter*, both of which have been detected in river environments previously (Kämpfer et al., 2011).

Similarly, several Firmicutes taxa were also exclusively identified in river sediments. Clostridiaceae (up to 5.4%) were especially enriched in Doyo and southern shore river sediments. *Bacillus* were detected in the sediments of three of the northern shore rivers, flowing through urban sites (Sentani City) into sub-basins 2 and 3, and the two southern rivers, also discharging into these two sub-basins.

4.5.7 Minor taxa also shape river communities

Additional river specific taxa were Chloroflexi, which could be more accurately classified as Anaerolinaeae (up to 11.6%), Planctomycetes of the family Gemmataceae (up to 1.4%) and Acidobacteriota of the family Blastocatellaceae (up to 2.2%). Sequences affiliated with these taxa were completely absent from the lake sub-basins (Fig. 3, Table SI 4.3). River sediments were also the only habitat in which phototrophic Cyanobacteriia (up to 8.0%), *Deinococci* (up to 2.7%), methane oxidizing *Methylomirabilia* (up to 4.9%), and archaeal *Methanobacterium* (up to 9.3%) signatures could be detected.

In summary, river sediment communities were defined by a high abundance of Alpha- and Gammaproteobacteria. Firmicutes and Bacteroidetes were especially present at selected sites along the northern shore. Locatio-driven differences were also emphasized by less frequently occurring taxa, as for example Cyanobacteria were only detected in one sample.

4.5.8 Anoxic conditions shape lake sediment communities

Lake sediment samples were found to harbor distinct microbial community distribution profiles, characterized by anaerobic and autotrophic microorganisms, and differed from river sediments especially at lower taxonomic levels. Lake communities were highlighted by high abundances of sulfate reducing Desulfobacterota (up to 9.0%), acidophilic Euryarchaeota (up to 4.9%) and overall greater archaeal diversities than observed in river and river mouth habitats.

Thermodesulfovibrionia (up to 4.5%) and Deltaproteobacterium candidatus Sva0485 (up to 13.9%), both sulfate reducers, were especially enriched and could be identified in almost every single sample across sub-basins 1, 2 and 3 and in the majority of samples from basin 4 (Fig. 3, Table SI 4.3). Sub-basin 4 communities were also characterized by frequent detection of Phycisphaerae (up to 3.7%), a taxon usually associated with marine environments. Sequences closely related to the anaerobic Latescibacterota candidatus taxa P9X2b3D02 (Youssef et al., 2015) were detected in samples across all sub-basins (up to 7.4%).

In contrast to river sediments, almost no Alphaproteobacteria were detected in lake sediments and Gammaproteobacteria signatures were less diverse. We specifically identified ASVs associated with thermophilic, potentially autotrophic and hydrogen utilizing Hydrogenophilaeceae and Rhodocyclaceae (especially in sub-basin 3 (up to 3.7% and 4.7%, respectively) and 1 (up to 1.4% and 4.6%, respectively)) and methane oxidizing Methylococcaceae (up to 0.5%)). Sequences closely related to the facultatively autotrophic, sulfur and hydrogen oxidizer *Sulfurisoma* (up to 1%) were detected in a limited number of sub-basin 1 samples and almost all sub-basin 3 lake sediments. Even more than the other two habitats, lake sediments were characterized by Chloroflexi. Chloroflexi communities were not just dominated by Anaerolineae (as the case in river and river mouth sediments), but also include high abundances of Dehalococcoidia. Finally, sequences classified as Aminicenantia, a recently proposed candidatus class, that is frequently observed in various subsurface marine and non-marine low oxygen environments, were detected in most lake sediment samples across all four basins (up to 6.0%, Table SI 3). *Thermoanaerobaculum* (up to 0.5%) were noticeably identified in all sub-basin 2 samples, but were only found sporadically across the remaining habitats.

As stated above, microbial communities in lake sediments distinguished themselves from those of the rivers and river mouths specifically by greater archaeal diversity and abundances. Lake sediments were especially enriched in Bathyarchaeia (up to 17.6%) and *Methanomethylicia* (up to 5.1%) (both Crenarcheota) and Thermoplasmata (up to 23.0%) (Fig. 3). In addition, Thermococci (up to 4.4%) and Nanoarchaeia (up to 7.3%) could be identified in several samples, mostly in sub-basins 2 and 4. Unlike in the river sediments, no *Methanobacterium* signatures were detected.

One sediment sample was collected from the Simporo channel connecting basins 1 and 2. Overall, microbial community composition in this sample was similar to those identified across the other lake samples but lacked some of the methanogenic and sulfate reducing taxa, particularly Thermodesulfovibrionia and *Methanomethyclica*. In addition, we could not detect any anaerobic Latescitbacterota candidatus taxa P9X2b3D02 (Youssef et al., 2015), Vicinamibacteria, or Aminicenantes candidatus signatures in channel sediments, although these taxa were frequently detected across the remaining parts of the lake. Channel sediments were especially characterized by high relative abundances of Bathyarchaeia (17.6%) and Nanoaerchaeia (3.4%).

4.5.9 Hybrid river mouth communities

Evaluation of river mouth sediments revealed dynamic microbial communities that exhibited influences by both river and lake habitats, depending on location. A small number of microbial taxa were specifically enriched in river mouth sediments. Notable are especially the identification of halo respiring, facultative anaerobic *Anaeromyxobacter* (up to 2.1%) and the thermophilic anaerobic taxa *Geothermobacter* (up to 2.1%). *Deferrisoma* (up to 0.7%), another thermophilic taxon, often associated with hydrothermal vents, were detected in the majority of river mouth samples, but absent on the southern shore and in river mouths or sediments of the outflow.

In contrast, methylotrophic Candidatus *Methanomethylicus* (up to 5.1%) and Latescibacteraceae (up to 8.2%), both of which were frequently and abundantly detected across lake sediments, were only detected in river mouth sediments on the southern shore and sediments from the Jayefuri (another written: Jaifuri) river at the outflow (Fig. SI 4.1.B and 4.6.A). Similarly, archaeal Thermoplasmata and Bathyarchaeia were abundant in river mouth samples from the same locations. Thermoplasmata were also detected in the sediments of one northern shore river mouth sediments (River 4 draining into sub-basin 4).

Ubiquitous detection of several Bacteroidia taxa suggests the majority of river mouth sediments are impacted by rivers. We were able to identify Chitinophagaceae sequences (up to 4.1%) in four and Saprospiraceae sequences (up to 1.7%) in six of the nine examined river mouth communities. Furthermore, Alpha- and Gammaproteobacteria that could be identified in river sediments were also detected in the corresponding river mouth samples. Especially noteworthy were elevated levels of Sphingomonadaceae (up to 8.3%), Comamonadaceae (up to 4.2%), and Methylomonadaceae (up to 2.5%) in northern shore river mouth sediments. On the contrary, Hydrogenophilaceae (up to 1.6%) and Rhodocyclaceae (up to 8.9%), which were more prominent in lake samples, were only detected in a small number of river mouths and the Jayefuri outflow sediment communities.

Anaerolinea (class Chloroflexi) were detected in all evaluated river mouth samples, independent of location or habitat (up to 13.0%), while Dehalococcoidia (up to 8.6%) were exclusively detected in river mouth sediments from the southern shore of sub-basin 3 (R15). Finally, sequences affiliated with the candidatus *Omnitrophus* taxon (up to 2.1%), an indicator for anoxic environments with a range of potential metabolic capabilities ranging from carbon fixation to dissimilatory nitrate reduction (Williams et al., 2021) were identified in all river mouth samples, except one location near Sentani City (Doyo).

These findings suggest river mouth communities are either driven by the rivers as shown by the enrichment in Alpha- and Gammaproteobacteria or Bacteroidetes, or in some locations, driven by lake communities and harbor thermophilic and methanogenic Archaea and sulfate reducers.

4.6 Discussion

Investigations of microbial communities in tropical lake systems and their response to geochemical and anthropogenic processes remain relatively sparse, limiting the current understanding on how ecosystem function, microbial distribution and diversity are linked in such environments. This is especially concerning as urban development and increases in anthropogenic activity in these historically rural regions are increasing. Lake Sentani and its surrounding areas have experienced rapid population growth over the past decade. Furthermore, the catchment of this lake, escpecially in Sentani sub-district, is also the center of sago production (the sago palm landscape covers 7,842.76 ha (Dimara et al., 2021)), and sago is considered as one of the local food assets (Sidiq et al., 2021). Therefore, this location is highly interesting and relevant for such a study. While previous work provided a thorough evaluation of sediments and water columns from a geochemical standpoint (Nomosatryo et al., 2021, 2022), a detailed assessment of microbial communities across the diverse Lake Sentani habitats allowed us to examine microbial distribution patterns across a unique tropical lake system and explore if and how far anthropogenic and geogenic features shape this ecosystem.

4.6.1 Geographical features and general findings

Going into this study, we expected to see major differences in community structure between lake and river sediments, but also across Lake Sentani'sfour sub-basins. Significant variations in urban structures between the northern shore and the southern shore of Lake Sentani were also expected to have an impact. The area around Sentani City (Sentani sub-district) is the most densely populated and is bordering sub-basins 2 and 3. Especially the northern shore is directly adjacent to human settlement and city limits of Sentani City. In addition, several rivers coming down from the Cycloop mountains run through urban settlements and likely impact microbial communities in river mouths and lake areas in close proximity to the shore. In contrast, the western part of Lake Sentani, i.e., sub-basin 1, is surrounded by secondary forest and less impacted by rivers originating in the Cycloop mountains and is most isolated, as it is only connected to the rest of the lake through a small, shallow channel. This area is also a lot less populated, however, human settlements exist along the shoreline. Easternmost sub-basin 4 has more exposure to anthropogenic activity in the north, as western limits of Jayapura city stretch to the lake shore, while its southern part is more rural with secondary forested shores and only small human settlements.

General findings of this study highlight the large degree of variation in the freshwater bacterial community in taxonomic composition across the different Lake Sentani habitats, as microbial communities in river sediments were especially enriched in Alphaproteobacteria and Bacteroidetes. Lake sediment communities were statistically different and especially enriched in Archaea and sulfate reducers. More subtle differences in microbial community structure across the sub-basins also suggest the different environmental and geochemical conditions at each location likely influence the microbial and diversity composition patterns. Several microbial groups, including Gammaproteobacteria and Chloroflexi could be identified across all habitats, showcasing the interconnectivity of the lake system. Our findings also suggest the river mouth habitats to be a transition zone between the river and lake ecosystems, as the microbial community in this area features a mixture of microorganisms found in the other two habitats, while only a small number of exclusive ASVs could be identified. These observations are consistent with the geochemical characteristics of surface sediments in this habitat as reported previously (Nomosatryo et al., 2022).

To address site specific differences and assess the role of anthropogenic factors at each site, the collected data will be discussed in more detail. This discussion focuses on biochemical and microbial interactions, microbial communities, and their potential lifestyles and roles in each habitat.

4.6.2 Anthropogenic activities may drive northern shore river and river mouth communities

One of the central objectives of this study was to evaluate distribution and composition of microbial communities across Lake Sentani with a special focus on the role anthropogenic pressures might play. We hypothesized that particularly river and lake sediments found along the more populated northern shore are characterized by microbial populations often associated with anthropogenic pressures. Our results partially confirmed these findings, as especially sediment samples taken from rivers and river mouths located along the northern shore and thus running through the populated areas of Sentani City and areas close to Jayapura city were enriched in Bacteroides and Firmicutes (Fig. 4.4).

While the population density and rate in the Lake Sentani area are still relatively low compared to the average value across other areas in Indonesia (Kementerian Lingkungan Hidup Republik Indonesia, 2011), the local populations in sub-districts located within the

Lake Sentani catchment area are increasing (Fig. 4.1.B) especially in the sub-districts Sentani and Heram and thus might directly or indirectly influence the river and lake water conditions. Closer taxonomic evaluation suggested the majority of identified Bacteroidetes signatures to belong to the genera *Terrimonas* and *Lacibacter* and thus represent common soil and sediment bacteria, while *Bacillus* and *Clostridium* were the most abundant Firmicutes in these river sediments. While these organisms do not serve as common fecal coliforms, as one may have expected, some can be considered common indicators for human activity, they are often identified in mammals (Shanks et al., 2011). Thus, the frequent identification of Bacteroidota and Firmicutes ASVs in river, but also river mouth habitats that lie in close proximity to the urban region of Lake Sentani might be caused by the untreated wastewater from residential areas containing pollutants like nitrates, ammonia, and feces.

Besides through the direct detection of human (waste) associated microorganisms, anthropogenic pressure on an ecosystem can also cause elevated nutrient loads resulting in increased carbon and nitrogen turnover, causing eutrophication. Eutrophication in lake Sentani was reported recently (Indrayani et al., 2015; Pattiselanno, 2013), suggesting the region's anthropogenic activity might lead to nutrient loading and domestic waste pollution in the river-lake system (Pattiselanno, 2013).

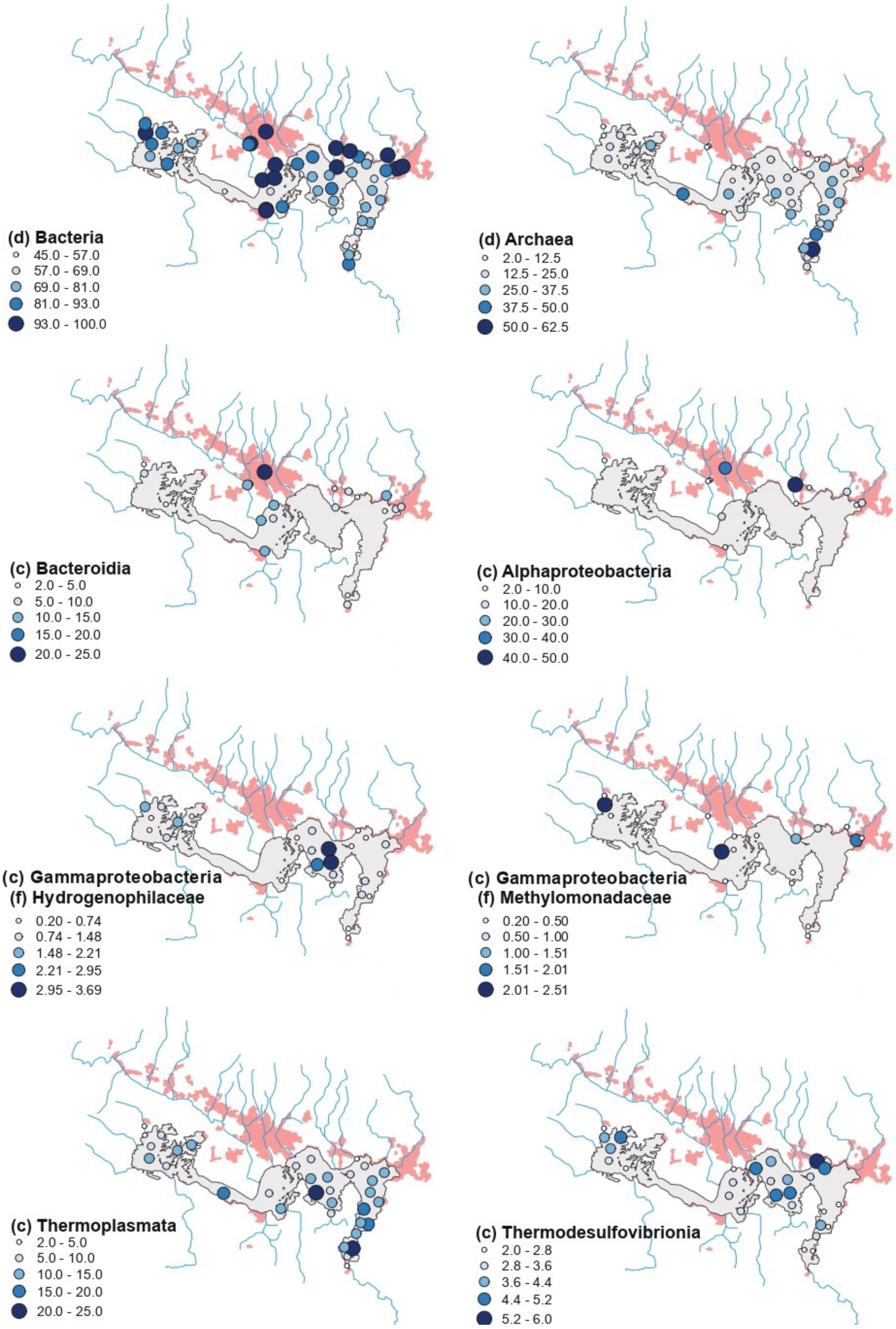

Figure 4.4 *Spatial distribution of selected relevant and abundant microbial taxa. The distribution is shown as relative abundance in %. The red color indicates the settlement area and the grey color represents the water body of the lake.*

Our study supports that especially northern shore river and river mouth sediments may be hotspots of microbially mediated carbon (C) and nutrient processing, as *Novosphingobium*, *Dechloromonas* and *Hydrogenophaga*, which are often associated with industrial and/or synthetic wastewaters (Bruce et al., 1999; Yoon et al., 2008), were detected frequently. While there is no major industry which could be considered as a point source for industrial wastewater in the catchment area of Lake Sentani (BPS Kabupaten Jayapura, 2022). There are smaller scattered operations (e.g., Sago flour mill (Dimara et al., 2021)) as well as the major airport runway sitting along the northern shoreline. In an alternative scenario, the increased levels of Alphaproteobacteria might simply be caused by elevated nutrient availability, as reported in the Mulargia River, Italy (Zoppini et al., 2010) and urban lakes in China (Cao et al., 2018; Zhao et al., 2016). While organic matter concentrations in the main river and river mouth habitats along the northern shore were found to be relatively low (average around $1.5\%_{\mathrm{dwt}}$) (Nomosatryo et al., 2022), they still represent an available energy source for heterotrophic bacteria, across the river system of Lake Sentani.

