

Observed Water Mass and Chlorophyll-a Distribution in the Western Maluku Sea: From BUDEE Cruise 2022

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Abstract

The Banggai Waters, located in the western Maluku Sea, are influenced by a secondary branch of the Indonesian Throughflow (ITF) and seasonal coastal upwelling, contributing to high biological productivity and important fisheries resources. This study aimed to characterize the horizontal and vertical distributions of temperature, salinity, potential density, dissolved oxygen (DO), and chlorophyll-a, and to examine how physical processes shape the spatial variability of the Deep Chlorophyll Maximum (DCM). We conducted hydrographic observations during the Banggai Upwelling Dynamics and Ecosystem Experiment (BUDEE) in September 2022 using Conductivity–Temperature–Depth (CTD) measurements at eight stations along two north–south transects. We classified the water column into three layers: the mixed layer, thermocline, and deep layer. Temperature, salinity, potential density, and DO exhibit clear vertical stratification and spatial variability between the two transects. Salinity profiles revealed a subsurface salinity maximum and an intermediate salinity minimum, indicating the presence of North Pacific Subtropical Water (NPSW) and North Pacific Intermediate Water (NPIW). Chlorophyll-a showed a surface maximum and a distinct DCM at 40–60 m near the base of the mixed layer and the upper thermocline. Spatial variations in the DCM closely tracked changes in thermocline depth, density stratification, and vertical water-mass displacement inferred from temperature and density profiles, indicating that physical processes regulate nutrient supply to the euphotic zone. These findings demonstrate that the hydrographic structure of the Banggai Waters plays a key role in controlling chlorophyll-a distribution and primary productivity.

Keywords: BUDEE, Hydrographic structure, Maluku Sea, Upwelling Dynamics, Water mass stratification.

INTRODUCTION

Indonesia's strategic position between the Pacific and Indian Oceans forms a major pathway for the Indonesian Throughflow (ITF), which transports warm and low-salinity Pacific waters into the Indian Ocean through key passages such as the Makassar Strait, Flores Sea, and Banda Sea. Along this route, water masses experience substantial modifications in temperature, salinity, density, and dissolved oxygen (Atmadipoera *et al.*, 2009), influencing regional climate processes, including the El Niño–Southern Oscillation (ENSO) (Puryajati *et al.*, 2021). Within this complex circulation system, upwelling plays a crucial role in elevating nutrient concentrations, enhancing chlorophyll-a levels, and supporting biological productivity (Setiawan and Habibi, 2011; Xu *et al.*, 2021). Upwelling-driven nutrient enrichment sustains phytoplankton biomass and underpins the productivity of marine ecosystems and fisheries across the Indonesian seas (Pauly & Christensen, 1995; Kunarso *et al.*, 2011).

Banggai waters are an ecologically important region influenced by both the Banda Sea and Maluku Sea, with dynamic hydrographic conditions characterized by strong water-mass mixing, nutrient-rich waters, and productive ecosystems (Thoha *et al.*, 2013). Their location within the ITF pathway further shapes the water column's physical and biogeochemical structure, as Pacific- and Indian-derived water masses contribute to stratification and nutrient distribution (Sprintall *et al.*, 2009). Seasonal monsoon winds modulate vertical mixing and upwelling intensity in the region, particularly during the southeast monsoon when southerly winds enhance nutrient uplift from the subsurface layers (Atmadipoera & Widyastuti, 2015; Fitriyan *et al.*, 2023). As a result, Banggai is recognized as

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one of Indonesia's productive marine regions, hosting fisheries hotspots and supporting diverse planktonic communities shaped by water mass interactions (Rachman & Asniariati, 2012; Simanjuntak 2012).

Despite this ecological significance, the Banggai region remains understudied compared with other Indonesian upwelling systems. Previous research has documented regional water mass characteristics, nutrient limitations, and upwelling-related productivity in several Indonesian seas (Thoha *et al.*, 2013; Widianingsih *et al.*, 2024; Bouman *et al.*, 2020); however, limited work has examined how ITF-driven stratification, monsoon forcing, and water mass mixing jointly influence the vertical and horizontal distribution of physical and biogeochemical parameters in the western Maluku Sea—particularly in Banggai. Knowledge gaps remain about the mechanisms controlling the depth and variability of the Deep Chlorophyll Maximum (DCM), how water-mass structure and nutrient availability interact, and the implications for ecosystem productivity.

Addressing these gaps is essential to improve scientific understanding of the Banggai system and support resource management in one of Indonesia's biologically rich marine areas. Therefore, this study aims to (i) characterize the vertical and horizontal distribution of key physical and chemical parameters, including temperature, salinity, density, dissolved oxygen, and chlorophyll-*a*, down to 1000 m depth; and (ii) identify the dominant physical processes that control the formation and spatial variability of the Deep Chlorophyll Maximum (DCM) in the Banggai waters.

MATERIAL AND METHODS

This study was conducted in September 2022 during the joint oceanographic cruise of Widya Nusantara Expedition titled "Banggai Upwelling Dynamics and Ecosystem Experiment (BUDEE 2022)." The BUDEE expedition was a collaborative research initiative involving multiple academic and research institutions, including the National Research and Innovation Agency (BRIN), IPB University, Diponegoro University, Indonesia University, and Pattimura University. Researchers conducted hydrographic observations in the southern Maluku Sea aboard the research vessel Baruna Jaya VIII.

The primary instrument used in this study was the CTD SBE 911 plus, which recorded vertical profiles of oceanographic parameters including temperature, salinity, density, and chlorophyll-*a* concentration, from the surface down to a depth of 1000 meters. Data processing and analysis were conducted using Microsoft Excel, Ocean Data View (ODV), and MATLAB.

The raw CTD data acquired from the field were not immediately suitable for analysis and required several preprocessing steps using SBE Data Processing software. The data processing workflow followed the standard procedures outlined by (Suteja *et al.*, 2015), which include: conversion of raw data files, wild Edit to remove outliers, cell Thermal Mass correction, filtering of sensor noise, loop Edit to remove ship-induced artifacts, derivation of secondary parameters, bin Averaging, and manual correction where necessary (SBE Data Processing, 2015).

