Diversity and Abundance of Phytoplankton in the Coastal Waters of South Sulawesi

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1. Introduction

Situated in the Coral Triangle and Wallacea biodiversity hotspots (Barber 2009; Michaux 2010; Ambo-Rappe and Moore 2019), the coastal waters around the coasts of South Sulawesi, Indonesia sustain valuable and biodiverse biotic communities (Saleh 2019; Furkon et al. 2020). Increasing human activities in recent decades have resulted in anthropogenic impacts including pollution (Edinger et al. 1998; Heery et al. 2018; Ambo-Rappe and Moore 2019; Duarte et al. 2020). Phytoplankton are small, often single-celled plants which, as primary producers, are vital to marine an estuarine food webs (Statham 2012; Day et al. 2012; Cermeño et al. 2013). Phytoplankton can serve as an indicator of aquatic ecosystem health (Borja et al. 2011; Hosmani 2013). In particular, phytoplankton abundance can provide information on the actual and potential productivity of aquatic ecosystems, the ability of the aquatic environment to support particular species of interest, and can be used as biological indicators (bioindicators) of water quality, including eutrophication and other forms of pollution (Borja et al. 2011; Kitsiou and Karydis 2011; Hosmani 2013; Parmar et al. 2016; Hemraj et al. 2017; Yeanny 2018; Pradisty et al. 2020). Phytoplankton community composition and abundance can greatly influence fisheries production, especially in estuarine waters (Day et al. 2012).

However, the functional roles of marine ecosystems can be affected by changes in phytoplankton community structure and abundance (Cermeño et al. 2013; Trombetta et al. 2019; Wurtsbaugh et al. 2019). Although phytoplankton are crucial for marine ecosystem health and productivity, population explosions of certain types of phytoplankton, called...
harmful algal blooms (HABs), can exceed the carrying capacity of the ecosystem and have negative impacts on other organisms, including mass die-offs of fish and other organisms due to anoxic conditions (O’Neil et al. 2012; Statham 2012; Paerl et al. 2014; Trombetta et al. 2019; Wurtsbaugh et al. 2019). Algal blooms due to explosive phytoplankton population growth can also impact the aesthetic, cultural and social value of coastal areas (Wurtsbaugh et al. 2019).

Knowledge regarding phytoplankton communities is important for the management of marine and coastal areas and resources. The objectives of this research were to determine the biodiversity and abundance of phytoplankton at strategic points around South Sulawesi and to examine the relationship between phytoplankton communities and physical-chemical factors in these coastal waters.

2. Materials and Methods

2.1. Study Sites

This research was conducted in the estuarine and coastal waters of South Sulawesi Province, Indonesia from January to March 2020. Seven sites (Figure 1) were selected through purposive sampling, based on the rationale was that rivers tend to carry nutrient loads from the land to the sea, and are considered likely to influence seawater quality and phytoplankton communities. The sites were also selected to represent the three coasts of South Sulawesi which face three different sea areas: Makassar Strait to the west, the Flores Sea to the South and the Gulf of Bone to the east. These sites comprised coastal waters around the estuary of the largest river in each of seven districts/cities around the province: Saddang...

Figure 1. Research area in South Sulawesi, Indonesia showing sampling sites and stations
River in Sidrap District, Binangasangkara River in Pangkep District, and Tallo River in Makassar City (Makassar Strait); Cikoang River in Takalar District and Ujung Loe River in Bulukumba District (Flores Sea); Lamasi River in Palopo City and Malili River in Malili City (Gulf of Bone).

2.2. Survey Method and Data Analysis

Data collection at each estuarine site took place at six stations. These comprised three inshore stations close to the mouth of the major river selected and three stations further offshore but still within the area influenced by the river outflow (Table 1). At each of the stations, five physical and chemical water quality parameters were measured using a multi-function water quality checker (TOA DKK Model WQC24-1-2): water temperature (°C), salinity (ppt), turbidity (NTU), pH, and nitrate concentration (mg/l). Station parameters also included a subjective estimate of the visible sources of pollution, especially nutrient sources.