Another type of microorganism that was strongly associated with the northern shore and mostly enriched in sediments from Sentani city and Jayapura River sites were the Planctomycetes. This widely distributed group includes common anammox bacteria, is found in marine and freshwater ecosystems and has an important role in organic matter decomposition of organic matter from dead organisms and higher plants (Lindeman, 1942; Tank et al., 2010; Zeglin, 2015). The presence of Planctomycetes is a potential indicator for ammonia oxidation, which could be driven by increased ammonia availability from agricultural and municipal runoff. Similarly, exclusive Cyanobacteria and Chloroflexi signatures in sediments from rivers located around Sentani City, suggest a link to anthropogenic activity. Cyanobacteria are very common indicators for increased nutrient availability and are often associated with eutrophication and pollution events (Cottingham et al., 2015; Huisman et al., 2018). Finally, sediments from the Doyo river site in Sentani City were found to harbor Holophagae and *Clostridium* senso stricto populations, Holophagae are known for their ability to anaerobically degrade aromatic compounds and can produce volatile sulfur compounds, while *Clostridum* senso stricto are common gut bacteria (Alou et al., 2018). While these two taxa are not directly associated with human pollution, their predominant presence in samples from the more urbanized locations around Lake Sentani may be early indicators for anthropogenic input.

4.6.3 Limited evidence for anthropogenic impact in lake sediments

Microbial communities in the lake sediments show a different structure than the river and river mouth microbial communities and exhibit few to none of the river and river mouth taxa that could be associated with anthropogenic stress. The only lake samples to harbor any Firmicutes or Bacteroidetes signatures were identified in sub-basins two and four, mostly in samples taken closest to the northern shore, and thus in proximity to the most urbanized areas of lake Sentani. While overall only a limited number of samples falls in this category, these observations could represent the first traces of anthropogenic impact on the lake. Interestingly, highest TOC, which is usually associated with eutrophication, were measured in sub-basin 3 (Nomosatryo et al., 2022). Sub-basin 2 also represents the only sub-basin in Lake Sentani to have a fully oxidized water column (Fig. SI 4.1.B). Additional, temporal assessments to evaluate further dispersal of these taxa throughout the lake sediments are thus highly recommended to estimate the anthropogenic impact going forward.

Analysis of the remaining lake data suggested the majority of microbial populations to be primarily driven by the geochemical conditions. The organic matter concentration in Lake Sentani is relatively high (up to 27.9 % dw) (Nomosatryo, 2022). Therefore, the reduced conditions caused by anaerobic processes are prevalent in the sediments across the analyzed lake locations. Consequently, the frequent observation of anoxic fermenters such as Crenarchaeota, Thermoplasmatota or Acidobacteriota in lake sediments was expected. These microbial distribution patterns are similar to those observed in the iron-rich methanic sediments of Lake Kinneret, where microorganisms fermenting amino acids and other products of necromass degradation are abundant and include taxa like Anaerolineaceae, Thermodesulfovibrionia, SVA0485, and Bathyarchaeia (Elul et al., 2021).

In addition, the dominance of *Anaerolinea* (Chloroflexi), *Thermodesulfovibrionia* (Nitrospirae), and Sva0485 in the lake sediments emphasizes the high potential for dissimilatory sulfate reduction. Similar microbial groups also contribute to sulfate reduction in the low sulfate ferruginous lake Towuti, which has low µM sulfate concentrations (Vuillemin et al., 2018). With generally higher sulfate concentrations being available (Nomosatryo et al., 2021), these processes likely play an even bigger role in Lake Sentani. Porewater geochemistry data further support the potential for microbial sulfate reduction.

4.6.4 Methanogens and thermophiles shape archaeal Lake Sentani communities

Besides sulfate reducing taxa, lake sediments were especially abundant and diverse in Archaea (Fig. 4). The presence of strict or facultative anaerobes, like methanogenic Methanomethylicia, thermophilic Themococci, as well as Thermoplasmata and Bathyarchaeia, which have also been suggested to contribute to methane production (Offre et al., 2013; Romano et al., 2021) are indicative of the limited oxygen availability in the sediments. Our results suggest methane production in Lake Sentani sediments to be mostly driven by methylotrophic methanogens, classified as Candidatus Methanomethylicus and Thermoplasmata, of which no representatives have been isolated so far, but which are believed to contribute to methane production by potentially re-mineralizing organic matter to methane as their genomes have been proposed to encode distinct methyl-coenzyme M reductase genes (Clesceri et al., 1998; Ji et al., 2016; Moguel et al., 2021; Poulsen et al., 2013). Thermoplasmata were enriched across all sub-basins, emphasizing their general role in sediments of tropical lakes. Another group of Archaea, which was identified across the majority of the analyzed lake samples and especially abundant in basin 4 were the Bathyarchaeota. This group has previously been detected in high abundance in sediments across tropical lakes (Romano et al., 2021; Vuillemin et al., 2018; Zhou et al., 2018) and is generally widely distributed across nutrient-poor marine and terrestrial sediments. Certain members of this candidatus taxon are believed to fix CO_2 via the Wood Ljungdahl pathway and acetogenesis (He et al., 2016). While the ability of Bathyarchaeota to undergo methanogenesis has not been proven through direct measurements of metabolism, genomic data suggests several members of this group to have the ability to form methane from methanol and methylamines (Evans et al., 2015; Zhou et al., 2018). Their ubiquitous presence in Lake Sentani further supports their role in tropical lakes and highlights the need to evaluate their metabolism and role in biogeochemical interactions in more detail. Notable was also the detection of extremophilic, organotrophic sulfidogenic *Thermococcus*, which are usually detected in higher temperature environments, in certain basin locations. Some *Thermoocccus* species can produce O_2, H_2, and H_2S, which may be used by autotrophic neighbors, such as methanogens (Cho et al., 2017). Interestingly, Thermococci occurred together with Nanoarchaeia, another closely related thermophile known for their occurrence in very high temperature environments, which however lacks the ability to utilize sulfur species or H_2 (Brochier et al., 2005)

Overall, the wide distribution of distinct archaeal taxa across Lake Sentani sediments agrees with observations made for water column and sediment samples in other tropical lakes, such as Lake Towuti and Lake Kivu (İnceoğlu et al., 2015). Our findings suggest an overall, high potential for methane production from these sediments, not just from classical methanogens, while at the same time identifying several chemo- and autotrophic archaeal groups, which could be indicators for a variety of metabolic processes occurring within Lake sediments. This means our data underlines the role of thermophilic, methanogenic and acidophilic archaeal groups in natural, undisturbed tropical lake settings and highlights an elevated potential for methane production, but also the generation of CO_2 and sulfide.

4.6.5 Geographic features translate to microbial distribution across lake basins

Even though lake sediments across the four major sub-basins share a lot of similar microbial taxa, few but distinct differences could be observed, suggesting that each sub-basin's geogenic but also anthropogenic features may play an important role. As discussed above, the only lake samples to harbor any Firmicutes or Bacteroidetes signatures were identified in sub-basins 2 and 4, suggesting these lake areas to be impacted by the first on-sets of anthropogenic stress.

The shallow channel connecting sub-basin 1 and 2 especially stands out, as microbial populations are less diverse overall and lack taxa like Thermodesulfovibrionia and *Syntrophia*, both sulfate reducers, or *Methanomethylicus,* a relatively newly described methylotrophic methanogen (Vanwonterghem et al., 2016), which was observed across the other basins. On the contrary, Bathyarchaeia and Thermococci were most abundant in this shallow and organic rich environment. The channel has a depth of about 4 m, and its unique features are the high TOC (27.1%) and high relative distribution of S compare to the other location (Nomosatryo et al., 2022). An accumulation of decaying aquatic plants most probably causes the high TOC concentration in this channel, and even though oxygen could penetrate to the bottom (Nomosatryo et al., 2021), elevated sulfide concentrations at this location indicate the surface sediment to be anoxic, conditions, which should make this area a habitat for methanogens. With classical methanogens being absent, Bathyarchaeia might be the microorganisms filling these roles. In addition, high abundances of chemotrophic Thermococci could be driven by the high TOC levels in this habitat.

While our data suggests northern shore river and river mouth communities to be impacted by anthropogenic activity and urban runoff, samples from other locations in the Lake Sentani catchment area were found to harbor distinct microbial populations that are more representative of those found in the anoxic lake sediments, including sulfate reducers and methanogens, suggesting these areas to remain more pristine compared to the northern parts. Especially communities in river and river mouth samples draining into the more secluded sub-basin 1 fall into this category. Similarly, southern river mouth and river communities, which drain into sub-basin 2 and 3 seem less diverse, compared to those found on the northern shore. Communities found in river mouth samples lack the Bacteroidetes and Proteobacteria signatures that were observed in the remaining river mouth samples and could be the result of anthropogenic stressors. In contrast, the two southern river mouth populations were enriched in Candidatus *Methanomethylicus*, which was only identified in two of the three southern river mouth communities. The detection of this methylotrophic methanogen suggests these river mouth habitats are likely more influenced by lake communities, where methanogens are more abundant.

4.7 Conclusion

This study provides crucial information to understand the Lake Sentani ecosystem under changing environmental conditions in the catchment due to growing environmental and anthropogenic pressure. In conjunction with our previous work on Lake Sentani, data from this study provides valuable and rare insights into a tropical lake system, its ecological, socioeconomic role and biogeochemical processes of the Sediment Water Interface (SWI). Our results suggest microbial communities in rivers to be directly influenced by anthropogenic pressure and are markedly different from the lake sediment. Our study also suggested increased anthropogenic stressors, most probably caused by population growth and urbanization, especially along the northern and northeastern parts, to be reflected in the microbial community composition. River and river mouth sediments, particularly from these more urbanized areas, were enriched in microbial taxa frequently associated with eutrophication and affiliated with human and industrial pollution. In contrast, lake sediment microbial communities were found to reflect the anoxic condition in the sediments.

4.8 Acknowledgments

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5 Synthesis, Implication, Conclusion and Outlook

5.1 Synthesis

To date, the biogeochemistry of Lake Sentani is much less investigated than other topics, such as its biodiversity. In this thesis, we attempt to close this gap, at least to some degree. Lake Sentani has a unique shape with its four sub-basins and is surrounded by different lithologies influencing each basin's (bio)geochemical characteristics. This thesis provides the first comprehensive biogeochemical dataset on Lake Sentani's sediment and water column, expanding our understanding on the biogeochemistry of this lake. This thesis contains two interrelated geochemical and one geomicrobiology paper. The synthesis of the thesis is illustrated in Figure 5.1.

An integrated geochemical study of the water column and short sediment cores was conducted and published (Nomosatryo et al., 2021). Physicochemical measurements of the water column indicate that the sub-basins could be representative of different lacustrine systems, based on the stratification of the water column. We found that the deepest sub-basins (sub-basins 1 and 4) are meromictic. In contrast, in the shallowest sub-basin (sub-basin 2), the water column is fully oxygenated. Processes at the sediment-water interface of sub-basin 3 fluctuate between oxic and anoxic as the water column just reaches oxygen depletion at the sediment-water interface (SWI), so even minor fluctuations of the oxygen depletion depth can have profound implications on biogeochemical processes at the SWI. These differences in lacustrine conditions are important to explain the processes in the SWI in the different sub-basins.

This first manuscript describes that water column stratification, particularly bottom water oxygenation, strongly influences the elemental composition of the sediment and pore water composition. Furthermore, the vertical distribution patterns found in the water column and the porewater profiles of the upper 50cm of sediment across the four different sub-basins revealed that each sub-basin is unique due to its water column structure and specific sediment input under identical climatic and hydrological conditions (Nomosatryo et al., 2021). However, the differences in sediment composition between sub-basins are influenced mainly by catchment geology.

The influence of lithological variations in the catchment on the sediment composition in the lake is described in more detail in our second manuscript (Nomosatryo et al., 2022). We took a large number of surface samples, not only from the lake sediment but also from other depositional environments, such as rivers and river mouths. To prove that each basin has a different input of specific elements from the catchment, we measured the spatial distribution of the sediment composition in surface sediments to describe the fate and transport of major elements (Nomosatryo et al., 2022). In this paper, we show not only the different geochemical characteristics of surface sediments at each basin but also that μ-XRF core scanning, customarily used for paleoenvironmental studies of long sediment cores, can be effectively utilized to measure large numbers of discrete samples.

We found that the geochemical characteristics of rivers, river mouth, and lake surface sediment samples differ, informing us of differences in catchment geology and water column processes. Having such detailed geochemical data on surface sediments, we studied the geomicrobiology of the different sub-basins and compared the trends in the geochemical data with those from the genomic analyses (Nomosatryo et al., 2022, in preparation). While some general patterns were similar, there were several distinct differences between the datasets, proving that the analyses complement each other rather than contradict. These differences are mainly caused by microbial communities being more susceptible to changes in environmental conditions than minerals (Nomosatryo et al., 2020, in preparation). Our geomicrobiological study also suggested increased anthropogenic stressors, most probably caused by population growth and urbanization, especially along the northern and northeastern parts, to affect the microbial community.

The three manuscripts contain a combination of limnologic, geochemical, mineralogical, and geomicrobiological data and study both water column profiles and pore water and solid phase of geochemical profiles in surface sediments within the sub-basins and habitats.Altogether, by combining findings from these three manuscripts, it is possible to assess the internal and external factors that can control the composition of sediments deposited in the different sub-basins of Lake Sentani.

Finally, biogeochemistry work presented here provides novel and useful insights into a unique tropical lake characterized by four lacustrine sub-systems with different catchment lithologies and also evaluates the effects of anthropogenic pressure on such an environment.

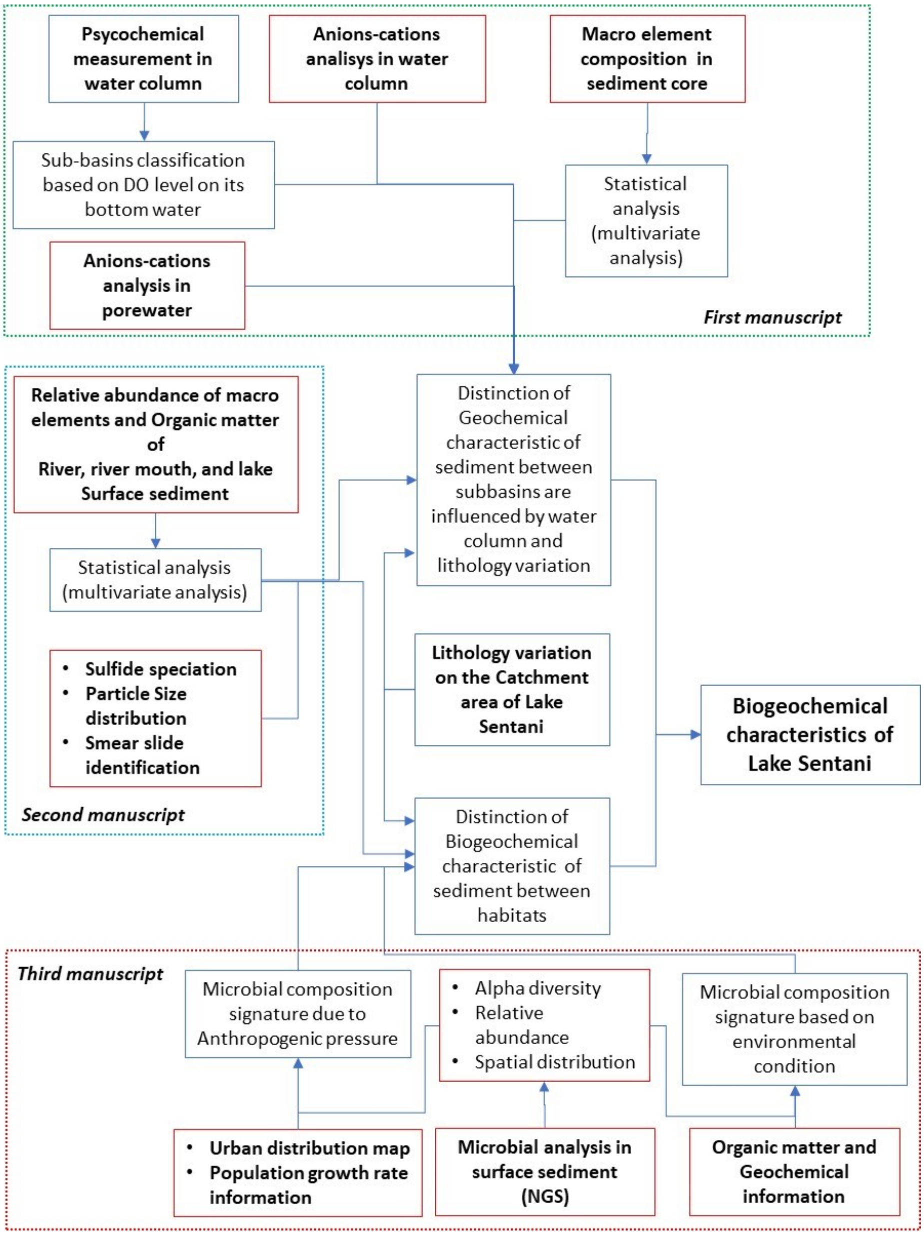

Figure 5.1. *Synthesis framework of the thesis cumulated from three manuscripts*

5.2 Implications

Conflicts of interests of ecosystem services and lake exploitation for economic purposes in the catchment area and the water body has impacted Lake Sentani's ecosystem. The indications for elevated pollutant (especially nutrient) and suspended solids input from the tributaries, runoff, and even direct input of pollutants from anthropogenic activities, might cause deterioration of lake water quality, lake eutrophication, and lead to habitat loss, particularly for endemic species.