The vertical water column was classified into three layers, namely Mixed Layer Depth (MLD), Thermocline layer, and Deep (interior) layer. The mixed layer was defined as the surface layer where the temperature gradient is less than 0.1°C/m. The thermocline layer was identified based on a temperature gradient $\geq 0.1^\circ\text{C/m}$ and a density gradient $\geq 0.02 \text{ kg/m}^3$, relative to the surface reference point (Prihatiningsih *et al.*, 2021). The boundary between the mixed layer and the thermocline was determined from the density profile and confirmed using the temperature profile. This boundary was characterized by a marked increase in density with depth.

CTD data collected in the field were processed using Sea-Bird (SBE) Data Processing through the following steps: raw data conversion, outlier removal, thermal mass correction, sensor response filtering, loop editing, derivation of secondary parameters, bin averaging, and data quality control in accordance with standard procedures (SBE Data Processing, 2015). Next, the data were analyzed

using Microsoft Excel, MATLAB, and Ocean Data View (ODV). Microsoft Excel was used to calculate the density gradient ($\Delta\rho$) and compile data from all stations; MATLAB was used to filter out noise and spikes prior to visualization; and ODV was used to generate vertical profiles and cross-sections of oceanographic parameters, as well as diagrams of Temperature - Salinity (TS), Temperature - Oxygen (TO), and Salinity - Oxygen (SO) diagrams.

We analyzed temperature, salinity, potential density, dissolved oxygen, and chlorophyll-*a* horizontally and vertically at each observation station. The water column was divided into three layers: the Mixed Layer Depth (MLD), the thermocline, and the deep layer based on temperature gradients ($< 0.1\text{ }^{\circ}\text{C m}^{-1}$ for the MLD and $\geq 0.1\text{ }^{\circ}\text{C m}^{-1}$ for the thermocline) and density gradients ($\geq 0.02\text{ kg m}^{-3}$), (Prihatiningsih *et al.*, 2021). We identified water masses by analyzing TS, TO, and SO diagrams based on temperature, salinity, and dissolved oxygen characteristics, as described by Gao *et al.* (2020). We also identified the Deep Chlorophyll Maximum (DCM) as the depth with the maximum chlorophyll-*a* fluorescence value in each CTD profile. We analyzed the spatial variation of the DCM and the physical processes influencing its formation descriptively through the relationships among the vertical distributions of temperature, salinity, density, chlorophyll-*a*, and the water-column stratification structure.

To analyze the spatial variation of oceanographic conditions in the Banggai Waters, eight observation stations were grouped into two transects: the northern transect (Stations 34, 35, 36, and 38) and the southern transect (Stations 14, 16, 18, and 20), in accordance with the north-south orientation of the observation route. This division into transects aims to represent the hydro-oceanographic conditions in the two parts of the study area and to facilitate the analysis and comparison of the vertical and horizontal distributions of temperature, salinity, density, dissolved oxygen, and chlorophyll-*a*, including the stratification structure of the water column and the spatial variation of the Deep Chlorophyll Maximum (DCM).

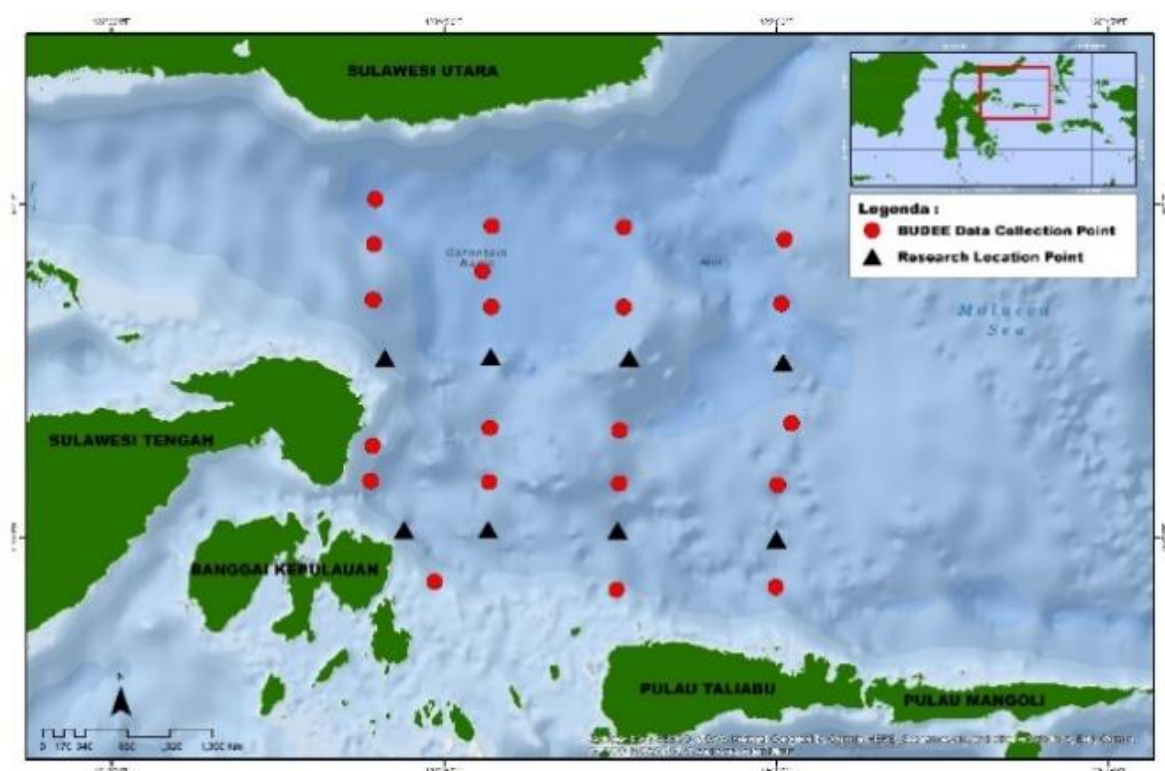


Figure 1. Study area in the western Maluku Sea. The eight black triangle symbols indicate selected CTD stations, chosen from all CTD stations (red dots) collected during the BUDEE 2022 expedition.