Table 1. Site and station geographical coordinates and characteristics

| Site       | Station | Latitude S | Longitude E | Distance | Current | Visible pollution sources |
|------------|---------|------------|-------------|----------|---------|--------------------------|
| Makassar Strait |         |            |             |          |         |                          |
| Pinrang    | P13     | 5°50.65"   | 119°26.50.57" | Inshore  | upstream | medium                   |
| Pinrang    | P15     | 4°22.52"   | 119°26.32.16" | Offshore | upstream | low                      |
| Pinrang    | P9      | 5°55.60"   | 119°25.37.75" | Offshore | middle   | low                      |
| Pinrang    | P14     | 5°51.65"   | 119°26.48.58" | Inshore  | middle   | medium                   |
| Pinrang    | P15     | 5°53.44"   | 119°26.47.93" | Inshore  | downstream | high                        |
| Pinrang    | P20     | 5°38.18"   | 119°25.19.17" | Offshore | downstream | low                      |
| Pangkep    | P3      | 4°52.48.32" | 119°30.53.91" | Inshore  | upstream | high                      |
| Pangkep    | P8      | 4°51.44.90" | 119°29.50.98" | Offshore | upstream | medium                   |
| Pangkep    | P9      | 4°52.51.13" | 119°29.23.75" | Offshore | middle   | high                      |
| Pangkep    | P14     | 4°52.50.64" | 119°30.52.95" | Inshore  | middle   | medium                   |
| Pangkep    | P15     | 4°52.53.51" | 119°30.54.71" | Offshore | downstream | high                      |
| Pangkep    | P20     | 4°54.13.07" | 119°30.13.89" | Offshore | downstream | high                      |
| Makassar   | MK3     | 5°50.65"   | 119°26.30.12" | Inshore  | upstream | medium                   |
| Makassar   | MK8     | 5°42.22.52" | 119°26.22.06" | Offshore | upstream | low                      |
| Makassar   | MK9     | 5°45.50.60" | 119°25.37.75" | Offshore | middle   | low                      |
| Makassar   | MK14    | 5°51.65"   | 119°26.48.58" | Inshore  | middle   | high                      |
| Makassar   | MK15    | 5°53.44"   | 119°26.47.93" | Inshore  | downstream | high                      |
| Makassar   | MK20    | 5°38.18"   | 119°25.19.17" | Offshore | downstream | medium                   |
| Flores Sea |         |            |             |          |         |                          |
| Takalar    | TA3     | 5°32.15.06" | 119°26.3.66" | Inshore  | upstream | low                      |
| Takalar    | TA8     | 5°30.53.64" | 119°25.24.60" | Offshore | upstream | low                      |
| Takalar    | TA9     | 5°31.37.74" | 119°24.40.02" | Offshore | middle   | low                      |
| Takalar    | TA14    | 5°32.16.74" | 119°26.1.86" | Inshore  | middle   | low                      |
| Takalar    | TA15    | 5°32.19.14" | 119°26.1.92" | Inshore  | downstream | low                      |
| Takalar    | TA20    | 5°32.42.30" | 119°24.34.20" | Offshore | downstream | medium                   |
| Bulukumba  | BL3     | 5°32.17.64" | 120°14.24.42" | Inshore  | upstream | medium                   |
| Bulukumba  | BL8     | 5°33.33.96" | 120°13.35.04" | Offshore | upstream | low                      |
| Bulukumba  | BL9     | 5°33.48.00" | 120°14.38.82" | Offshore | middle   | low                      |
| Bulukumba  | BL14    | 5°32.18.60" | 120°14.27.30" | Inshore  | middle   | high                     |
| Bulukumba  | BL15    | 5°32.17.16" | 120°14.29.64" | Inshore  | downstream | medium                   |
| Bulukumba  | BL20    | 5°33.18.42" | 120°15.37.44" | Offshore | downstream | low                      |
| Gulf of Bone |        |            |             |          |         |                          |
| Palopo     | PL3     | 2°57.17.04" | 120°13.47.04" | Inshore  | upstream | medium                   |
| Palopo     | PL8     | 2°58.45.78" | 120°13.29.46" | Offshore | upstream | low                      |
| Palopo     | PL9     | 2°58.42.00" | 120°14.23.94" | Offshore | middle   | low                      |
| Palopo     | PL14    | 2°57.17.22" | 120°13.49.98" | Inshore  | middle   | medium                   |
| Palopo     | PL15    | 2°57.14.82" | 120°13.51.96" | Inshore  | downstream | high                      |
| Palopo     | PL20    | 2°58.47.44" | 120°15.72.96" | Offshore | downstream | low                      |
| Malili     | ML3     | 4°52.48.32" | 119°30.53.91" | Inshore  | upstream | low                      |
| Malili     | ML8     | 4°51.44.90" | 119°29.50.98" | Offshore | upstream | medium                   |
| Malili     | ML9     | 4°52.51.13" | 119°29.23.75" | Offshore | middle   | medium                   |
| Malili     | ML14    | 4°52.50.64" | 119°30.52.95" | Inshore  | medium   | medium                   |
| Malili     | ML15    | 4°52.53.51" | 119°30.54.71" | Inshore  | downstream | medium                   |
| Malili     | ML20    | 4°54.13.07" | 119°30.13.89" | Offshore | downstream | medium                   |
enrichment (low, medium, high), the distance from the coast (inshore or offshore), and the position relative to the prevailing current direction within each set of three stations (upstream, middle and downstream). The rationale for these was that phytoplankton communities would likely differ in abundance and/or composition depending on the levels of pollution (including parameters not measured in the water quality analysis), and that effects would likely be less further offshore and/or upstream compared to further inshore and/or in the middle (i.e. exposed to the major river outflow) or downstream of the river and other sources of pollution.