Lake Sentani has been designated as one of the national priority lakes to be included in the Indonesian government's lake rehabilitation program for its ecosystem conservation. The program includes delineating and validating lake spatial zoning according to lake ecosystem function and services. Ministry of Agrarian Affairs and Spatial Planning /National Land Agency (ATR/BPN) as a legal authority and decision-making agency with the local government and local people, will arrange the lake spatial zoning based on scientific findings.

The research findings indicate that Lake Sentani has unique biogeochemical characteristics that can serve as valuable resources for research and education. These characteristics vary across habitats and sub-basins, making the lake an excellent natural laboratory. However, the scarcity of biogeochemical studies in the area challenges scientists to study the lake's specific features. Therefore, there is room for future studies to deeply understand the biogeochemical processes in Lake Sentani and provide scientific evidence for future management plans for the Lake.

5.3 Conclusion

Lake Sentani's four sub-basins all reveal highly variable geochemical characteristics, not just between each other but there are also great differences between different habitats, i.e. rivers, river mouth, and lake sediment, as well as between the water column and the porewater. The patterns found in the spatial distribution of major elements in the surface sediments of Lake Sentani reveal that rivers and estuaries are closely related, mainly due to the strong influence of detrital elements. In contrast, the lake sediment composition is different in each basin and likely controlled by the catchment geology. The basins directly connected to rivers draining from ultramafic catchment areas receive a strong input of iron-rich material. The water column in the two deepest basins (>30 m depth) is stratified with anoxic conditions in the bottom water and in some cases, considerable enrichment of dissolved, reduced species. The concomitant chemocline forms an effective barrier for reduced species (HS^-, PO_4^{3-}) to reach the oxic epilimnion. However, due to anaerobic mineralization of organic matter in the sediment, reduced species occur in the porewater and diffuse out of the sediment in all basins even though the water at the SWI still contains oxygen. While in the stratified basins the reduced species diffuse out of the sediment into the monimolimnion, they become oxidized at the SWI in the oxygenated basins.

Lake Sentani and its surrounding catchment represent a tropical lake ecosystem typically found in these regions of Southeast Asia. Due to its unique characteristics, consisting of four sub-basins and differently developing shore regions, it is a good site to study not only advance the general understanding of microbial life in tropical lake system, but also assess to what extent urbanization along its northern and eastern shores has had an impact on life at its simplest form, and thus obtain valuable data on this region's ecosystem health. Overall, we detected highly diverse microbial communities across the different Lake Sentani and catchment river sediments, suggesting a wide variety of biogeochemical processes to take place in this lake ecosystem. These processes likely play important roles in the decomposition of organic matter from internal or external input. For example, natural sources of Fe and Mn, which may reach the lake through runoff from the Cyclops Mountains, are assumed to provide electron acceptors for microbial activity. However, our study also suggested increased anthropogenic stressors, most probably caused by population growth and urbanization, especially along the northern and northeastern parts, to reflect in the microbial community. River and river mouth sediments, particularly from these more urbanized areas, were enriched in microbial taxa frequently associated with eutrophication and affiliated with human waste and industrial pollution. A small number of lake sediments, also all geographically located close to the more urban areas, were enriched in these taxa and thus represented early indicators for the dispersion of microbial populations driven by non-natural but human-made factors into the lake. While data from the river sediments provided indicators for anthropogenic stressors, most of the evaluated lake sediments were enriched in methanogenic and autotrophic archaea and sulfate cycling taxa. It emphasizes that anoxic sediments are a source of methane and H_2S emissions, especially if the mixed layer of the water column turns anoxic.

5.4 Outlook

Our investigation offered a unique opportunity to study biogeochemistry in four tropical lacustrine systems with different catchment lithologies in a single lake in great detail. The different geochemical characteristics of the sub-basins would allow for additional in-depth biogeochemical and paleoenvironment studies, but great care should be taken to choose the right sampling site, depending on the specific question to be addressed.

For example, a study on the influence of high sedimentation rates should be conducted in a sub-basin dominated by lithogenic sediment (sub-basin 2). Considering the redox-controlled differences in iron and manganese distribution, sub-basin 1 is suitable for studying biogeochemical processes in response to variable organic matter input. Iron plays an essential role in this lake, since several rivers drain from areas with ultramafic lithology and carry abundant iron minerals into the lake, esp. sub-basin 4. The meromictic conditions in sub-basin 4 provide optimal conditions for studying Fe cycling, esp. the diagenetic transformation of lithogenic iron minerals into authigenic ones. This sub-basin can also be considered a representative of a tropical lake that is influenced by appreciable iron input but far below levels that would deem it ferruginous, like for example, lakes in the Malili lake system on Sulawesi Island. Our data revealed indicators for eutrophication in the lake Sentani ecosystem, which can affect the carbon cycle, so additional, especially temporal investigations of microbial markers are recommended. This could include a more detailed assessment of methanogen and methanotrophy potential, for example, through metagenomics or metatranscriptomics, in the future. The increasing impact of anthropogenic factors on the Lake Ecosystem is expected to be a major challenge in the future as population growth continues to grow annually. This development could result in additional nutrient and organic matter loading and water quality deterioration. In addition, the development of fish aquaculture industries along the lake could supply other nutrients and organic matter loading. Moreover, fish cage aquaculture could supply more nutrients and organic matter loading. Again, the role of sulfate-reducing bacteria and methanogenic archaea will be important in driving the carbon cycle. Finally, from a limnological standpoint, future research can answer whether the lake can be a potential source or sink of Green House Gasses (GHGs) due to organic matter loading. In general, besides for global science purposes, all studies should be conducted in agreement with and supported by local government policies to ensure the holistic management of the lake.

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7 Appendix

7.1 Supplementary materials for Manuscript 1

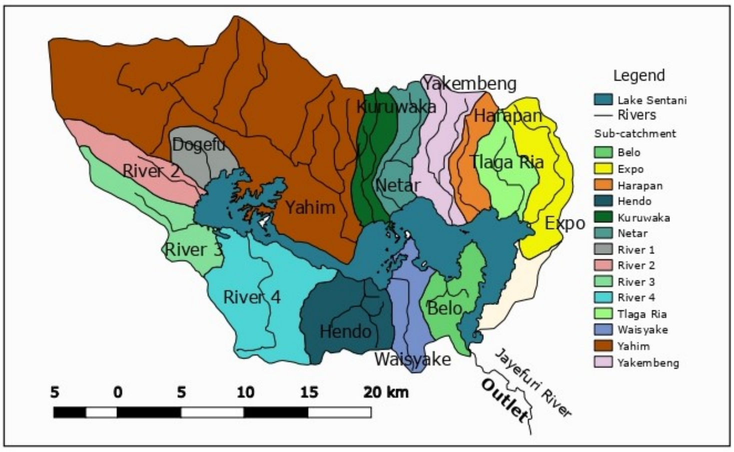

Figure SI 2.1. *The Sub-catchments in Lake Sentani (modified after Sartimbul et al., 2015)*

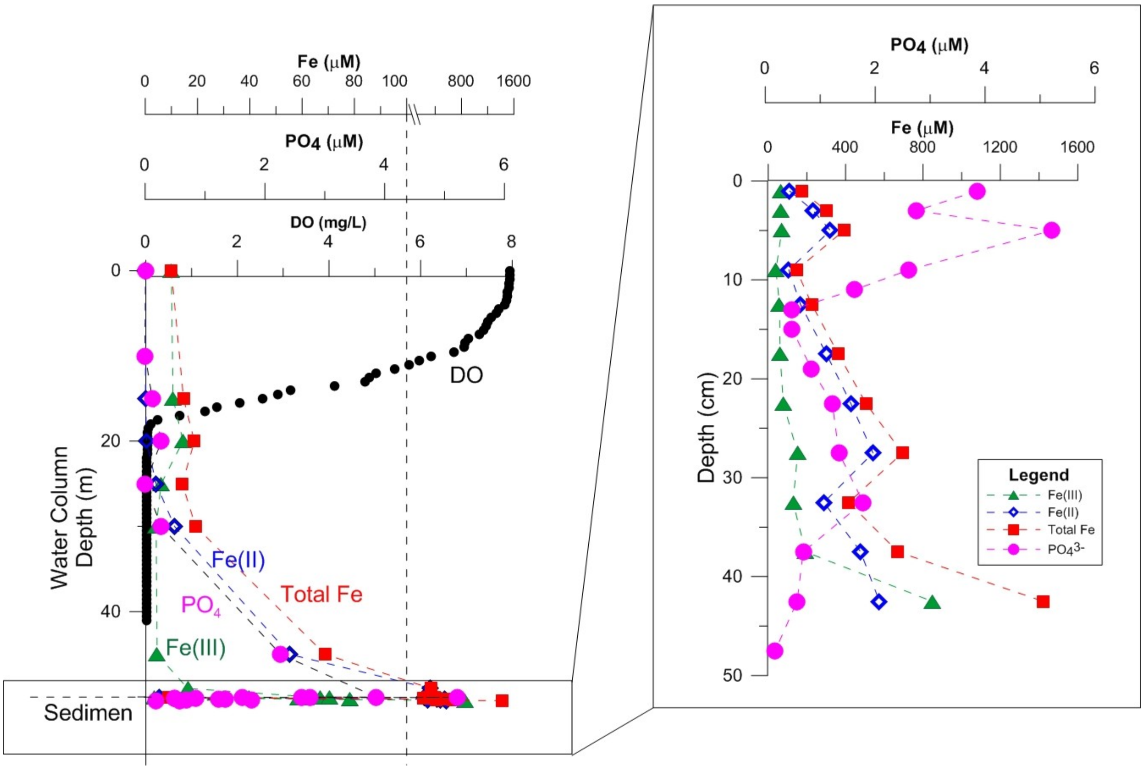

Figure SI 2.2. *Concentration profiles of Dissolved Oxygen (DO), iron species, and phosphate in the water column and sediment pore water at location 1. Inset: Iron speciation and phosphate profile in the porewater.*

Table SI 2.1. *Names and characteristics of the Lake Sentani's sub-catchments and their riversdraining into the lake. Many catchment areas and rivers are known under different names.*

Bungkang et al. (2014); Fauzi et al. (2014)				Handoko et al. (2014)	
Sub Catchments	Area (km^2)	Length of the river (m)	Slope (s)	Name of river	Debit m^{3}s^{-1}
1	17.1	5010	0.0581	Dogefu/Kanda	0.240
2	25.5	6281	0.0718		n/a
3	29.7	6822	0.0475		n/a
4	64.2	14099	0.053	Benali	0.144
Yahim	236.1	33670	0.0424	Doyo Kemiri	18.980 0.360
Kuruwaka	23.5	12165	0.1277	Belo Warno	0.620 5.470
Netar	24.8	12243	0.1034	Flavouw	0.360
Yakembeng	32.5	13061	0.0715	Yabawi	0.840
Harapan	18.9	9070	0.1072	Telaga maya	0.092
Expo	34.5	14877	0.0664	Espo	0.230
Tiaga Ria	24.4	7769	0.0667		n/a
Hendo	40.3	5815	0.0253		n/a
Belo	23.8	6733	0.0148	Jembatan 2	0.550
Waisyake	24.9	10598	0.0139		n/a

Table SI 2.2. *The correlation coefficient of elements used for XRF calibration*

No.	Elements	R^2
1	Al_2O_3	0.8
2	CaO	0.09
3	MgO	0.93
4	MnO	0.86
5	TiO_2	0.89
6	Fe_2O_3	0.76
7	K_2O	0.92
8	SO_3	0.68
9	SiO_2	0.82

Table SI 2.3. *Values of pH and porosity at location 1. We used these values for the Phreeqc and reaction rate calculations. Porosity is given as the ratio of the volume of pore water to the volumeof bulk sediment.*

Depth (cm)	pH	Porosity
1	6.8	0.983
3	6.8	0.968
5	6.8	0.953
7	6.9	0.949
9	6.9	0.968
12.5	6.8	0.988
17.5	6.8	0.949
22.5	6.8	0.933
27.5	6.8	0.922
32.5	6.8	0.93
37.5	6.7	0.971
47.5	6.6	0.943
52.5	6.	0.964

Table SI 2.4. *Main element concentrations in Lake Sentani sediment.*

Location	Element									
	Depth	SiO_2	Al_2O_3	TiO_2	K_2O	CaO	MgO	Fe_2O_3	MnO	SO_3	Other
	(cm)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Location 1	1	59.41	18.28	0.68	1.04	1.48	4.02	4.12	0.71	2.57	7.69
	3	59.07	19.04	0.74	1.12	1.53	4.00	2.87	0.97	2.57	8.10
	5	58.90	18.45	0.71	0.96	1.61	4.11	2.62	1.06	2.77	8.80
	7	61.23	15.28	0.57	0.70	1.21	5.40	3.03	1.61	3.87	7.10
	11	60.96	17.93	0.67	1.00	1.52	4.64	2.95	0.91	2.17	7.23
	13	60.47	16.53	0.65	0.93	1.47	4.86	3.67	0.91	2.99	7.52
	15	60.92	16.32	0.61	0.90	1.21	4.57	4.27	0.99	3.49	6.73
	17	60.77	17.71	0.68	1.07	1.38	4.09	3.17	0.97	3.03	7.13
	19	58.04	19.16	0.74	1.19	1.44	3.54	4.26	0.71	2.84	8.08
	21	55.84	22.84	0.86	1.90	1.37	3.75	4.28	0.63	1.56	6.99
	27.5	60.07	19.99	0.70	1.51	1.10	2.76	5.20	0.53	2.49	5.65
	32.5	58.02	19.28	0.73	1.49	1.34	3.10	6.56	0.40	2.45	6.64
	375	60.71	17.40	0.62	1.17	1.28	3.12	6.88	0.36	2.61	5.85
	42.5	60.31	18.93	0.73	1.29	1.41	3.89	3.50	0.76	2.33	6.85
	average	59.62	18.37	0.69	1.16	1.38	3.99	4.10	0.82	2.69	7.17
Location 2	1	48.11	17.78	0.71	1.00	2.16	4.57	12.01	0.22	2.24	11.22
	3	43.59	15.03	0.60	0.86	1.69	6.89	18.76	0.25	2.75	9.58
	5	42.28	17.73	0.75	0.98	2.39	6.36	13.64	0.24	2.04	13.60
	7	42.33	14.51	0.61	0.76	1.64	5.02	19.41	0.25	3.74	11.73
	9	42.54	14.97	0.65	0.90	1.81	5.25	18.35	0.23	3.88	11.41
	11	44.26	15.86	0.67	0.91	1.71	4.38	16.34	0.26	3.76	11.86
	13	43.46	17.48	0.81	1.20	2.01	4.98	13.38	0.29	3.21	13.19
	15	46.98	18.13	0.78	1.15	2.05	4.49	11.10	0.28	2.80	12.24
	17	44.65	16.85	0.68	0.91	1.71	5.17	14.78	0.32	3.18	11.73
	19	42.23	17.90	0.77	1.02	2.03	5.47	13.40	0.32	2.78	14.08
	22.5	46.57	17.37	0.74	1.06	1.80	4.03	12.68	0.29	3.54	11.92
	27.5	42.71	16.43	0.79	1.13	1.97	5.44	14.53	0.29	3.33	13.39
	32.5	45.23	16.63	0.66	0.92	1.65	4.90	15.75	0.29	3.27	10.71
	average	44.23	16.67	0.71	0.98	1.89	5.15	14.93	0.27	3.12	12.05
Location 3	1	47.69	15.28	0.56	0.69	2.05	10.87	11.77	0.36	1.61	9.11
	3	48.50	14.72	0.48	0.62	1.60	9.26	15.70	0.29	1.66	7.16
	5	49.61	17.42	0.57	0.86	1.81	8.63	12.20	0.29	1.19	7.42
	7	45.68	16.19	0.53	0.69	1.94	11.86	13.80	0.29	0.99	8.02
	9	41.61	15.10	0.55	0.65	2.04	19.97	10.29	0.47	0.69	8.64
	11	45.32	11.72	0.42	0.43	1.89	20.08	11.42	0.43	1.12	7.18
	13	52.37	13.85	0.48	0.56	1.78	10.61	11.06	0.37	1.58	7.33
	15	49.13	13.18	0.48	0.62	1.72	13.37	12.74	0.37	1.51	6.88
	17	60.43	12.49	0.41	0.59	1.40	6.67	10.52	0.29	2.49	4.70
	19	53.15	12.49	0.46	0.50	1.84	10.33	10.92	0.38	2.12	7.80
	22.5	45.96	14.65	0.57	0.71	2.05	10.13	13.80	0.32	2.08	9.73
	27.5	49.19	14.82	0.58	0.74	1.84	6.46	13.92	0.28	2.74	9.43
	32	44.10	14.41	0.61	0.83	1.96	10.13	14.73	0.36	3.01	9.86
	average	48.67	14.33	0.51	0.65	1.84	11.41	12.53	0.35	1.75	7.94
Location 4	1	47.52	11.25	0.45	0.36	2.08	6.85	15.48	0.26	3.92	11.84
	3	48.39	12.67	0.47	0.44	1.95	10.31	12.98	0.38	2.41	9.99
	5	43.52	13.09	0.52	0.49	2.12	16.41	10.69	0.55	1.71	10.90
	7	45.41	12.29	0.49	0.39	2.12	14.73	9.25	0.69	2.45	12.17
	9	45.72	9.53	0.36	0.28	1.40	16.47	13.79	0.72	3.24	8.49
	11	45.90	12.07	0.47	0.35	2.10	16.84	6.12	1.17	3.08	11.90
	13	54.61	11.71	0.43	0.37	1.60	9.07	8.38	0.73	4.15	8.95
	15	56.28	13.28	0.49	0.43	1.96	8.64	5.31	0.79	3.18	9.63
	19	53.18	10.36	0.42	0.28	1.89	12.62	5.94	1.02	3.66	10.64
	22.5	51.19	10.54	0.44	0.32	1.80	11.66	8.30	0.81	4.11	10.84
	27.5	43.56	10.18	0.42	0.32	1.66	15.02	12.37	0.79	4.48	11.19
	32.5	47.05	11.34	0.47	0.44	1.52	9.97	13.21	0.64	5.14	10.22
	37.5	48.69	13.84	0.59	0.53	2.02	9.42	6.78	0.90	4.12	13.11
	average	48.54	11.70	0.46	0.38	1.86	12.15	9.89	0.73	3.51	10.76