RESULT AND DISCUSSION

Oceanographic data acquisition using a CTD profiler was conducted from the surface down to 1000 m depth. The data were presented as vertical profiles of temperature, salinity, and density. The temperature profile showed a gradual decrease with depth, ranging from 4.48 to 29.62°C. A thermocline layer was identified between 41 and 247 m depth, marked by a decline in temperature. However, this decrease was not always abrupt but rather formed a stepped profile, characterized by gradual changes within relatively stable layers. Below the thermocline, at depths of 247 to 1033 m, the temperature ranged between 4.48 and 15.17°C. This decrease in temperature in deeper layers reflects a continuation of vertical stratification from the surface, strongly influenced by the diminishing penetration of solar radiation with increasing depth (Herni, 2014).

Spatially, thermocline thickness and depth varied between stations. Thermocline profiles at several stations showed non-uniform changes in temperature and density gradients, forming a step-like thermocline structure that indicates variations in water-mass stratification, as reported by Ryanto *et al.* (2024). Among all stations, Station 36 exhibits the most distinct characteristics, with warmer water penetrating deeper than at other stations, even though surface temperatures are relatively similar. These variations indicate differences in the vertical structure of the water column at each observation site, which contribute to the diversity of hydro-oceanographic characteristics in the Banggai Sea.

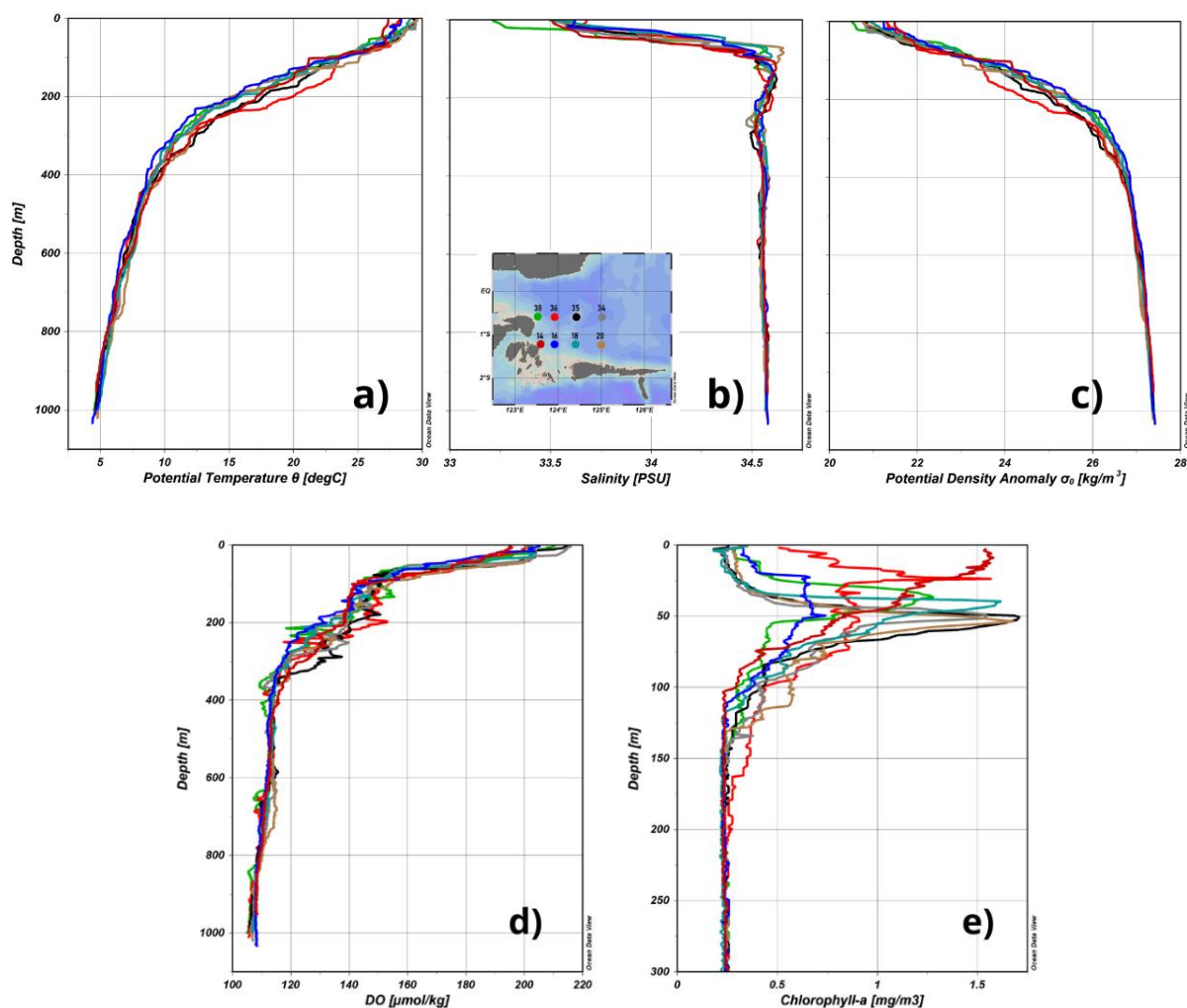


Figure 2. Vertical profiles of potential temperature (a), salinity (b), potential density anomaly (c), dissolved oxygen (d), and chlorophyll-a (e) for 8 CTD casts in the study area. Color dots denote for CTD position (inset).

The vertical distribution of salinity (Figure 2b) showed a clear stratification from the surface to depth, which can be divided into three main layers: the mixed layer, halocline layer, and deep layer. Surface salinity tended to be lower due to freshwater dilution, whereas maximum salinity was recorded between 84–152 m depth, ranging from 34.60 to 34.65 PSU, coinciding with the halocline layer. In deeper layers, salinity was relatively uniform, reflecting stable water-column conditions with minimal vertical mixing in Banggai waters.

Overall, density increased with depth, consistent with the principle that in stable conditions, lighter water masses reside above denser ones. The vertical density profile (Figure 2c) indicated that the mixed layer had density values ranging from 20.51 to 22.48 σ_θ at depths of 1–78 m. In the thermocline layer (41–247 m), density increased to 21.57–25.72 σ_θ , which is consistent with the range reported by Andre *et al.* (2023), i.e., 2–26 σ_θ . In the deep layer, densities ranged from 25.59 to 27.41 σ_θ . This sharp density gradient plays a critical role in maintaining stratification and limiting vertical mixing, thereby preserving the physical characteristics—such as temperature and salinity—within each layer of the Banggai waters.