Phytoplankton samples were obtained by collecting 100 l samples of seawater and straining them through a No. 25 plankton net (Bengen 1999). The plankton retained in the net were preserved in Lugol 4% solution. Phytoplankton were identified and counted in the Chemical Oceanography Laboratory of the Marine Science Department at Universitas Hasanuddin based on references including books (e.g. Davis 1955; Yamaji 1976) and the on-line database AlgaeBase (Guiry and Guiry 2021). Representative specimens were photographed under the microscope.

### 2.3. Phytoplankton Abundance

Phytoplankton abundance was calculated using the equation in APHA (2012):

\[
N = n \times \frac{a \times \frac{V}{A} \times \frac{1}{V_c}}{V}
\]  

(1)

Where:
- \(N\) = plankton abundance (cells L\(^{-1}\))
- \(n\) = number of plankton counted (cells)
- \(a\) = covered glass area (\(\text{mm}^2\))
- \(v\) = concentrated water volume (ml)
- \(A\) = microscope viewing area (\(\text{mm}^2\))
- \(V_c\) = volume of water under the covered glass (ml)
- \(V\) = volume of water filtered (L). Abundance was calculated for the community as a whole, by class and by species

### 2.4. Phytoplankton Community Structure

The phytoplankton community structure was analysed through the calculation of three ecological indices based on the equations in Odum (1998) as follows:

- **Shannon-Wiener Diversity Index (H')**
  
  \[
  H' = -\sum_{i=1}^{S} p_i \log(p_i)
  \]  

(2)

where:
- \(H'\) = diversity index
- \(p_i\) = proportion of the \(i\)th species = \(n_i/N\)
- \(n_i\) = number of individuals of the \(i\)th species (ind/cm)
- \(N\) = number of individuals of all species (ind/cm)
- \(S\) = number of species identified

The Shannon-Wiener Evenness Index (E)

\[
E = H' / \log(S)
\]  

(3)

where:
- \(E\) = evenness index
- \(H'\) = diversity index
- \(S\) = number of species identified

The Simpson Dominance Index (D)

\[
D = \sum_{i=1}^{S} \frac{(n_i)^2}{N^2}
\]  

(4)

where:
- \(n_i\) = number of individuals of the \(i\)th species (ind/cm)
- \(N\) = number of individuals of all species (ind/cm)

### 2.5. Data Analysis

The phytoplankton and environmental data were tabulated and analysed descriptively. Community structure and distribution analyses were conducted and graphics produced in Microsoft Excel 2010. The ecological indices were evaluated as follows: (i) Diversity Index: low diversity \(H'\leq 2\); moderate diversity \(2 < H'\leq 3\); and high diversity \(H' > 3\); (ii) Dominance Index: low dominance \(0 < C \leq 0.5\); moderate dominance \(0.5 < C \leq 0.75\); and high dominance \(0.75 < C \leq 1\); (iii) Evenness Index: community under pressure: \(0 < E \leq 0.5\); unstable community \(0.5 < E \leq 0.75\); stable community \(0.75 < E \leq 1\) (Morris et al. 2014). Correlations between phytoplankton community characteristics and environmental parameters were analysed in R Version 3.6.0 (R Core Team 2019) in the RStudio Version 1.1.456 environment (RStudio Team 2016) using the glm (general linear model) function, with significance evaluated at the 95% (**), 99% (****) and 99.9% (*****) confidence limits (\(\alpha = 0.05, 0.01, \text{and} 0.001\), respectively).