7.2 Supplementary materials for Manuscript 2

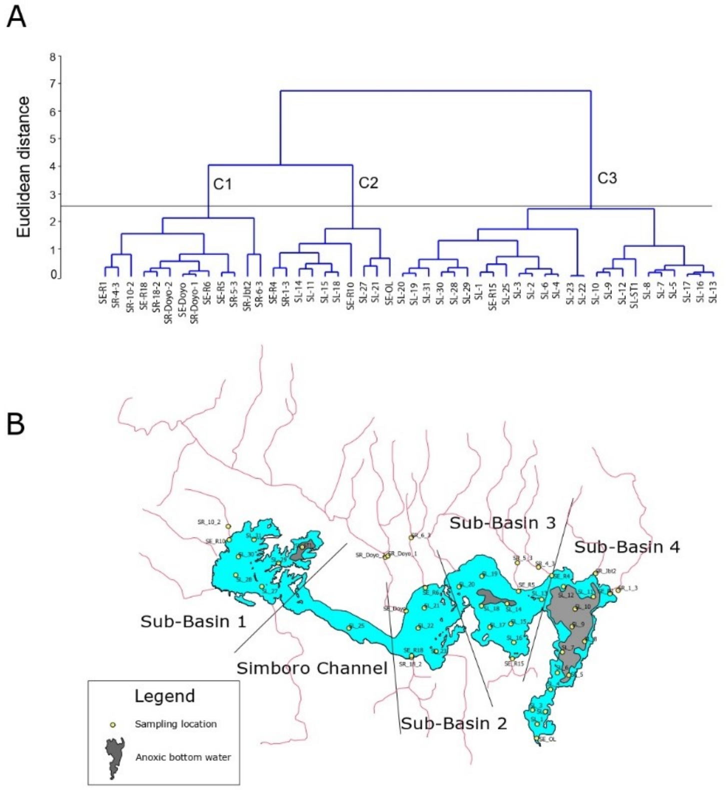

Figure SI 3.1 *Full clustering analysis and sample location codes*

Table SI 3.1 *Results of smear slide analyses*

No	SUB-BASIN	Environment	Catchment	Sample code (Fig. SI3)	Si diatoms	Si spicules	Si detrital	Qtz	Mafics	Carbonate	Carbonate (possible origin)
1	Simboro	channel oxic		SL-25 (few	10%	35%	50%	common	rare	NO	
2	1	lake oxic		SL-28	60%	10%	20%	present	present	present	<50 m; micritic-like, clotts; authigenic?
3	1	lake oxic		SL-31	65%	5-10%	25%	common	present	NO	
4	1	lake anoxic		SL-ST1	85%	NO	10-15%	present	present	present	<50 m; micritic-like, clotts; authigenic?
5	1	river mouth (N)	alluvial	SE-R10	1-2%	5-7%	80%	abundant	present	NO	
6	1	river (N)	alluvial	SE-102	1-2%	1-2%	95%	abundant	present	NO	
7	2	lake oxic		SL-21	5%	10-15%	70%	common	abundant	present	microstructure; biogenic?
8	2	lake oxic		SL-22 (few materi	5%	25%	60%	common	present	present	microstructure; biogenic?
9	2	estuary (N)	mafic	SE- 6	10%	NO	80%	present	abundant	NO	
10	2	river (N)	mafic	SR- 6-3	NO	NO	100%	present	abundant	NO	
11	2	river mouth (S)	alluvial/limestone	SE-R18	12-15%	NO	75%	abundant	common	present?	50 m, sub-euhedral
12	2	river (S)	alluvial/limestone	SR-18-2	5%	NO	95%	abundant	abundant	present?	>50 m, sub-euhedral, corroded; detrital?
13	3	lake anoxic		SL-14	30-40%	NO	40-50%	common	common	NO	
14	3	lake anoxic		SL-18	60%	5%	35%	common	common	NO	
15	3	lake oxic		SL-16	60%	10%	30%	present	present	NO	
16	3	lake oxic		SL-19	25%	2-5%	65%	common	common	NO	
17	3	estuary (S)	alluvial	SE-R15	5-7%	10-15%	60%	common	common	NO	
18	4	lake anoxic		SL-10	60%	5%	30%	present	common	NO	
19	4	lake anoxic		SL-7	60%	5-10%	20-30%	present	present	NO	
20	4	lake oxic		SL-1	5%	15%	70%	common	abundant	NO	
21	4	lake oxic		SL-13	50%	5-10%	35-40%	present	common	NO	
22	4	river mouth(N)	ultramafic	SE-R4	5%	2%	85%	present	abundant	NO	
23	3/4	river (N)	ultramafic	SR-4-3	NO	NO	100%	common	abundant	NO	
24	4	river (S)	alluvial/siltstone	SE-OL	30-40%	2%	50%	common	common	NO	

7.3 Supplementary materials for Manuscript 3

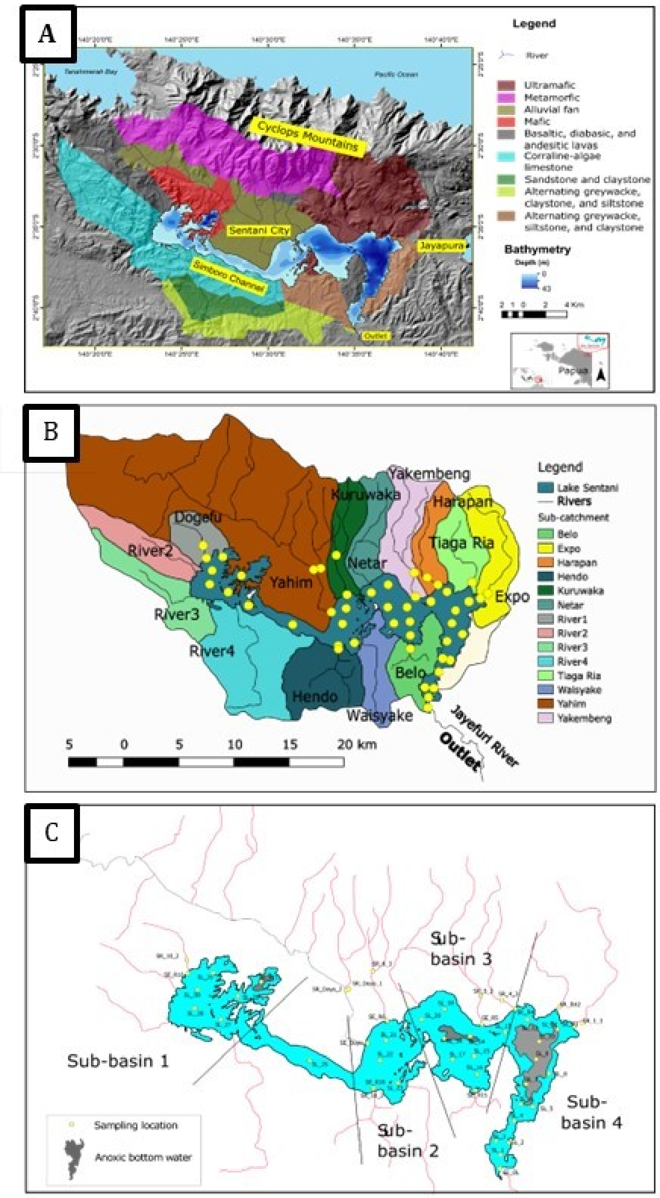

Figure SI 4.1 *Lake Characteristics. (A) Map of Lake Sentani and its surrounding watershed. Catchment lithology is indicated by different colors. The lake is bounded by the Cyclops Mountains to the north and lowlands to the south. The low-resolution bathymetric map is modified after Sadi (2014) with the deepest part at 43 m, the lithology of Lake Sentani's* catchment is modified after Suwarna and Noya (1995) and the catchment boundary is modified after Sartimbul et al. (2015). (B) The Sub-catchments in Lake Sentani (modified after Sartimbul et al., 2015) and sampling location (yellow circles). (C) The division of sub-basins and anoxic bottom water zones in Lake Sentani.

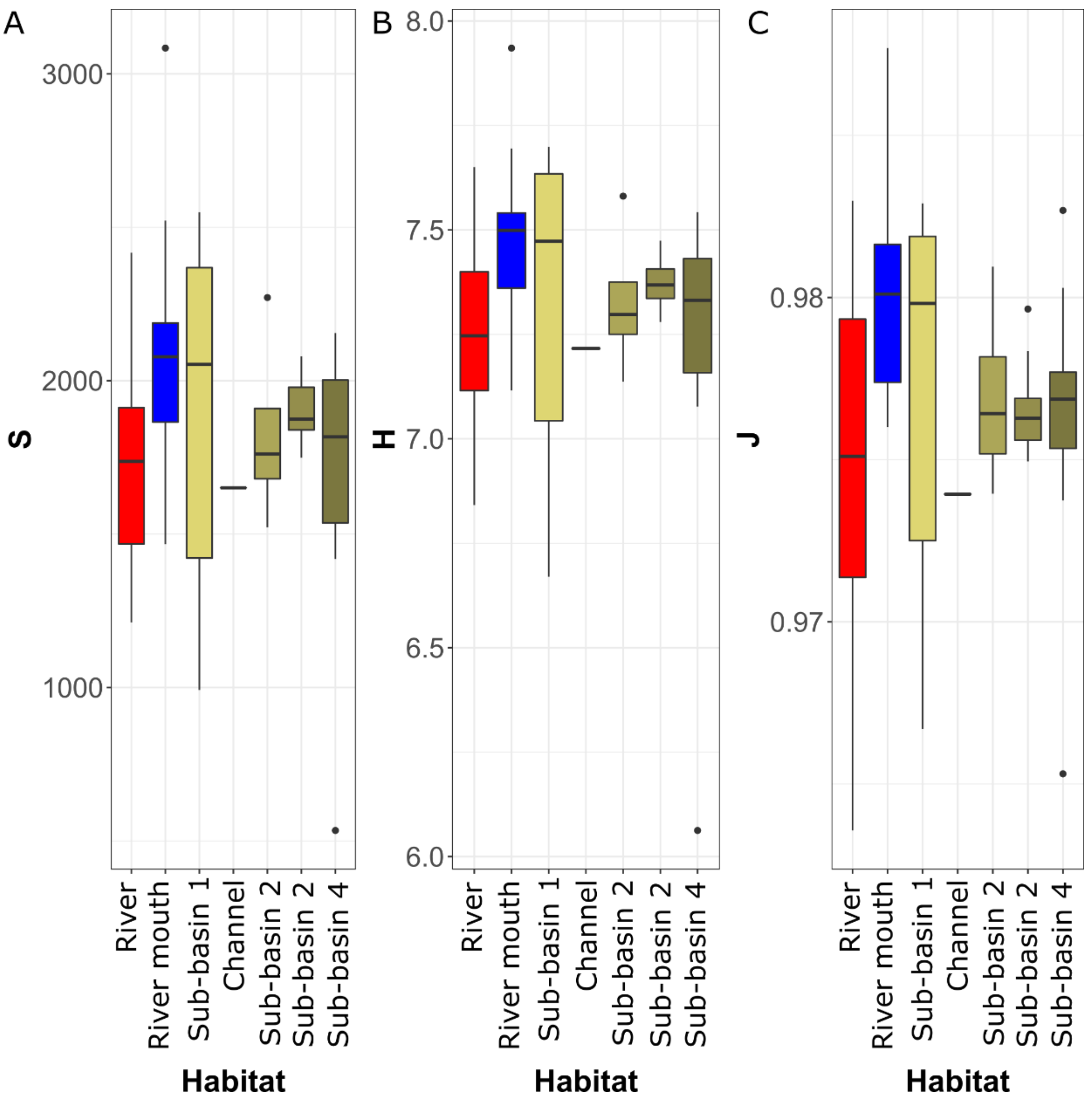

Figure SI 4.2 *Alpha diversity measurements based on the relative abundance of observed ASVs: A) Species richness (S), B) Shannon indices (H), and C) Evenness indices (J). The habitats refer to Figure 1B. Before calculation, each sample was rarefied 100 times to a depth of 10,000 sequences.*

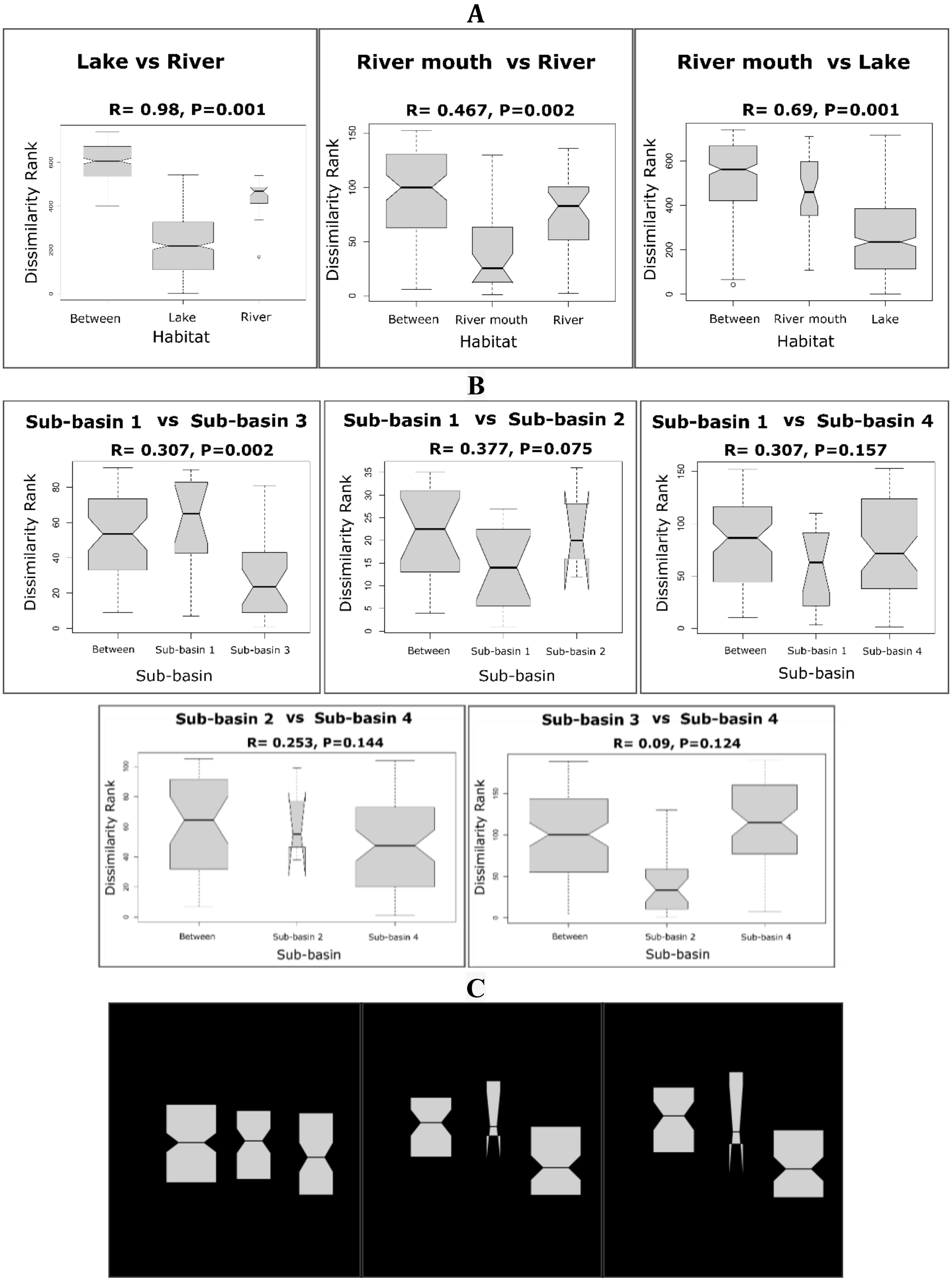

Figure SI 4.3 *ANOSIM (Analysis of similarity) test results between habitats (A), sub-basins (B) and the condition of water column (C). R-value indicates a very high degree of separation between habitats which ranges from -1 to 1, with 1 indicating complete separation of habitats and -1 indicating complete overlap. Significance if p <0.05. Permutation 999. The dissimilarity metric used is Bray-Curtis dissimilarity, which measures the difference in species composition between habitats.*