Dissolved oxygen (DO) values at all stations and observation depths ranged from 104.93 to 215.99 $\mu\text{mol/kg}$, with the highest concentrations found in the mixed layer at Stations 34 and 35. In general, DO concentrations decreased with increasing depth. The high oxygen content in the mixed layer is influenced by air–sea exchange processes and phytoplankton photosynthetic activity in the surface layer. A significant decrease in concentration occurs in the thermocline due to oxygen consumption during the decomposition of organic matter and limited vertical ventilation into deeper layers. At depths of 400–1,000 m, DO concentrations are relatively stable and show no notable variations between stations. However, at a depth of approximately 200 m, Station 36 exhibits relatively higher values for temperature, salinity, DO, and chlorophyll-a compared to the other stations. These characteristics indicate variations in water mass properties or local mixing processes that result in different hydro-oceanographic conditions at that station compared to the surrounding areas.

Stations 18, 20, 34, and 35, located in the offshore area, exhibit a Deep Chlorophyll Maximum (DCM) pattern, with peak chlorophyll-a concentrations occurring at depths of approximately 30–60 m, near the lower boundary of the Mixed Layer Depth (MLD) and the upper part of the thermocline. The greater DCM depth at these stations indicates that the euphotic zone and the upper boundary of the thermocline are deeper, causing the optimal zone where light penetration and nutrient supply intersect to shift to greater depths. These conditions support phytoplankton biomass accumulation in that layer (Hamzah *et al.*, 2025; Khairunnisa, 2024; Rosdiana, 2017). In contrast, Station 16 does not show a clear Subsurface Chlorophyll Maximum (SCM) or DCM pattern because chlorophyll-a concentrations are relatively homogeneous down to a depth of about 100 m. This pattern indicates more intensive vertical mixing, resulting in a more even distribution of phytoplankton throughout the water column. This interpretation is supported by Saputra *et al.* (2026), who reported high values of vertical eddy diffusivity (K_p) in the Banggai Sea, indicating that strong vertical mixing enhances nutrient supply to the euphotic zone and supports phytoplankton growth. At depths greater than 100 m, chlorophyll-a concentrations at all stations decreased to $<0.2 \text{ mg/m}^3$ as light intensity diminished and water mass density increased ($25\text{--}27 \text{ kg/m}^3$), thereby severely limiting photosynthetic activity.

The vertical distribution of chlorophyll-a (Figure 2e) in the Banggai waters showed significant spatial variation across stations. The highest concentrations were generally observed in the surface layer to depths of 50 m, with maximum values recorded at Station 20 (1.68 mg/m^3) and Station 35 (1.71 mg/m^3). Several stations, such as 14, 36, and 38, also exhibited high surface concentrations ($>1.2 \text{ mg/m}^3$). Station 18 showed a relatively uniform vertical distribution down to $\sim 100 \text{ m}$, indicating weak stratification and adequate light and nutrient availability to support productivity at mid-depths. At Station 16, the chlorophyll-a peak was detected between 30–50 m, forming a sharp profile that suggests phytoplankton aggregation within a thin layer due to optimal light and nutrient conditions. In contrast, very low concentrations ($<0.2 \text{ mg/m}^3$) were observed at all stations below 100 m,

reflecting light limitation and reduced productivity in deeper layers. Chlorophyll-a measurements were limited to 300 m depth since light penetration below the euphotic zone is minimal, rendering chlorophyll-a concentrations near zero and indicative of negligible photosynthetic activity.

The horizontal structure of potential temperature in Banggai waters (Figure 3) reveals pronounced thermal stratification in both transects. The surface layer (0–50 m) is warm (28–30 °C) due to tropical solar heating and limited vertical mixing, forming a stable mixed layer that supports high primary productivity.

Mixed layer thickness ranges from 0–43 m at Stations 14 and 38 (26–29 °C) to 0–78 m at Station 16 (26–28 °C), consistent with Latuapo *et al.* (2024) who reported 26–29 °C in the Maluku Sea. The thermocline, found at 41–247 m, separates warm surface water from cooler subsurface water, restricting nutrient upwelling and influencing chlorophyll-a distribution.

Transect 2 (Figure 3b) features a shallower, sharper thermocline—likely driven by water mass intrusion or upwelling—while Transect 1 (Figure 3a) shows a deeper, more gradual gradient, possibly shaped by topographic or circulation effects. The mixed layer records the highest temperatures (26.33–29.62 °C; mean 27.92 °C), with the warmest at Station 20 and coolest at Station 35. Thermocline temperatures range from 14.58–27.59 °C (mean 20.94 °C; Figure 4). Beneath it lies a nearly homogeneous cold layer, reaching 4.48 °C at ~1000 m (Nontji, 1993). Below this depth, temperature remains ~0–3 °C year-round, maintained by dense, cold polar waters advected toward the equator (Supangat and Susanna, 2007).

Figure 5 shows the horizontal distribution of salinity across two transects in the Banggai waters. The salinity pattern in both transects shows relatively strong stratification, marked by differences in salinity concentration between layers. In Transect 1 (Figure 5a), the surface layer exhibits lower salinity, ranging between 33.25 and 33.75 PSU at depths around 0–50 m. This indicates dilution of surface water mass, possibly caused by precipitation, land runoff, or intrusion of fresher Pacific water. Beneath this layer, salinity increases with depth, reaching higher values below 200 m (~34.6 PSU), and remains relatively stable from 400 to 1000 m, reflecting a more homogeneous water column.

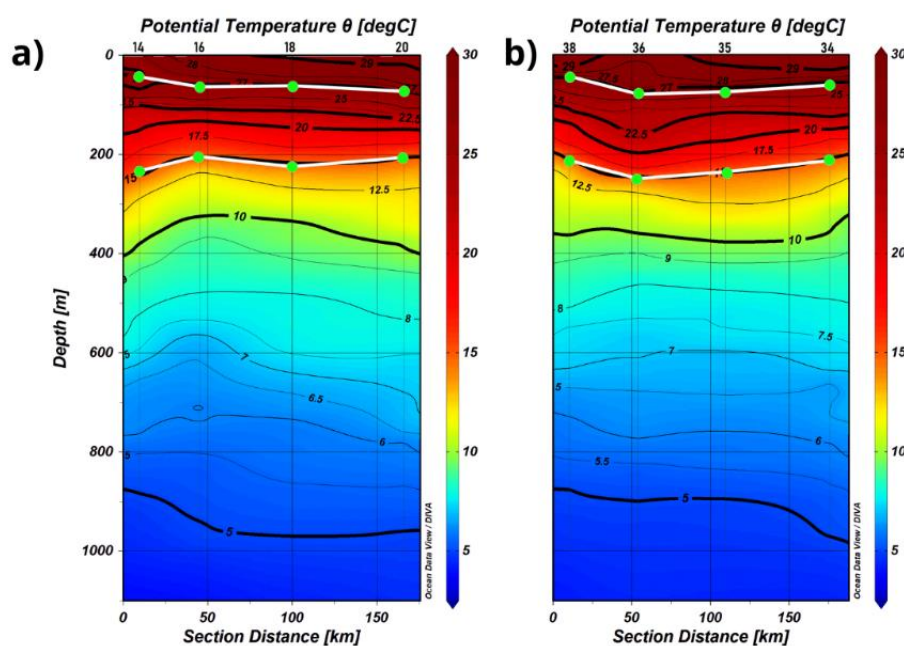


Figure 3. Cross-section of potential temperature in the northern section (a), and southern section (b). White lines show mixed layer and thermocline thickness.

In the thermocline layer (78–247 m), salinity increased to approximately 34.65 PSU, forming a maximum salinity layer at depths of approximately 70–120 m in the southern transect and 110–170 m in the northern transect. This pattern indicates the intrusion of a high-salinity water mass characteristic of North Pacific Subtropical Water (NPSW), as demonstrated by the results of water mass identification via T–S diagrams. Below this layer, at depths of approximately 200–390 m, a minimum salinity layer was observed with a value of about 34.50 PSU, which is relatively lower than the layers above and below it. This characteristic indicates the presence of an intermediate water mass with lower salinity associated with the North Pacific Intermediate Water (NPIW). These maximum and minimum salinity patterns indicate that water mass stratification remains intact from the thermocline to the intermediate layer.

In the deep layer (>400 m), salinity was relatively homogeneous, ranging from 34.47 to 34.58 PSU, and showed only minor variations between stations, reflecting the greater stability of the deep seawater mass compared to the overlying layers. Spatially, both transects showed similar salinity distribution patterns; however, the layer of maximum salinity in the northern transect was at a greater depth than in the southern transect. This difference indicates variations in the vertical structure of the water masses between the transects. Additionally, the surface layer exhibits relatively lower salinity with a horizontally elongated distribution, suggesting variations in the distribution of surface water masses in the Banggai Sea. Overall, the salinity distribution suggests that the vertical structure of the water mass in the Banggai Sea is controlled by water column stratification processes and the presence of Pacific water masses entering the study area via the Indonesian Throughflow (ITF).

In Transect 2 (Figure 5b), surface salinity is also relatively low, similar to Transect 1. However, the high-salinity layer appears at greater depths. This pattern may be influenced by variations in local currents, seafloor contours, or differences in vertical mixing. At depths of 100–500 m, a gradual increase in salinity is observed, indicating the transition from fresher surface water to deeper, saltier, and more stable water. In general, density distribution increases vertically from the surface to depth, which is a common pattern in the ocean due to decreasing temperature and increasing salinity. In both transects, the surface layer (0–100 m) has low density values (~ 21.5 – 23 kg/m^3), associated with high temperature and low salinity at the surface. This layer is relatively stable and reflects the presence of the mixed layer (Figure 6).

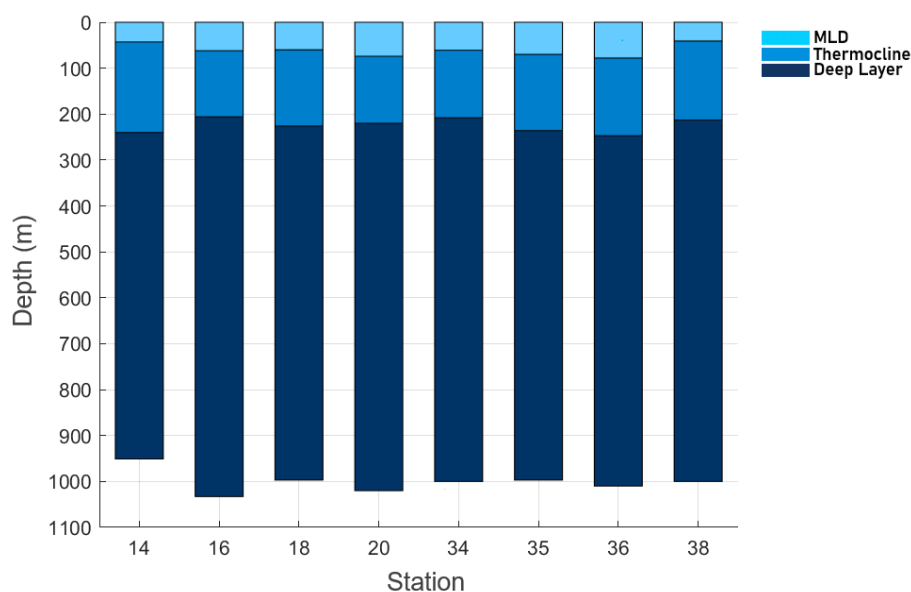


Figure 4. Schematic diagram of mixed layer depth (MLD), thermocline thickness, and deep layer for southern section (St. 14, 16, 18, and 20) and northern section (Sta. 34, 35, 36, and 38).

The distribution of potential density ($\sigma\theta$) in the Banggai Waters shows a vertical increase from the surface layer toward the deeper layers. This pattern is a common characteristic of tropical waters, where density increases due to a decrease in temperature and an increase in salinity with increasing depth. The surface layer down to a depth of about 100 m has a relatively low density ($<24 \text{ kg m}^{-3}$), whereas at depths greater than 700 m, the density increases to $>27 \text{ kg m}^{-3}$ and tends to be homogeneous. At depths of approximately 100–300 m, a sharp density gradient is identified as the pycnocline, which acts as the boundary between the surface water mass and the deep water mass and limits vertical mixing.