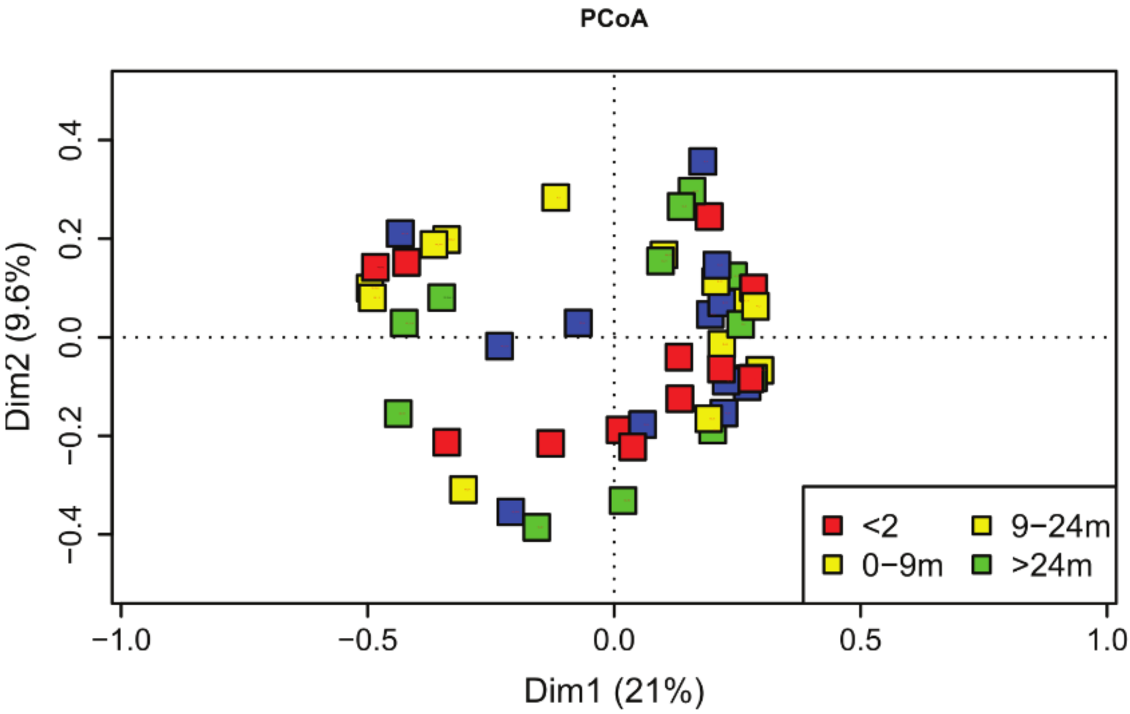

Figure SI 4.4. *Microbial Community Structure Analysis of Euphotic (<9 m) and Anoxic Zones (>24m) using PCoA and Bray-Curtis Distances.*

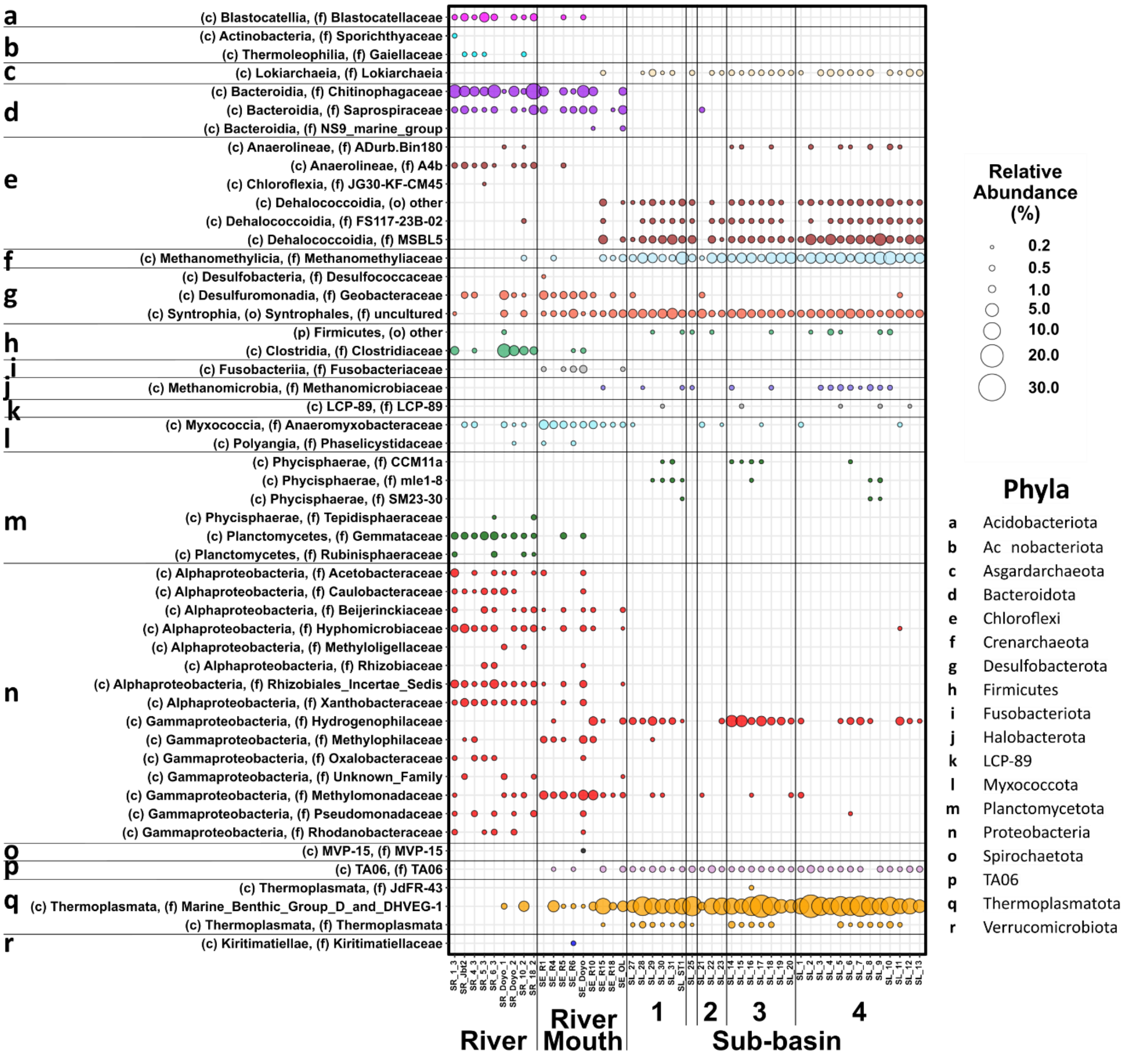

Figure SI 4.5. *Bubble Plot depicting microbial relative abundance at family level, as determined by Indicator Species Analysis (p=0.005), using a 0.2% abundance cut-off.*

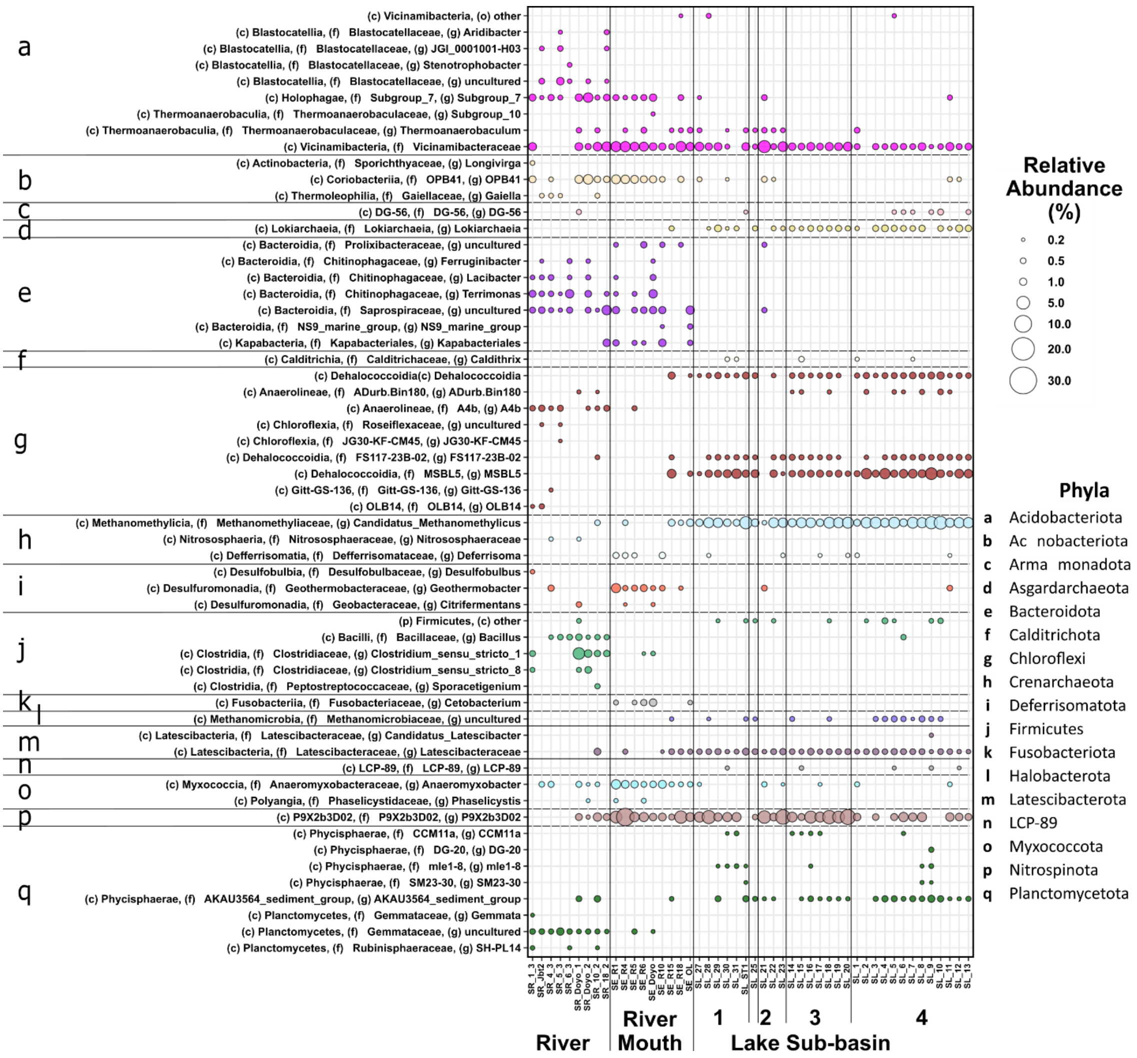

Figure SI 4.6. *Bubble Plot depicting relative microbial abundance at genus level, as determined by Indicator Species Analysis (p=0.005), using a 0.2% abundance cut-off.*

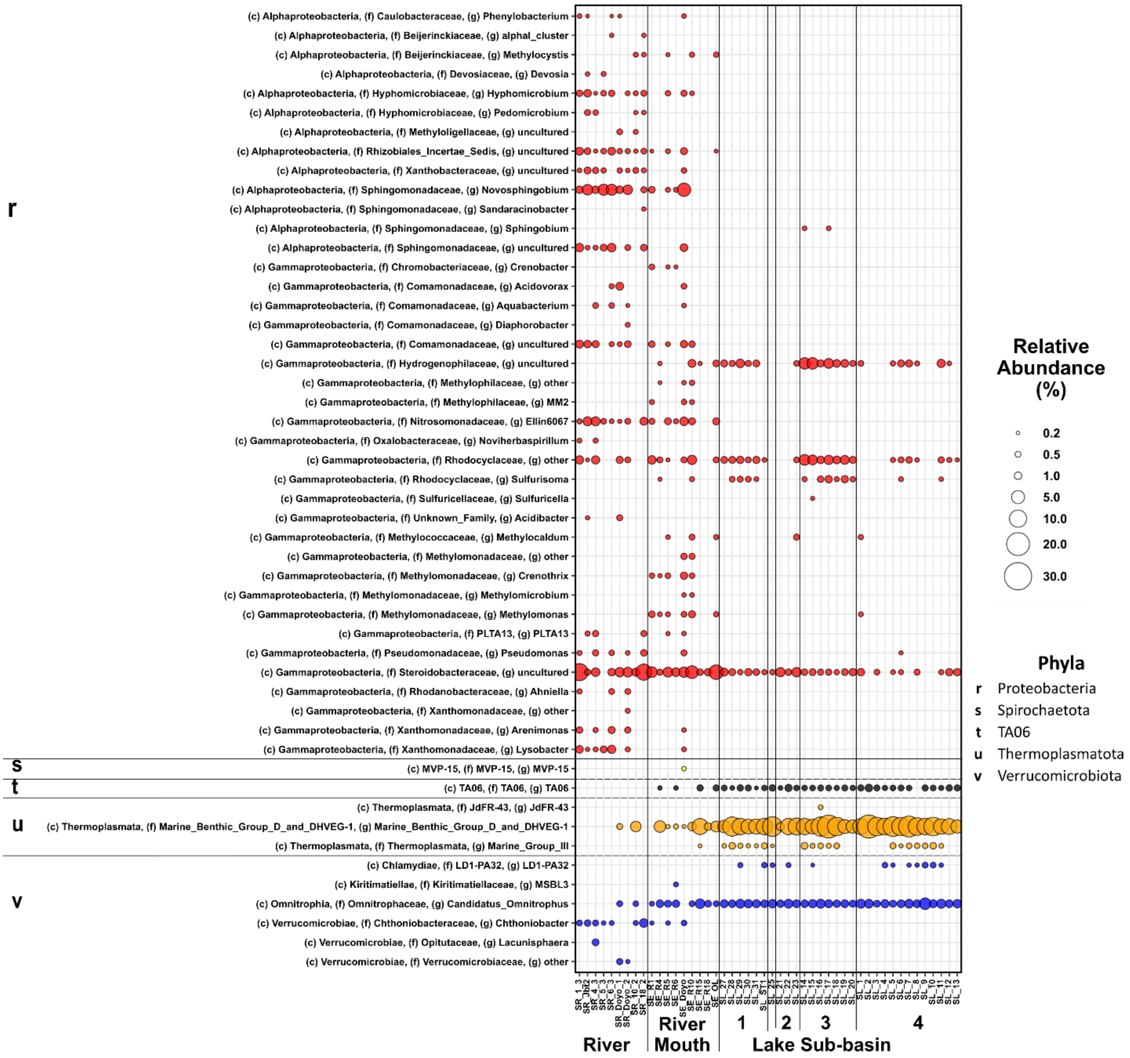

Figure SI 4.6 (continued). *Bubble Plot depicting microbial relative abundance at genus level, as determined by Indicator Species Analysis (p=0.005), using a 0.2% abundance cut-off.*

Table SI 4.1. *The Alpha diversity results. S= Species Richness, H= Shannon Indices, J= Evenness Indices*

Habitat	Location	ASV's total read	S	H	J
River	SR_1_3	116268	1341	6.9670	0.9675
	SR_10_2	52152	2049	7.4957	0.9830
	SR_18_2	96023	1542	7.1286	0.9711
	SR_4_3	114702	1929	7.4084	0.9793
	SR_5_3	140226	1758	7.2609	0.9718
	SR_6_3	136948	1187	6.8140	0.9625
	SR_Doyo_1	39351	1460	7.1051	0.9751
	SR_Doyo_2	101930	1841	7.3314	0.9752
	SR_Jbt2	225572	2408	7.6457	0.9819
	Min	39351	1187	6.8140	0.9625
	Max	225572	2408	7.6457	0.9830
	Median	114702	1758	7.2609	0.9751
	Q1	-	1460	7.1051	0.9711
	Q3	-	1929	7.4084	0.9793
	Q3-Q1	-	469	0.3033	0.0082
River mouth	SE_Doyo	97760	2226	7.5605	0.9809
	SE_OL	46793	1463	7.1110	0.9757
	SE_R1	169342	1907	7.3854	0.9778
	SE_R10	115916	1723	7.2803	0.9770
	SE_R15	169467	2434	7.6561	0.9819
	SE_R18	235214	2065	7.4956	0.9820
	SE_R4	181165	2153	7.5195	0.9798
	SE_R5	250876	3068	7.9320	0.9879
	SE_R6	102093	1965	7.4182	0.9782
	Min	46793	1463	7.1110	0.9757
	Max	250876	3068	7.9320	0.9879
	Median	169342	2065	7.4956	0.9798
	Q1	-	1907	7.3854	0.9778
	Q3	-	2226	7.5605	0.9819
	Q3-Q1	-	319	0.1751	0.0041
Sub-basin 1	SL_27	104852	2393	7.6478	0.9830
	SL_28	65893	1263	6.9352	0.9711
	SL_29	165368	2501	7.6806	0.9816
	SL_30	264922	1952	7.4102	0.9780
	SL_31	58015	1012	6.6887	0.9666
	SL_ST1	141358	2210	7.5601	0.9817
	Min	58015	1012	6.6887	0.9666
	Max	264922	2501	7.6806	0.9830
	Median	123105	2081	7.4852	0.9798
	Q1	-	1435.25	7.0539	0.9729
	Q3	-	2347.25	7.6259	0.9817
	Q3-Q1	-	912	0.5719	0.0088
Shallow Channel	SL_25	121234	1644	7.2110	0.9738
	Min	121234	1644	7.2110	0.9738
	Max	121234	1644	7.2110	0.9738
	Median	121234	1644	7.2110	0.9738
	Q1		1644	7.2110	0.9738
	Q3		1644	7.2110	0.9738
	Q3-Q1		0	0.0000	0.0000