The cross-sectional density distribution also reveals different isopycnal deformations along the two transects. In the southern transect, the isopycnal $\sigma\theta \approx 27$ exhibits uplift toward shallower layers at a distance of approximately 30–70 km, whereas in the northern transect, the isopycnal $\sigma\theta \approx 24.5$ shows a depression at a depth of approximately 150–250 m. The uplift and depression of these isopycnals indicate variations in the vertical structure of the water mass between the transects, suggesting that water mass dynamics are governed not only by vertical stratification but also by regional circulation processes and horizontal and vertical water mass transport. Overall, the density distribution in the Banggai Sea reveals a well-stratified water column, with isopycnal deformations reflecting the complexity of hydro-oceanographic dynamics in the study area.

At depths of 100–500 m, a significant change in seawater density is observed, forming a transition layer known as the pycnocline. This layer marks the separation between lighter surface water and denser deep water. This condition generally coincides with changes in temperature (thermocline) and salinity (halocline), indicating strong stratification in the water column. Such stratification can inhibit vertical mixing, which limits nutrient supply from deep to surface layers. The sharp density gradient indicates strong stratification that may restrict mixing between surface and deeper layers, affecting nutrient and chlorophyll-a distribution. The highest density values ($>27 \text{ kg/m}^3$) were found below 700 m, reflecting cold and saline deep water conditions. The relatively homogeneous appearance of high-density values in the bottom layer indicates the stability of the deep water column and minimal vertical disturbance at those depths. Density values are used to determine the mixed layer, since density is calculated based on temperature and salinity parameters. This shows that variations in temperature and salinity directly influence the distribution of seawater density in the Banggai waters.

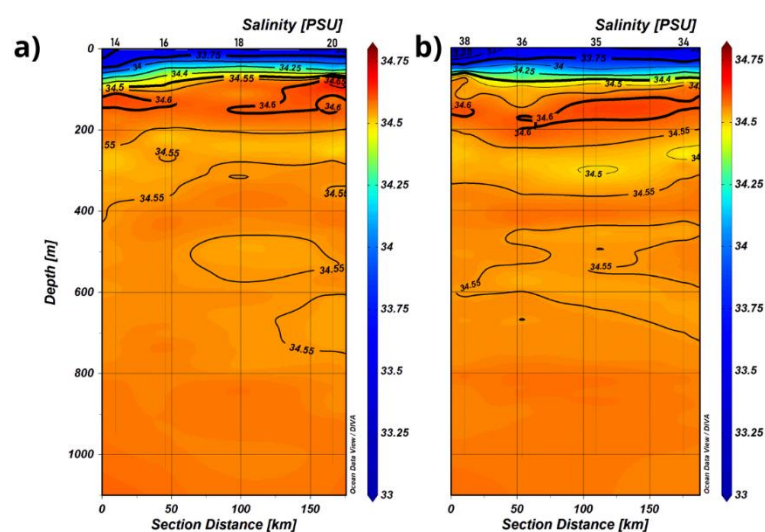


Figure 5. Cross-section of salinity in the northern section (a), and southern section (b).

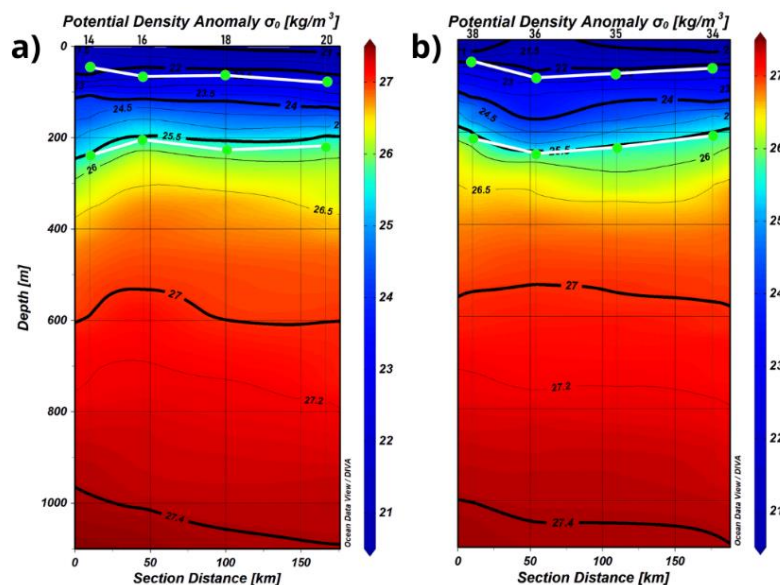


Figure 6. Cross-section of potential density anomaly in the northern section (a), and southern section (b).

The vertical distribution of dissolved oxygen (DO) in the Banggai waters shows a decrease in concentration with increasing depth along both transects (Figure 7). The highest DO concentrations (153–215 $\mu\text{mol/kg}$) were found in the mixed layer down to a depth of approximately 100 m as a result of oxygen exchange with the atmosphere and photosynthetic activity in the euphotic zone (Latuapo *et al.*, 2024; Ryanto *et al.*, 2024). In contrast, DO concentrations drop sharply at depths of 100–500 m, reaching 104–139 $\mu\text{mol/kg}$, forming the Oxygen Minimum Zone (OMZ). This zone forms due to limited oxygen supply from the surface layer caused by strong thermoclines and pycnoclines, as well as increased oxygen consumption through respiration and the decomposition of organic matter sinking from the upper layers.

Spatially, the northern transect exhibited a thicker oxygen-rich layer compared to the southern transect, whereas the decline in DO in the southern transect occurred more rapidly with increasing depth. These differences indicate variations in water column stratification between the transects that influence oxygen distribution. At depths greater than 600 m, DO concentrations are relatively stable with little variation between stations, reflecting the more homogeneous characteristics of deep seawater. This DO distribution pattern indicates that oxygen conditions in the Banggai Sea are controlled by the interaction between physical processes primarily water column stratification—and biological processes, such as photosynthesis in the surface layer and the decomposition of organic matter in the lower layers.

The horizontal distribution of chlorophyll-a in Transect 1 (Figure 8a) and Transect 2 (Figure 8b) shows elevated concentrations in the surface layer, with values peaking at 1.71 mg/m^3 within the upper 50 m and forming a distinct Deep Chlorophyll Maximum (DCM) at 30–50 m, driven by an optimal balance between light availability and nutrient supply near the euphotic base (Bouman *et al.*, 2020; Cornec *et al.*, 2021; Xu *et al.*, 2021). Chlorophyll-a concentrations decline sharply below 100 m due to light limitation, while high surface values near the coast are likely supported by nutrient enrichment from runoff, vertical mixing, or resuspension processes (Thoha *et al.*, 2013; Widianingsih *et al.*, 2024). Offshore regions also exhibit enhanced chlorophyll-a, potentially associated with localized upwelling or frontal interactions that transport deep, nutrient-rich waters toward the surface (Fitriyan *et al.*, 2023; Susanto *et al.*, 2001). In these offshore zones, a relatively shallow thermocline shortens the vertical distance between nutrient sources and the euphotic zone, promoting efficient nutrient entrainment and sustaining high phytoplankton productivity.

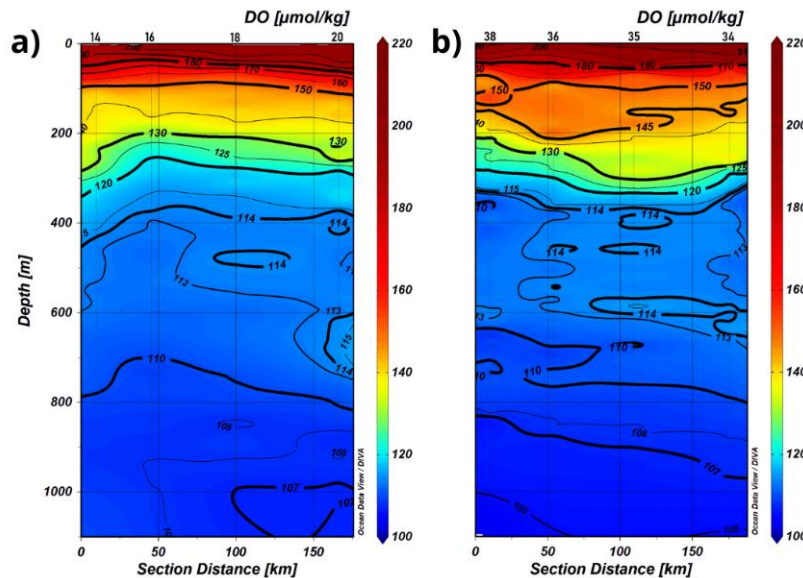


Figure 7. Cross-section of dissolved oxygen (DO) in the northern section (a), and southern section (b).

Spatially, the distribution of chlorophyll-a showed differences between the two transects. In the southern transect, high chlorophyll-a concentrations were observed around Station 14, with a relatively limited distribution at depths of up to about 75 m. In contrast, in the northern transect, high chlorophyll-a concentrations had a wider horizontal distribution, particularly around Station 36, at depths of about 25–75 m. Although the maximum chlorophyll-a value at Station 14 was slightly higher than that at Station 36, the larger area of chlorophyll-a distribution in the northern transect indicates that phytoplankton productivity is influenced not only by concentration levels but also by the spatial distribution of productive water masses.

This pattern is consistent with temperature and density profiles showing isothermal and isopycnal upwelling around Stations 16 and 38. The shallowing of these isotherms and isopycnals indicates the movement of water masses from deeper layers toward shallower layers, thereby shortening the distance between the nutrient-rich layer and the euphotic zone. These conditions increase the likelihood that nutrients will reach the layer where photosynthesis occurs and support the formation of DCM at depths of 40–60 m. Conversely, at locations that do not show isothermal or isopycnal upwelling, chlorophyll-a distribution tends to be more limited, resulting in relatively lower phytoplankton productivity.

Overall, the distribution of chlorophyll-a in the Banggai Waters shows a close relationship with the thermal structure and density of the water column. Thermocline shallowing, isotherm upwelling, and isopycnals play a role in increasing the supply of nutrients to the euphotic zone, thereby forming a Deep Chlorophyll Maximum (DCM) and enhancing primary productivity. Similar phenomena have been widely reported in tropical waters, where variations in water column structure are the primary factors controlling the vertical distribution of phytoplankton (Bouman *et al.*, 2020; Cornec *et al.*, 2021; Xu *et al.*, 2021; Hamzah *et al.*, 2015).

Temperature–Salinity (TS), Temperature–Oxygen (TO), and Salinity–Dissolved Oxygen (SO) diagrams along the longitudinal transect (Figure 9) illustrate spatial variability of physical properties in Banggai waters. Point colors indicate station groups: blue (west), green (central), and red (east), with each point representing in-situ measurements across depths. Contour lines denote potential density (σ_θ).

In the TS diagram (Figure 9a), western stations show warmer surface waters (29.52–29.62 °C) with uniform salinity (34.2–34.4 PSU), while eastern stations are cooler (<26 °C) with slightly higher, more variable salinity (up to 34.5 PSU). This reflects the dominance of North Pacific Subtropical Water (NPSW) in the upper western layer and colder, more stable North Pacific Intermediate Water (NPIW) in the east. The South Pacific Subtropical Lower Thermocline Water (SPSLTW) is marked by salinity near 34.60 PSU. Below the 27 σ_θ isopycnal, Antarctic Intermediate Water (AAIW) is observed with salinity 34.55–34.58 PSU and temperatures 4.72–6.98 °C, consistent with Atmadipoera *et al* (2022) and Ilahude and Gordon (1996), who reported AAIW between 27–27.6 σ_θ at ~34.5 PSU.