Habitat	Location	ASV's total read	S	H	J
Sub-basin 2	SL_21	175763	2283	7.5852	0.9809
	SL_22	88607	1547	7.1534	0.9740
	SL_23	130261	1818	7.3202	0.9753
	Min	88607	1547	7.1534	0.9740
	Max	175763	2283	7.5852	0.9809
	Median	130261	1818	7.3202	0.9753
	Q1	-	1682.5	7.2368	0.9747
	Q3	-	2050.5	7.4527	0.9781
	Q3-Q1	-	368	0.2159	0.0034
Sub-basin 3	SL_14	149733	2062	7.4638	0.9780
	SL_15	84068	1875	7.3825	0.9796
	SL_16	144947	1868	7.3604	0.9771
	SL_17	165352	1924	7.3766	0.9755
	SL_18	125043	1787	7.3139	0.9767
	SL_19	165829	1744	7.2755	0.9748
	SL_20	184765	1877	7.3520	0.9754
	Min	84068	1744	7.2755	0.9748
	Max	184765	2062	7.4638	0.9796
	Median	149733	1875	7.3604	0.9767
	Q1	-	1827.5	7.3329	0.9754
	Q3	-	1900.5	7.3795	0.9776
	Q3-Q1	-	73	0.0466	0.0022
Sub-basin 4	SL_1	180915	1918	7.3837	0.9768
	SL_2	12729	536	6.0646	0.9651
	SL_3	203279	1745	7.2699	0.9739
	SL_4	104915	1413	7.0707	0.9748
	SL_5	128142	2145	7.5084	0.9788
	SL_6	108849	1774	7.3046	0.9764
	SL_7	126648	1865	7.3577	0.9770
	SL_8	68304	1583	7.1923	0.9763
	SL_9	91044	2022	7.4635	0.9805
	SL_10	39718	1491	7.1308	0.9759
	SL_11	86877	2154	7.5382	0.9822
	SL_12	188415	1972	7.4061	0.9762
	SL_13	292628	2103	7.4742	0.9769
	Min	12729	536	6.0646	0.9651
	Max	292628	2154	7.5382	0.9822
	Median	108849	1865	7.3577	0.9764
	Q1	-	1583	7.1923	0.9759
	Q3	-	2022	7.4635	0.9770
	Q3-Q1	-	439	0.2712	0.0011

Table SI 4.2. *Relative abundance (%) of microbial community in Lake Sentani at Phyla Level (Bacteria)*

.

Location	Habitat	Proteobacteria	Thermoplasmatota	Bacteroidota	Crenarchaeota	Chloroflexi
SR_1_3	River	50.96	0.04	9.52	0.09	6.99
SR_Jbt2	River	45.22	0.10	12.42	0.83	4.95
SR_4_3	River	40.74	0.25	9.37	2.01	4.33
SR_5_3	River	48.35	0.17	3.76	0.23	3.93
SR_6_3	River	54.14	0.10	20.24	0.07	1.30
SR_Doyo_1	River	20.37	0.71	8.18	1.34	14.10
SR_Doyo_2	River	27.48	0.05	12.81	0.20	4.60
SR_10_2	River	12.42	3.48	4.26	2.36	12.22
SR_18_2	River	32.48	0.04	14.59	0.22	5.97
Min		**12.42**	**0.04**	**3.76**	**0.07**	**1.30**
Max		**54.14**	**3.48**	**20.24**	**2.36**	**14.10**
SE_R1	River mouth	28.89	0.20	10.36	0.13	6.62
SE_R4	River mouth	10.22	4.30	4.39	1.36	13.36
SE_R5	River mouth	20.43	0.52	9.45	0.66	10.06
SE_R6	River mouth	9.01	0.98	16.07	0.29	5.46
SE_Doyo	River mouth	43.65	0.26	11.76	0.76	5.27
SE_R10	River mouth	36.85	2.16	12.52	1.16	4.85
SE_R15	River mouth	7.04	9.64	2.34	15.46	14.27
SE_R18	River mouth	6.11	1.87	6.54	0.63	13.90
SE_OL	River mouth	24.12	3.52	10.03	6.55	8.75
Min		**6.11**	**0.20**	**2.34**	**0.13**	**4.85**
Max		**43.65**	**9.64**	**16.07**	**15.46**	**14.27**
SL_27	Sub-Basin 1	13.75	5.79	5.10	2.05	9.70
SL_28	Sub-Basin 1	19.57	15.03	1.63	3.71	10.83
SL_29	Sub-Basin 1	10.75	10.51	2.30	5.44	13.01
SL_30	Sub-Basin 1	24.21	8.39	3.08	2.31	10.28
SL_31	Sub-Basin 1	24.19	8.19	1.36	3.24	9.99
SL_ST1	Sub-Basin 1	3.69	10.31	2.65	8.40	14.64
Min		**3.69**	**5.79**	**1.36**	**2.05**	**9.70**
Max		**24.21**	**15.03**	**5.10**	**8.40**	**14.64**
SL_25	Shallow channel	6.20	15.22	1.54	19.38	9.74
Min		**6.20**	**15.22**	**1.54**	**19.38**	**9.74**
Max		**6.20**	**15.22**	**1.54**	**19.38**	**9.74**
SL_21	Sub-Basin 2	9.57	1.58	11.39	0.66	6.62
SL_22	Sub-Basin 2	11.03	9.82	1.04	13.11	11.88
SL_23	Sub-Basin 2	17.85	11.18	2.16	4.18	13.35
Min		**9.57**	**1.58**	**1.04**	**0.66**	**6.62**
Max		**17.85**	**11.18**	**11.39**	**13.11**	**13.35**
SL_14	Sub-Basin 3	20.48	11.00	2.66	4.11	11.07
SL_15	Sub-Basin 3	14.04	7.65	2.91	5.53	11.73
SL_16	Sub-Basin 3	12.05	14.37	2.19	4.69	12.48
SL_17	Sub-Basin 3	16.80	22.44	2.30	2.92	9.37
SL_18	Sub-Basin 3	9.61	13.42	1.25	6.30	17.95
SL_19	Sub-Basin 3	23.03	6.79	2.16	5.95	11.94
SL_20	Sub-Basin 3	21.22	5.69	2.51	5.47	12.06
Min		**9.61**	**5.69**	**1.25**	**2.92**	**9.37**
Max		**23.03**	**22.44**	**2.91**	**6.30**	**17.95**
SL_1	Sub-Basin 4	21.93	9.70	5.20	6.17	8.94
SL_2	Sub-Basin 4	2.27	22.95	0.60	12.26	10.84
SL_3	Sub-Basin 4	20.80	13.96	1.26	10.69	10.59

Location	Habitat	Proteobacteria	Thermoplasmatota	Bacteroidota	Crenarchaeota	Chloroflexi
SL_4	Sub-Basin 4	7.01	11.29	0.61	19.09	12.81
SL_5	Sub-Basin 4	3.53	15.75	1.63	8.58	15.91
SL_6	Sub-Basin 4	9.31	13.25	1.39	5.15	15.56
SL_7	Sub-Basin 4	6.47	17.28	1.26	8.21	16.66
SL_8	Sub-Basin 4	5.99	12.26	0.82	9.45	19.12
SL_9	Sub-Basin 4	0.63	11.16	1.49	9.87	15.42
SL_10	Sub-Basin 4	2.69	14.32	1.20	12.92	16.76
SL_11	Sub-Basin 4	7.85	10.51	3.25	3.35	13.85
SL_12	Sub-Basin 4	17.41	9.41	1.20	10.69	12.51
SL_13	Sub-Basin 4	22.66	6.63	1.17	7.49	12.50
Min		**0.63**	**6.63**	**0.60**	**3.35**	**8.94**
Max		**22.66**	**22.95**	**5.20**	**19.09**	**19.12**

Table SI 4.2. *(continued) Relative abundance (%) of microbial community in Lake Sentani at Phyla Level (Bacteria)*

Location	Habitat	Acidobacteriota	Sva0485	Verrucomicrobiota	Firmicutes	Nitrospinota
SR_1_3	River	5.67	0.04	3.80	4.47	0.14
SR_Jbt2	River	8.84	0.02	4.33	0.27	0.00
SR_4_3	River	8.74	0.19	6.00	1.97	0.09
SR_5_3	River	5.27	0.11	2.00	8.70	0.07
SR_6_3	River	1.99	0.07	4.52	6.38	0.00
SR_Doyo_1	River	11.90	0.50	3.22	8.80	0.88
SR_Doyo_2	River	8.62	0.05	2.94	11.68	0.24
SR_10_2	River	16.55	2.74	4.02	3.77	1.55
SR_18_2	River	14.88	0.13	11.34	3.08	0.91
Min		**1.99**	**0.02**	**2.00**	**0.27**	**0.00**
Max		**16.55**	**2.74**	**11.34**	**11.68**	**1.55**
SE_R1	River mouth	8.09	0.22	12.42	1.59	4.01
SE_R4	River mouth	11.10	2.63	4.70	0.99	11.03
SE_R5	River mouth	10.38	0.84	7.38	1.49	2.15
SE_R6	River mouth	10.62	1.35	11.06	3.90	2.02
SE_Doyo	River mouth	7.77	0.24	5.55	2.34	1.11
SE_R10	River mouth	4.49	2.01	5.43	0.33	1.26
SE_R15	River mouth	7.30	10.11	3.81	0.54	0.58
SE_R18	River mouth	15.82	1.20	10.73	3.03	4.65
SE_OL	River mouth	8.14	4.88	4.79	0.42	1.82
Min		**4.49**	**0.22**	**3.81**	**0.33**	**0.58**
Max		**15.82**	**10.11**	**12.42**	**3.90**	**11.03**
SL_27	Sub-Basin 1	9.76	3.80	7.43	1.46	2.70
SL_28	Sub-Basin 1	6.60	4.72	3.75	0.50	5.33
SL_29	Sub-Basin 1	9.16	3.66	7.67	0.96	1.50
SL_30	Sub-Basin 1	4.51	6.54	4.94	0.46	1.99
SL_31	Sub-Basin 1	3.29	13.97	2.32	0.53	1.94
SL_ST1	Sub-Basin 1	13.00	4.54	4.64	1.31	0.16
Min		**3.29**	**3.66**	**2.32**	**0.46**	**0.16**
Max		**13.00**	**13.97**	**7.67**	**1.46**	**5.33**
SL_25	Shallow channel	4.16	8.24	3.12	0.75	0.46
Min		**4.16**	**8.24**	**3.12**	**0.75**	**0.46**
Max		**4.16**	**8.24**	**3.12**	**0.75**	**0.46**
SL_21	Sub-Basin 2	13.74	2.11	10.29	2.40	4.79
SL_22	Sub-Basin 2	5.38	8.68	3.44	0.72	1.24
SL_23	Sub-Basin 2	9.61	3.49	4.38	0.45	6.92
Min		**5.38**	**2.11**	**3.44**	**0.45**	**1.24**
Max		**13.74**	**8.68**	**10.29**	**2.40**	**6.92**
SL_14	Sub-Basin 3	7.73	3.57	4.51	0.62	2.41
SL_15	Sub-Basin 3	10.12	3.86	4.84	1.28	0.90
SL_16	Sub-Basin 3	8.44	5.25	5.38	0.51	4.29
SL_17	Sub-Basin 3	6.41	4.05	4.57	0.52	2.61
SL_18	Sub-Basin 3	10.88	3.55	3.39	0.71	5.59
SL_19	Sub-Basin 3	7.00	4.81	4.04	0.52	4.16
SL_20	Sub-Basin 3	8.00	3.79	4.63	0.48	7.42
Min		**6.41**	**3.55**	**3.39**	**0.48**	**0.90**
Max		**10.88**	**5.25**	**5.38**	**1.28**	**7.42**
SL_1	Sub-Basin 4	4.83	8.59	4.91	0.46	1.09
SL_2	Sub-Basin 4	7.42	8.41	2.19	0.53	0.20
SL_3	Sub-Basin 4	4.50	5.38	3.19	0.57	0.73

Location	Habitat	Acidobacteriota	Sva0485	Verrucomicrobiota	Firmicutes	Nitrospinota
SL_4	Sub-Basin 4	5.11	6.29	2.55	1.00	0.14
SL_5	Sub-Basin 4	10.84	3.91	4.48	0.82	0.90
SL_6	Sub-Basin 4	7.97	7.71	3.48	2.69	2.11
SL_7	Sub-Basin 4	8.19	4.52	3.68	0.78	1.46
SL_8	Sub-Basin 4	12.40	5.75	2.64	0.69	1.96
SL_9	Sub-Basin 4	10.65	9.31	5.58	1.05	0.03
SL_10	Sub-Basin 4	9.24	5.30	3.21	1.24	0.19
SL_11	Sub-Basin 4	11.95	2.46	6.57	1.01	1.56
SL_12	Sub-Basin 4	5.02	6.03	2.38	0.63	1.18
SL_13	Sub-Basin 4	5.28	7.41	2.75	0.60	0.88
Min		**4.50**	**2.46**	**2.19**	**0.46**	**0.03**
Max		**12.40**	**9.31**	**6.57**	**2.69**	**2.11**

Table SI 4.2. *(continued) Relative abundance (%) of microbial community in Lake Sentani at Phyla Level (Bacteria)*

Location	Habitat	Euryarchaeota	Desulfobacterota	Cyanobacteria	Actinobacteriota	Nanoarchaeota
SR_1_3	River	3.12	2.34	0.24	5.07	0.05
SR_Jbt2	River	0.00	1.34	0.50	3.15	0.22
SR_4_3	River	0.04	2.45	1.24	1.93	0.81
SR_5_3	River	0.08	0.27	8.19	7.32	0.02
SR_6_3	River	0.08	0.18	1.09	2.27	0.01
SR_Doyo_1	River	0.25	6.41	0.72	3.63	0.30
SR_Doyo_2	River	10.06	2.62	0.98	6.52	0.14
SR_10_2	River	1.59	5.45	0.06	3.72	0.76
SR_18_2	River	0.24	1.86	0.74	2.15	0.14
Min		**0.00**	**0.18**	**0.06**	**1.93**	**0.01**
Max		**10.06**	**6.41**	**8.19**	**7.32**	**0.81**
SE_R1	River mouth	0.62	6.19	1.38	2.95	0.48
SE_R4	River mouth	0.50	5.54	0.07	3.97	1.11
SE_R5	River mouth	0.70	5.76	0.36	3.94	1.46
SE_R6	River mouth	1.02	9.07	0.45	3.02	2.61
SE_Doyo	River mouth	0.56	3.68	0.78	2.66	0.16
SE_R10	River mouth	0.87	5.99	0.35	2.17	1.78
SE_R15	River mouth	1.60	3.94	0.07	0.89	1.61
SE_R18	River mouth	0.58	6.03	0.28	1.62	0.78
SE_OL	River mouth	1.59	3.90	1.30	1.25	0.91
Min		**0.50**	**3.68**	**0.07**	**0.89**	**0.16**
Max		**1.60**	**9.07**	**1.38**	**3.97**	**2.61**
SL_27	Sub-Basin 1	1.05	8.50	0.32	1.81	1.01
SL_28	Sub-Basin 1	1.43	5.93	0.01	0.54	0.46
SL_29	Sub-Basin 1	2.70	5.12	0.10	0.77	1.28
SL_30	Sub-Basin 1	0.91	8.47	0.01	1.04	0.70
SL_31	Sub-Basin 1	1.37	9.47	0.01	0.84	0.44
SL_ST1	Sub-Basin 1	2.12	3.74	0.06	1.69	2.30
Min		**0.91**	**3.74**	**0.01**	**0.54**	**0.44**
Max		**2.70**	**9.47**	**0.32**	**1.81**	**2.30**
SL_25	Shallow channel	4.89	2.84	0.10	0.81	3.35
Min		**4.89**	**2.84**	**0.10**	**0.81**	**3.35**
Max		**4.89**	**2.84**	**0.10**	**0.81**	**3.35**
SL_21	Sub-Basin 2	0.85	9.03	0.31	2.37	1.02
SL_22	Sub-Basin 2	4.14	4.34	0.00	1.23	2.18
SL_23	Sub-Basin 2	1.25	3.54	0.10	0.71	1.10
Min		**0.85**	**3.54**	**0.00**	**0.71**	**1.02**
Max		**4.14**	**9.03**	**0.31**	**2.37**	**2.18**
SL_14	Sub-Basin 3	1.41	6.64	0.02	1.48	1.20
SL_15	Sub-Basin 3	1.28	7.60	0.02	2.29	1.03
SL_16	Sub-Basin 3	1.26	4.72	0.07	0.63	0.85