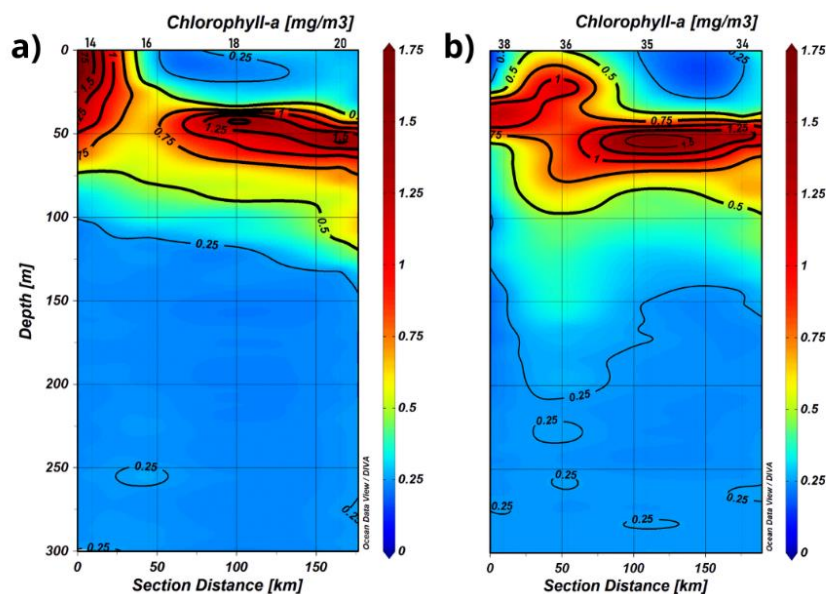


Figure 8. Cross-section of chlorophyll-a in the northern section (a), and southern section (b).

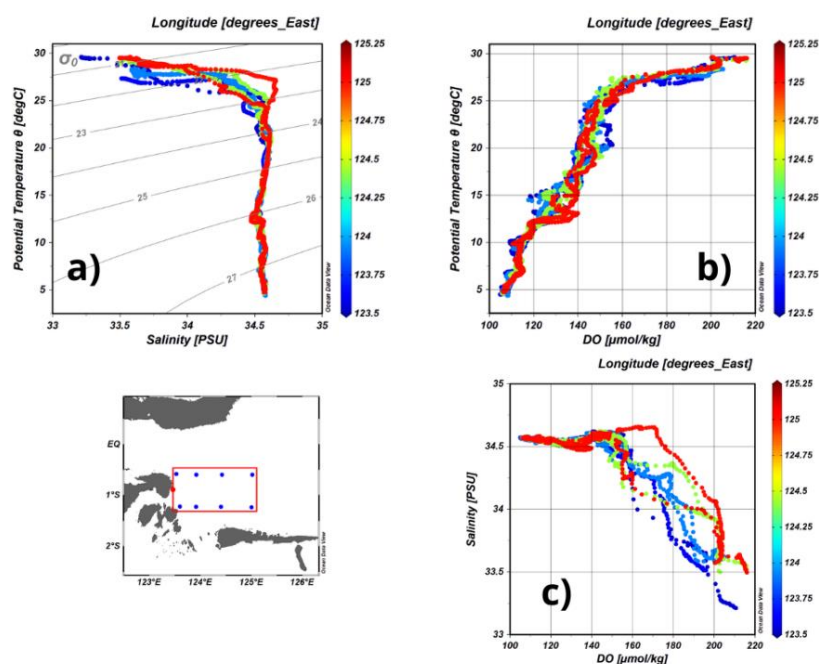


Figure 9. Structure of Indonesian Throughflow water masses in the study area, as shown by diagram temperature-salinity (a), temperature-dissolved oxygen (b), and salinity-dissolved oxygen (c).

The TO (Figure 9b) diagram shows that warmer waters, particularly in the western and central regions, have higher oxygen (195.88–215.99 $\mu\text{mol/kg}$) due to atmospheric ventilation. In contrast, cooler eastern waters exhibit lower oxygen (<160 $\mu\text{mol/kg}$), indicating older, deeper water masses with limited surface contact. In the SO diagram (Figure 9c), oxygen declines with increasing salinity before stabilizing above 34.5 PSU, reflecting vertical stratification that restricts oxygen transfer to depth. High salinity–low oxygen points (red) further indicate the presence of NPIW in intermediate to deep eastern waters.

Deep layer temperatures reaching 4.48°C correspond to Antarctic Intermediate Water (AAIW), as supported by T–S diagram patterns and $\sigma_\theta > 27$ isopycnals (Ilahude & Gordon, 1996; Atmadipoera *et al.*, 2022; Ryanto *et al.*, 2024). This finding confirms the presence of AAIW in the Banggai region, as previously hypothesized by Atmadipoera *et al.* (2022) and is now supported by vertical observations from BUDEE 2022. In addition, a secondary layer below 800 m, characterized by consistently cold temperatures ($\sim 4.5^\circ\text{C}$), high salinity (≥ 34.55 PSU), and low oxygen (<140 $\mu\text{mol/kg}$), may indicate the presence of Antarctic Deep Water (ADW), previously unconfirmed in this region. The occurrence of ADW in the Maluku-Banggai corridor presents a new finding and suggests the penetration of deeper Southern Ocean waters into the Indonesian interior seas (Gordon *et al.*, 2008; Yuan *et al.*, 2022).

CONCLUSION

The hydrographic characteristics of the Banggai Sea show distinct horizontal and vertical variability in temperature, salinity, potential density, dissolved oxygen, and chlorophyll-a. The water column is stratified into three distinct layers: the mixed layer, the thermocline, and the deep layer. Spatial differences between the northern and southern transects are reflected in variations in the thickness of the mixed layer, the depth of the thermocline, and hydrographic properties. The vertical salinity distribution shows distinct layers of maximum and minimum salinity, corresponding to the presence of North Pacific Subtropical Water (NPSW) and North Pacific Intermediate Water (NPIW), while the potential density distribution indicates well-developed stratification accompanied by isopycnal upwelling and downwelling, reflecting variations in the vertical structure of the water column. The formation and spatial variability of the Deep Chlorophyll Maximum (DCM) are closely related to the hydrographic structure of the water column. The DCM generally occurs at depths of 40–60 m near the base of the mixed layer and the upper thermocline, where light availability and nutrient supply are at optimal levels. Variations in the DCM among stations are related to differences in thermocline depth, density stratification, and indications of vertical water mass transport inferred from temperature and density distributions. These results indicate that the physical processes governing water column stratification play a crucial role in regulating nutrient availability and phytoplankton distribution in the Banggai Sea.

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