Location	Habitat	Euryarchaeota	Desulfobacterota	Cyanobacteria	Actinobacteriota	Nanoarchaeota
SL_17	Sub-Basin 3	0.88	5.27	0.02	0.68	0.91
SL_18	Sub-Basin 3	1.24	3.97	0.04	0.73	0.51
SL_19	Sub-Basin 3	1.46	5.23	0.00	0.69	0.78
SL_20	Sub-Basin 3	0.76	3.95	0.10	0.75	0.77
Min		**0.76**	**3.95**	**0.00**	**0.63**	**0.51**
Max		**1.46**	**7.60**	**0.10**	**2.29**	**1.20**
SL_1	Sub-Basin 4	1.77	3.62	1.84	0.83	2.14
SL_2	Sub-Basin 4	2.37	3.06	0.00	0.09	7.27
SL_3	Sub-Basin 4	1.85	3.95	0.32	0.44	1.78
SL_4	Sub-Basin 4	4.26	3.89	0.01	0.56	3.83
SL_5	Sub-Basin 4	1.42	4.47	0.09	0.68	0.80
SL_6	Sub-Basin 4	1.08	5.64	0.06	0.51	0.61
SL_7	Sub-Basin 4	0.95	4.84	0.08	0.68	1.66
SL_8	Sub-Basin 4	2.77	3.62	0.03	0.26	0.89
SL_9	Sub-Basin 4	3.62	2.90	0.01	0.95	2.96
SL_10	Sub-Basin 4	4.19	3.45	0.01	0.78	1.68
SL_11	Sub-Basin 4	0.49	6.24	0.19	1.70	1.76
SL_12	Sub-Basin 4	3.26	5.59	0.02	1.52	1.80
SL_13	Sub-Basin 4	3.58	5.38	0.01	1.35	1.65
Min		**0.49**	**2.90**	**0.00**	**0.09**	**0.61**
Max		**4.26**	**6.24**	**1.84**	**1.70**	**7.27**

Table SI 4.2. *(continued) Relative abundance (%) of microbial community in Lake Sentani at Phyla Level (Bacteria)*

Location	Habitat	Nitrospirota	Planctomycetota	Methylomirabilota	Myxococcota	Aenigmarchaeota
SR_1_3	River	0.08	3.44	0.12	0.46	0.00
SR_Jbt2	River	1.01	3.83	0.43	4.44	0.00
SR_4_3	River	1.14	2.60	4.91	2.11	0.01
SR_5_3	River	0.21	4.71	0.41	0.86	0.00
SR_6_3	River	0.01	4.32	0.12	0.43	0.00
SR_Doyo_1	River	0.38	2.63	0.97	1.32	0.03
SR_Doyo_2	River	0.13	1.93	0.28	0.97	0.00
SR_10_2	River	2.44	6.66	1.35	1.44	0.06
SR_18_2	River	0.30	3.77	0.93	0.71	0.00
Min		**0.01**	**1.93**	**0.12**	**0.43**	**0.00**
Max		**2.44**	**6.66**	**4.91**	**4.44**	**0.06**
SE_R1	River mouth	0.70	2.78	0.34	3.52	0.00
SE_R4	River mouth	6.84	3.05	0.84	2.42	0.07
SE_R5	River mouth	1.19	5.54	0.98	3.04	0.04
SE_R6	River mouth	2.71	2.70	0.19	2.77	0.00
SE_Doyo	River mouth	0.71	2.26	0.88	1.91	0.00
SE_R10	River mouth	5.60	1.37	0.14	2.75	0.00
SE_R15	River mouth	2.28	2.77	0.36	1.00	1.09
SE_R18	River mouth	1.04	6.05	1.64	1.55	0.01
SE_OL	River mouth	2.01	2.84	0.32	1.42	0.20
Min		**0.70**	**1.37**	**0.14**	**1.00**	**0.00**
Max		**6.84**	**6.05**	**1.64**	**3.52**	**1.09**
SL_27	Sub-Basin 1	2.29	5.09	0.91	1.60	0.15
SL_28	Sub-Basin 1	3.90	2.45	0.43	0.80	0.09
SL_29	Sub-Basin 1	2.07	5.85	0.38	1.05	0.28
SL_30	Sub-Basin 1	4.48	1.61	0.33	1.95	0.07
SL_31	Sub-Basin 1	4.59	2.48	0.49	1.04	0.09
SL_ST1	Sub-Basin 1	1.01	5.67	0.21	0.58	0.34
Min		**1.01**	**1.61**	**0.21**	**0.58**	**0.07**
Max		**4.59**	**5.85**	**0.91**	**1.95**	**0.34**
SL_25	Shallow channel	1.05	2.86	0.29	0.59	1.30
Min		**1.05**	**2.86**	**0.29**	**0.59**	**1.30**
Max		**1.05**	**2.86**	**0.29**	**0.59**	**1.30**
SL_21	Sub-Basin 2	3.59	4.11	0.40	1.97	0.00
SL_22	Sub-Basin 2	3.15	2.77	0.25	0.63	1.57
SL_23	Sub-Basin 2	3.63	2.95	0.47	1.02	0.25
Min		**3.15**	**2.77**	**0.25**	**0.63**	**0.00**
Max		**3.63**	**4.11**	**0.47**	**1.97**	**1.57**
SL_14	Sub-Basin 3	3.94	3.15	0.59	0.96	0.08
SL_15	Sub-Basin 3	4.49	4.91	0.44	0.81	0.10
SL_16	Sub-Basin 3	3.84	4.07	0.50	0.86	0.27
SL_17	Sub-Basin 3	4.80	2.62	0.43	1.02	0.14
SL_18	Sub-Basin 3	3.66	3.61	0.50	0.50	0.17
SL_19	Sub-Basin 3	4.67	2.90	0.41	0.92	0.22
SL_20	Sub-Basin 3	5.14	3.54	0.48	0.90	0.29
Min		**3.66**	**2.62**	**0.41**	**0.50**	**0.08**
Max		**5.14**	**4.91**	**0.59**	**1.02**	**0.29**
SL_1	Sub-Basin 4	2.37	2.04	0.24	1.29	0.34
SL_2	Sub-Basin 4	2.63	1.86	0.79	0.19	4.38

Location	Habitat	Nitrospirota	Planctomycetota	Methylomirabilota	Myxococcota	Aenigmarchaeota
SL_3	Sub-Basin 4	2.40	2.72	0.26	0.57	0.93
SL_4	Sub-Basin 4	2.92	3.34	0.33	0.55	1.61
SL_5	Sub-Basin 4	2.22	5.02	0.41	0.55	0.35
SL_6	Sub-Basin 4	3.83	3.87	0.54	0.78	0.48
SL_7	Sub-Basin 4	2.83	4.56	0.58	0.57	0.58
SL_8	Sub-Basin 4	2.98	4.01	0.52	0.44	0.65
SL_9	Sub-Basin 4	0.90	5.38	0.42	0.93	1.57
SL_10	Sub-Basin 4	1.37	4.98	0.58	0.43	0.68
SL_11	Sub-Basin 4	2.01	5.13	0.66	1.45	0.31
SL_12	Sub-Basin 4	5.07	2.18	0.31	0.90	0.54
SL_13	Sub-Basin 4	3.46	3.00	0.36	1.19	0.65
Min		**0.90**	**1.86**	**0.24**	**0.19**	**0.31**
Max		**5.07**	**5.38**	**0.79**	**1.45**	**4.38**

Table SI 4.2. *(continued) Relative abundance (%) of microbial community in Lake Sentani at Phyla Level (Bacteria)*

Location	Habitat	Latescibacterota	Spirochaetota	Deinococcota	Patescibacteria	Other
SR_1_3	River	0.17	0.45	0.17	0.71	1.87
SR_Jbt2	River	0.63	0.38	0.08	0.56	6.45
SR_4_3	River	2.04	0.72	0.02	0.77	5.52
SR_5_3	River	0.24	0.02	2.72	0.58	1.77
SR_6_3	River	0.07	0.03	0.51	0.78	1.28
SR_Doyo_1	River	1.62	1.62	0.00	1.28	8.83
SR_Doyo_2	River	0.56	1.90	0.13	1.82	3.28
SR_10_2	River	3.55	1.97	0.00	0.73	6.85
SR_18_2	River	1.38	0.26	0.03	0.76	3.09
Min		**0.07**	**0.02**	**0.00**	**0.56**	**1.28**
Max		**3.55**	**1.97**	**2.72**	**1.82**	**8.83**
SE_R1	River mouth	0.70	1.41	0.02	1.60	4.76
SE_R4	River mouth	1.55	1.86	0.00	1.53	6.57
SE_R5	River mouth	2.03	2.32	0.02	1.54	7.72
SE_R6	River mouth	0.81	3.56	0.01	1.52	8.78
SE_Doyo	River mouth	0.81	1.14	0.08	0.84	4.81
SE_R10	River mouth	1.18	1.38	0.00	0.32	5.02
SE_R15	River mouth	2.25	2.78	0.00	0.52	7.74
SE_R18	River mouth	2.80	2.70	0.00	1.26	9.16
SE_OL	River mouth	2.10	1.82	0.00	0.72	6.61
Min		**0.70**	**1.14**	**0.00**	**0.32**	**4.76**
Max		**2.80**	**3.56**	**0.08**	**1.60**	**9.16**
SL_27	Sub-Basin 1	2.07	3.27	0.00	1.75	8.64
SL_28	Sub-Basin 1	2.52	2.41	0.00	0.28	7.11
SL_29	Sub-Basin 1	2.90	2.38	0.01	0.84	9.32
SL_30	Sub-Basin 1	1.82	2.55	0.00	0.27	9.06
SL_31	Sub-Basin 1	2.17	1.79	0.00	0.29	5.92
SL_ST1	Sub-Basin 1	3.76	2.13	0.00	2.40	10.64
Min		**1.82**	**1.79**	**0.00**	**0.27**	**5.92**
Max		**3.76**	**3.27**	**0.01**	**2.40**	**10.64**
SL_25	Shallow channel	2.08	1.67	0.00	0.26	9.10
Min		**2.08**	**1.67**	**0.00**	**0.26**	**9.10**
Max		**2.08**	**1.67**	**0.00**	**0.26**	**9.10**
SL_21	Sub-Basin 2	1.62	2.74	0.00	1.55	7.26
SL_22	Sub-Basin 2	2.37	1.88	0.00	0.39	8.77
SL_23	Sub-Basin 2	2.85	1.58	0.00	0.64	6.35
Min		**1.62**	**1.58**	**0.00**	**0.39**	**6.35**
Max		**2.85**	**2.74**	**0.00**	**1.55**	**8.77**
SL_14	Sub-Basin 3	2.11	1.77	0.00	0.64	7.86
SL_15	Sub-Basin 3	2.24	2.08	0.00	0.93	8.93
SL_16	Sub-Basin 3	3.48	1.93	0.00	0.56	7.28
SL_17	Sub-Basin 3	1.93	1.85	0.00	0.33	7.14
SL_18	Sub-Basin 3	2.73	1.97	0.00	0.42	7.30
SL_19	Sub-Basin 3	2.38	2.03	0.00	0.36	7.56
SL_20	Sub-Basin 3	2.72	1.77	0.00	0.53	7.03
Min		**1.93**	**1.77**	**0.00**	**0.33**	**7.03**
Max		**3.48**	**2.08**	**0.00**	**0.93**	**8.93**
SL_1	Sub-Basin 4	1.70	1.55	0.00	0.53	7.90
SL_2	Sub-Basin 4	1.59	0.97	0.00	0.51	6.61
SL_3	Sub-Basin 4	2.65	1.82	0.00	0.15	8.50

Location	Habitat	Latescibacterota	Spirochaetota	Deinococcota	Patescibacteria	Other
SL_4	Sub-Basin 4	2.27	1.66	0.00	0.18	8.70
SL_5	Sub-Basin 4	3.80	2.65	0.00	1.00	10.19
SL_6	Sub-Basin 4	3.06	2.12	0.00	0.46	8.33
SL_7	Sub-Basin 4	3.48	2.01	0.00	0.85	7.84
SL_8	Sub-Basin 4	3.23	1.63	0.00	1.10	6.78
SL_9	Sub-Basin 4	2.42	2.75	0.09	1.27	8.65
SL_10	Sub-Basin 4	2.72	2.03	0.00	0.87	9.19
SL_11	Sub-Basin 4	2.75	2.58	0.00	1.95	10.42
SL_12	Sub-Basin 4	1.55	2.31	0.00	0.57	7.96
SL_13	Sub-Basin 4	1.93	1.20	0.00	0.70	8.17
Min		**1.55**	**0.97**	**0.00**	**0.15**	**6.61**
Max		**3.80**	**2.75**	**0.09**	**1.95**	**10.42**

Table SI 4.3.A *Relative abundance (%) of microbial community in Lake Sentani at Class Level (Bacteria).*

Location	Habitat	Bacteria								
		Acidobacteriota					Actinobacteriota		Bacteroidota	
		Aminicenantia	**Blastocatellia**	**Holophagae**	**Subgroup_18**	**Vicinamibacteria**	**Actinobacteria**	**Coriobacteriia**	**Bacteroidia**	**Kryptonia**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SR_1_3	River	0.18	0.51	1.1	0.04	3.39	3.28	0.9	9.18	0.06
SR_Jbt2	River	0	2.61	0.27	0.01	4.24	1.23	0.03	11.94	0.31
SR_4_3	River	0.02	1.39	1.43	0.07	4.14	0.31	0.29	8.64	0.49
SR_5_3	River	0.01	2.94	0.33	0.05	1.54	5.32	0.04	3.67	0.03
SR_6_3	River	0.02	0.87	0.16	0.04	0.79	1.54	0.22	20.21	0
SR_Doyo_1	River	1.89	0.22	1.78	1.93	3.5	0.28	1.44	7.47	0.42
SR_Doyo_2	River	1.26	0.73	3	0.07	2.63	2.95	2.51	12.35	0.11
SR_10_2	River	2.06	0.57	0.37	2.14	9.43	0.28	0.74	2.99	0.66
SR_18_2	River	0.42	1.18	0.8	0.18	11.17	0.48	0.71	12.76	0.29
Min		**0**	**0.22**	**0.16**	**0.01**	**0.79**	**0.28**	**0.03**	**2.99**	**0**
Max		**2.06**	**2.94**	**3**	**2.14**	**11.17**	**5.32**	**2.51**	**20.21**	**0.66**
SE_R1	River mouth	0.73	0.13	0.8	0.23	5.21	0.47	1.95	8.87	0.59
SE_R4	River mouth	2.26	0.04	0.34	1.12	5.76	0.09	1.65	2.55	1.27
SE_R5	River mouth	1.09	0.5	0.74	0.75	5.24	0.52	1.37	7.04	1.21
SE_R6	River mouth	2.66	0.02	0.82	0.55	3.92	0.15	0.99	11.62	2.44
SE_Doyo	River mouth	0.39	0.54	1.54	0.52	3.49	0.79	1.13	10.72	0.39
SE_R10	River mouth	0.35	0.08	0.32	0.27	2.29	0.26	0.48	8.39	1.89
SE_R15	River mouth	2.74	0.03	0.03	1.3	1.74	0.03	0.09	1.12	0.99
SE_R18	River mouth	4.49	0.17	0.57	0.69	7.18	0.09	0.62	4.99	0.87
SE_OL	River mouth	1.74	0.2	0.31	0.63	3.54	0.11	0.15	6.2	2.4
Min		**0.35**	**0.02**	**0.03**	**0.23**	**1.74**	**0.03**	**0.09**	**1.12**	**0.39**
Max		**4.49**	**0.54**	**1.54**	**1.3**	**7.18**	**0.79**	**1.95**	**11.62**	**2.44**
SL_27	Sub-basin 1	2.51	0.05	0.27	0.56	4.11	0.1	0.34	2.86	0.75
SL_28	Sub-basin 1	1.28	0	0.02	0.98	2.96	0.01	0.06	0.66	0.73

1	2	3	4	5	6	7	8	9	10	11
SL_29	Sub-basin 1	3.26	0.01	0.1	0.96	3.08	0.02	0.02	1.18	0.73
SL_30	Sub-basin 1	0.8	0.01	0.06	0.41	1.23	0.03	0.21	1.39	1.29
SL_31	Sub-basin 1	1.15	0	0.02	0.39	0.75	0.06	0.04	0.69	0.58
SL_ST1	Sub-basin 1	5.79	0	0.04	1.4	3.69	0.05	0.01	1.4	0.78
SL_21	Sub-basin 2	2.39	0.03	0.7	0.75	7.51	0.16	0.54	7.76	2.13
SL_22	Sub-basin 2	2.07	0	0.01	0.53	1.49	0.04	0.22	0.34	0.63
SL_23	Sub-basin 2	2.16	0.02	0.14	1.11	4.59	0.06	0.04	1.07	0.73
SL_25	Shallow Channel	1.95	0	0.01	0.39	0.85	0.02	0.2	0.52	0.94
SL_14	Sub-basin 3	2.29	0.01	0.08	0.97	2.76	0.05	0.14	1.33	0.95
SL_15	Sub-basin 3	4.15	0.02	0.08	1.95	2.69	0.07	0.12	1.28	1.08
SL_16	Sub-basin 3	2.42	0.02	0.02	0.99	3.47	0.01	0.05	1.16	0.78
SL_17	Sub-basin 3	1.86	0.01	0.07	0.68	2.13	0.03	0.03	1.11	0.83
SL_18	Sub-basin 3	3.79	0.01	0.03	1.7	3.71	0.02	0.06	0.53	0.54
SL_19	Sub-basin 3	1.52	0.01	0.08	0.94	2.9	0.03	0.09	1.07	0.81
SL_20	Sub-basin 3	1.48	0.02	0.09	0.89	4	0.02	0.14	1.24	0.92
SL_1	Sub-basin 4	1.22	0.03	0.1	0.42	1.41	0.05	0.09	2.08	2.33
SL_2	Sub-basin 4	5.71	0	0	0.63	0.21	0	0	0.15	0.45
SL_3	Sub-basin 4	1.01	0.02	0.03	0.56	1.65	0.02	0.05	0.52	0.66
SL_4	Sub-basin 4	1.93	0.01	0	0.84	1.3	0	0.1	0.19	0.4
SL_5	Sub-basin 4	3.52	0.02	0.05	2.03	3.51	0.01	0.04	0.78	0.67
SL_6	Sub-basin 4	2.64	0.02	0.05	1.72	2.07	0.01	0.03	0.62	0.61
SL_7	Sub-basin 4	3.27	0.01	0.02	1.52	2.11	0.01	0.05	0.56	0.54
SL_8	Sub-basin 4	5.83	0	0.02	1.87	3.37	0	0.04	0.54	0.26
SL_9	Sub-basin 4	5.98	0	0.02	1.08	1.53	0.03	0	0.62	0.82
SL_10	Sub-basin 4	4.73	0	0.01	1.15	2.11	0.07	0.02	0.69	0.48
SL_11	Sub-basin 4	3.81	0.09	0.41	1.65	4.26	0.09	0.39	2.04	0.77
SL_12	Sub-basin 4	1.41	0.01	0.03	0.56	1.51	0.04	0.27	0.6	0.49
SL_13	Sub-basin 4	1.57	0	0.01	0.52	1.87	0.14	0.19	0.61	0.48
Min		**0.8**	**0**	**0.01**	**0.52**	**1.51**	**0**	**0**	**0.54**	**0.26**
Max		**5.98**	**0.09**	**0.41**	**2.03**	**4.26**	**0.14**	**0.39**	**2.04**	**0.82**

Table SI 4.3.A (Continued) *Relative abundance (%) of microbial community in Lake Sentani at Class Level (Bacteria).*

Location	Habitat	Chloroflexi			Cyanobacteria	Deinococcota	Desulfobacterota			
		Anaerolineae	**Dehalococcoidia**	**SHA-26**	**Cyanobacteriia**	**Deinococci**	**Desulfobacteria**	**Desulfuromonadia**	**Syntrophia**	**uncultured**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SR_1_3	River	5.48	0.01	0	0.16	0.17	0.52	0.29	0.25	0.08
SR_Jbt2	River	2.17	0.19	0	0.17	0.08	0.01	0.84	0	0.36
SR_4_3	River	2.36	0.36	0	1.11	0.02	0.04	1.46	0.09	0.67
SR_5_3	River	1.36	0.12	0.01	7.95	2.72	0.02	0.1	0.05	0.07
SR_6_3	River	0.77	0.01	0.01	1.05	0.51	0.01	0.06	0.02	0.03
SR_Doyo_1	River	11.59	0.53	0.1	0.7	0	0.35	2.29	1.79	0.8
SR_Doyo_2	River	3.38	0.07	0.01	0.78	0.13	0.15	0.41	0.21	0.14
SR_10_2	River	9.14	0.96	0.03	0.02	0	1.12	0.46	1.14	0.8
SR_18_2	River	3.93	0.08	0	0.67	0.03	0.28	0.33	0.12	0.16
	Min	**0.77**	**0.01**	**0**	**0.02**	**0**	**0.01**	**0.06**	**0**	**0.03**
	Max	**11.59**	**0.96**	**0.1**	**7.95**	**2.72**	**1.12**	**2.29**	**1.79**	**0.8**
SE_R1	River mouth	5.71	0.03	0.02	1.19	0.02	0.64	3.87	0.68	0.18
SE_R4	River mouth	11.5	0.51	0.16	0.03	0	1.66	0.84	1.15	0.82
SE_R5	River mouth	8.38	0.28	0.01	0.15	0.02	0.85	1.65	1.21	0.59
SE_R6	River mouth	4.84	0.15	0	0.39	0.01	1.67	2.01	2.73	0.41
SE_Doyo	River mouth	3.74	0.18	0.03	0.64	0.08	0.52	1.63	0.49	0.37
SE_R10	River mouth	4.04	0.33	0.02	0.24	0	2.22	1.01	0.76	0.72
SE_R15	River mouth	5.22	8.63	0.1	0.06	0	1.05	0.13	0.7	1.53
SE_R18	River mouth	13.01	0.11	0.03	0.17	0	1.01	0.73	2.17	0.61
SE_OL	River mouth	6.31	1.69	0.17	1.26	0	1.27	0.14	1.32	0.72
	Min	**3.74**	**0.03**	**0**	**0.03**	**0**	**0.52**	**0.13**	**0.49**	**0.18**
	Max	**13.01**	**8.63**	**0.17**	**1.26**	**0.08**	**2.22**	**3.87**	**2.73**	**1.53**
SL_27	Sub-basin 1	7.6	1.21	0.06	0.23	0	1.68	0.73	3.03	1

1	2	3	4	5	6	7	8	9	10	11
SL_28	Sub-basin 1	7.95	2.25	0.2	0	0	1.73	0.09	2.07	0.9
SL_29	Sub-basin 1	8.85	3.2	0.68	0.07	0.01	1.34	0.19	2.03	0.56
SL_30	Sub-basin 1	7.18	2.78	0.14	0.01	0	2.22	0.19	2.71	1.48
SL_31	Sub-basin 1	4.66	4.51	0.48	0.01	0	2.14	0.18	3.33	2.2
SL_ST1	Sub-basin 1	10.73	3.15	0	0.02	0	0.83	0.03	1.6	0.62
SL_21	Sub-basin 2	5.54	0.21	0.03	0.2	0	2.15	1.06	2.78	0.75
SL_22	Sub-basin 2	6.24	4.7	0.37	0	0	0.95	0	0.76	2.04
SL_23	Sub-basin 2	11.57	1.29	0.11	0.06	0	1.12	0.22	1.11	0.58
SL_25	Shallow Channel	4.13	4.32	1.03	0.07	0	0.45	0.01	1.05	1.08
SL_14	Sub-basin 3	7.78	2.57	0.15	0	0	2	0.23	2.15	0.89
SL_15	Sub-basin 3	8.38	2.47	0.1	0.02	0	1.77	0.14	3.14	0.91
SL_16	Sub-basin 3	8.91	2.47	0.72	0.02	0	1.19	0.11	1.74	1.02
SL_17	Sub-basin 3	6.3	2.38	0.49	0.01	0	1.45	0.08	1.79	0.79
SL_18	Sub-basin 3	14.48	2.4	0.51	0	0	1.09	0.06	1.43	0.64
SL_19	Sub-basin 3	8.75	2.3	0.4	0	0	1.58	0.06	1.61	0.95
SL_20	Sub-basin 3	9.89	1.42	0.21	0.08	0	1.43	0.12	0.76	0.84
SL_1	Sub-basin 4	5.82	2.18	0.75	1.83	0	1.32	0.02	0.96	1.08
SL_2	Sub-basin 4	3.94	5.43	1.45	0	0	0.14	0.06	1.44	1.14
SL_3	Sub-basin 4	6.35	2.5	1.57	0.31	0	1.07	0.08	1.43	0.93
SL_4	Sub-basin 4	4.43	6.99	1.08	0.01	0	0.37	0.05	1.34	1.45
SL_5	Sub-basin 4	10.79	3.49	1.26	0.03	0	0.92	0.07	2	0.79
SL_6	Sub-basin 4	8.68	4.33	2.21	0.02	0	1.09	0.13	2.31	1.52
SL_7	Sub-basin 4	10.28	4.86	1.12	0.04	0	1.19	0.03	1.77	1.08
SL_8	Sub-basin 4	13.28	5.07	0.38	0.03	0	0.72	0.02	1.39	1.04
SL_9	Sub-basin 4	6.41	8.55	0.14	0	0.09	0.59	0.01	0.74	1.14
SL_10	Sub-basin 4	10.98	4.82	0.13	0.01	0	0.85	0.09	1.39	0.61
SL_11	Sub-basin 4	11.17	1.83	0	0.05	0	0.95	0.96	2.68	0.61
SL_12	Sub-basin 4	6.89	4.83	0.21	0	0	1.72	0.07	1.33	1.21
SL_13	Sub-basin 4	7.23	4.68	0.15	0	0	1.39	0.1	1.32	1.4
Min		**6.41**	**1.83**	**0**	**0**	**0**	**0.59**	**0.01**	**0.74**	**0.61**
Max		**13.28**	**8.55**	**2.21**	**0.05**	**0.09**	**1.72**	**0.96**	**2.68**	**1.52**

Table SI 4.3.A (Continued) *Relative abundance (%) of microbial community in Lake Sentani at Class Level (Bacteria).*

Location	Habitat			
		Verrucomicrobiota		
		Kiritimatiellae	**Omnitrophia**	**Verrucomicrobiae**
1	**2**	**3**	**4**	**5**
SR_1_3	River	0.15	0.02	3.6
SR_Jbt2	River	0.07	0.3	3.83
SR_4_3	River	0.16	0.24	5.57
SR_5_3	River	0.01	0.03	1.94
SR_6_3	River	0.01	0	4.49
SR_Doyo_1	River	0.24	0.49	2.29
SR_Doyo_2	River	0.28	0.03	2.6
SR_10_2	River	0.43	0.43	3.04
SR_18_2	River	0.12	0.02	11.16
Min		**0.01**	**0**	**1.94**
Max		**0.43**	**0.49**	**11.16**
SE_R1	River mouth	0.83	0.32	11.17
SE_R4	River mouth	1.68	1.1	1.75
SE_R5	River mouth	1.58	0.86	4.7
SE_R6	River mouth	5.68	0.98	4.07
SE_Doyo	River mouth	0.24	0.06	5.21
SE_R10	River mouth	2.02	0.57	2.75
SE_R15	River mouth	0.41	2.15	1.08
SE_R18	River mouth	2.96	0.79	6.71
SE_OL	River mouth	1.09	0.52	3.08
Min		**0.24**	**0.06**	**1.08**
Max		**5.68**	**2.15**	**11.17**
SL_27	Sub-basin 1	2.77	1.22	2.75
SL_28	Sub-basin 1	0.74	1.04	1.83
SL_29	Sub-basin 1	1.86	1.73	3.48

1	**2**	**3**	**4**	**5**
SL_30	Sub-basin 1	1.93	1.46	1.38
SL_31	Sub-basin 1	0.3	1.25	0.62
SL_ST1	Sub-basin 1	1.7	1.07	1.33
SL_21	Sub-basin 2	4.7	1.04	4.14
SL_22	Sub-basin 2	0.55	1.67	0.82
SL_23	Sub-basin 2	1.18	1.18	1.82
SL_25	Shallow Channel	0.35	1.52	0.93
SL_14	Sub-basin 3	1.51	1.1	1.52
SL_15	Sub-basin 3	1.45	1.43	1.58
SL_16	Sub-basin 3	1.21	1.82	2.07
SL_17	Sub-basin 3	1.45	1.33	1.5
SL_18	Sub-basin 3	0.81	0.98	1.38
SL_19	Sub-basin 3	1.18	1.21	1.43
SL_20	Sub-basin 3	1.37	0.92	2.02
SL_1	Sub-basin 4	1.26	1.86	1.6
SL_2	Sub-basin 4	0.02	1.64	0.39
SL_3	Sub-basin 4	0.41	0.83	1.67
SL_4	Sub-basin 4	0.18	1.34	0.55
SL_5	Sub-basin 4	1.2	0.87	1.98
SL_6	Sub-basin 4	0.75	1.18	1.26
SL_7	Sub-basin 4	0.5	1.64	1.25
SL_8	Sub-basin 4	0.4	1.19	0.77
SL_9	Sub-basin 4	0.79	3.64	0.56
SL_10	Sub-basin 4	0.63	1.26	0.76
SL_11	Sub-basin 4	1.48	1.88	2.59
SL_12	Sub-basin 4	0.54	1.14	0.45
SL_13	Sub-basin 4	0.47	1.48	0.56
Min		**0.4**	**0.87**	**0.45**
Max		**1.48**	**3.64**	**2.59**

Table SI 4.3.B *Relative abundance (%) of microbial community in Lake Sentani at Class Level (Archaea).*

Location	Habitat	Archaea						
		Aenigmarchaeota	**Crenarchaeota**		**Euryarchaeota**		**Nanoarchaeota**	**Thermoplasmatota**
		Aenigmarchaeia	**Bathyarchaeia**	**Methanomethylicia**	**Methanobacteria**	**Thermococci**	**Nanoarchaeia**	**Thermoplasmata**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SR_1_3	River	0	0.07	0	3.1	0.01	0.05	0.04
SR_Jbt2	River	0	0.01	0	0	0	0.22	0.1
SR_4_3	River	0	0.28	0	0.04	0	0.81	0.25
SR_5_3	River	0	0	0.03	0.08	0	0.02	0.17
SR_6_3	River	0	0.03	0	0.06	0.01	0.01	0.1
SR_Doyo_1	River	0	0.9	0.08	0.19	0.06	0.3	0.71
SR_Doyo_2	River	0	0.09	0	10.05	0.01	0.14	0.05
SR_10_2	River	0.02	1.71	0.46	1.43	0.15	0.76	3.48
SR_18_2	River	0	0.08	0	0.23	0.01	0.14	0.04
Min		**0**	**0**	**0**	**0**	**0**	**0.01**	**0.04**
Max		**0.02**	**1.71**	**0.46**	**10.05**	**0.15**	**0.81**	**3.48**
SE_R1	River mouth	0	0.08	0.04	0.62	0.01	0.48	0.2
SE_R4	River mouth	0.07	0.83	0.45	0.34	0.17	1.11	4.3
SE_R5	River mouth	0	0.45	0.05	0.66	0.03	1.46	0.52
SE_R6	River mouth	0	0.21	0.04	0.97	0.06	2.61	0.98
SE_Doyo	River mouth	0	0.48	0.02	0.56	0	0.16	0.26
SE_R10	River mouth	0	1.04	0.1	0.77	0.1	1.78	2.16
SE_R15	River mouth	1	14.16	0.85	0.41	1.16	1.61	9.63
SE_R18	River mouth	0.01	0.18	0.41	0.52	0.06	0.78	1.87
SE_OL	River mouth	0.18	5.29	1.08	0.14	1.45	0.91	3.5
Min		**0**	**0.08**	**0.02**	**0.14**	**0**	**0.16**	**0.2**
Max		**1**	**14.16**	**1.08**	**0.97**	**1.45**	**2.61**	**9.63**
SL_27	Sub-basin 1	0.13	0.85	1.01	0.8	0.24	1.01	5.79
SL_28	Sub-basin 1	0.09	1.13	2.55	0.7	0.72	0.46	14.99

1	2	3	4	5	6	7	8	9
SL_29	Sub-basin 1	0.24	3	2.24	1.88	0.79	1.28	10.48
SL_30	Sub-basin 1	0.06	1.14	1.11	0.6	0.28	0.7	8.37
SL_31	Sub-basin 1	0.09	2.32	0.81	0.57	0.77	0.44	8.18
SL_ST1	Sub-basin 1	0.26	3.81	4.44	1.05	1.07	2.3	10.31
SL_21	Sub-basin 2	0	0.38	0.28	0.75	0.1	1.02	1.58
SL_22	Sub-basin 2	1.45	10.45	2.51	0.2	3.86	2.18	9.8
SL_23	Sub-basin 2	0.22	1.9	2.19	0.47	0.78	1.1	11.18
SL_25	Shallow Channel	1.26	17.64	1.22	0.38	4.37	3.35	15.19
SL_14	Sub-basin 3	0.06	2.41	1.44	0.78	0.61	1.2	11
SL_15	Sub-basin 3	0.08	2.89	2.53	0.71	0.57	1.03	7.62
SL_16	Sub-basin 3	0.24	2.22	2.38	0.66	0.59	0.85	14.35
SL_17	Sub-basin 3	0.12	1.71	1.09	0.46	0.4	0.91	22.41
SL_18	Sub-basin 3	0.16	2.96	3.17	0.66	0.57	0.51	13.41
SL_19	Sub-basin 3	0.2	3.12	2.71	1.09	0.35	0.78	6.78
SL_20	Sub-basin 3	0.19	2.12	3.26	0.61	0.14	0.77	5.68
SL_1	Sub-basin 4	0.29	5.21	0.84	0.2	1.56	2.14	9.67
SL_2	Sub-basin 4	4.27	8.58	2.98	0.02	2.2	7.27	22.95
SL_3	Sub-basin 4	0.79	7.15	3.35	0.53	1.3	1.78	13.91
SL_4	Sub-basin 4	1.56	16.54	1.83	0.64	3.43	3.83	11.25
SL_5	Sub-basin 4	0.32	5.12	3.27	0.69	0.71	0.8	15.75
SL_6	Sub-basin 4	0.43	3.75	1.25	0.36	0.68	0.61	13.23
SL_7	Sub-basin 4	0.51	4.82	3.2	0.23	0.7	1.66	17.28
SL_8	Sub-basin 4	0.56	6.55	2.67	0.88	1.86	0.89	12.26
SL_9	Sub-basin 4	1.51	5.38	4.38	0.14	3.42	2.96	11.16
SL_10	Sub-basin 4	0.57	7.54	5.05	0.77	3.41	1.68	14.32
SL_11	Sub-basin 4	0.29	1.28	1.98	0.19	0.3	1.76	10.51
SL_12	Sub-basin 4	0.35	7.65	2.74	1.51	1.63	1.8	9.39
SL_13	Sub-basin 4	0.55	4.47	2.81	1.16	2.3	1.65	6.59
Min		**0.29**	**1.28**	**1.25**	**0.14**	**0.3**	**0.61**	**6.59**
Max		**1.51**	**7.65**	**5.05**	**1.51**	**3.42**	**2.96**	**17.8**