### 3. Results

#### 3.1. Water Quality Parameters

Water quality parameters measured at each site (Table 2) show considerable between-site variation
Table 2. Water quality parameters at seven sites around the coast of South Sulawesi

| Parameter | Unit | Pinrang | Pangkep | Makassar | Takalar | Bulukumba | Palopo | Malili |
|-----------|------|---------|---------|----------|---------|------------|--------|--------|
| Temperature | ppt  | 30.13 ± 1.33 | 30.30 ± 1.47 | 31.13 ± 1.55 | 30.70 ± 1.47 | 30.70 ± 1.16 | 30.37 ± 1.17 | 31.00 ± 1.10 |
| Salinity | °C   | 16.45 ± 11.59 | 28.30 ± 1.06 | 21.75 ± 5.71 | 29.80 ± 0.40 | 28.58 ± 3.38 | 28.43 ± 1.73 | 22.00 ± 6.67 |
| pH |      | 7.80 ± 0.28 | 8.01 ± 0.05 | 7.87 ± 0.19 | 7.86 ± 0.17 | 7.87 ± 0.34 | 7.89 ± 0.06 | 7.88 ± 0.10 |
| Turbidity | NTU | 26.68 ± 18.93 | 45.43 ± 1.92 | 34.08 ± 9.43 | 48.30 ± 0.76 | 43.15 ± 9.66 | 45.42 ± 2.78 | 34.97 ± 11.34 |
| Nitraten | mg/l | 0.532 ± 0.013 | 0.567 ± 0.034 | 0.595 ± 0.021 | 0.510 ± 0.050 | 0.582 ± 0.050 | 0.608 ± 0.025 | 0.597 ± 0.008 |

as well as within-site variation, the latter evidenced by the high standard deviation (SD) values for several parameters at most sites. The Takalar site had the highest mean salinity and Pinrang the lowest. Mean water temperature and pH were highest at the Pangkep site, and lowest in Pinrang which also had the lowest turbidity and lowest nitrate concentration. The Palopo site had the highest nitrate concentration.

### 3.2. Phytoplankton Taxonomic Composition

Phytoplankton identified belonged to three classes, the Bacillariophyceae, Cyanophyceae, and Dinophyceae (Table 3, Figure 2). Overall, the phytoplankton community in the coastal waters of South Sulawesi tended to be dominated by the Bacillariophyceae, followed by the Dinophyceae. The Cyanophyceae was the least abundant class at five of the seven sites and overall.

Examples of 30 out of the 31 phytoplankton species identified are shown in Figures 3, 4, and 5. These 31 species comprised 20 members of the Bacillariophyceae, 4 members of the Cyanophyceae and 7 members of the Dinophyceae.

### 3.3. Phytoplankton Abundance

Phytoplankton abundance varied between stations (Table 4). The Pangkep District station had by far the highest phytoplankton abundance (5,094,333 cells/l), with a community dominated by members of the Class Dinophyceae.

### 3.4. Phytoplankton Community Structure

Based on the three ecological indices calculated (Table 5), the phytoplankton community structure varied between the seven study sites around the coast of South Sulawesi. The Diversity Index (H') was low (<2) at all sites, but was highest at the Bulukumba District site (Flores Sea), followed by the Malili District site (Gulf of Bone) and by far the lowest at the Pangkep District site (Makassar Strait). The Evenness Index (E) was highest at the Palopo City site (Gulf of Bone) followed by Bulukumba, and was also lowest at the Pangkep site. The Dominance Index (D) was by far the highest at the Pangkep District site, followed by the other two Makassar Strait coast sites (Makassar and Pinrang), and lowest at the Palopo City site. The large standard deviations indicate significant differences in the taxa present as well as their relative abundance at each of the six stations within each site.

### 3.5. Phytoplankton Distribution

Out of the 31 species identified in this study, on average 18 were found at each site and 7.4 at each station, with high between-station variation at most sites (Table 6). Six taxa were found at all sampling sites: Chaetoceros sp., Coscinodiscus, Pleurosigma sp., and Thalassiosira (Bacillariophyceae), Oscillatoria sp. (Cyanophyceae) and Ceratium furca (Dinophyceae). Seven taxa were found at just one site, all of which belonged to the Class Bacillariophyceae. Three taxa were found at all stations in any one site, comprising two species of Bacillariophyceae, Chaetoceros sp. at the Makassar (Makassar Strait) and Malili (Gulf of Bone) sites, and Coscinodiscus in Takalar (Flores Sea); and one species of Dinophyceae, Ceratium furca at the Pangkep site (Makassar Strait). Based on seaway, 27 species were identified from the Makassar Strait (3 sites), and 21 each from the Flores Sea (2 sites) and Gulf of Bone (2 sites). A Venn diagram (Figure 6) shows the overlap in taxonomic composition between seaways based on presence-absence data.

### 3.6. Correlations between Phytoplankton Community, Location and Site Characteristics

The correlations between phytoplankton community characteristics and site characteristics (Table 7) show that all phytoplankton abundance and community structure indicators except species richness were significantly influenced by location (site and seaway). The site(s) differing significantly varied between the variables or indicators. Pangkep had significantly higher total phytoplankton abundance, Dinophyceae abundance, Ceratium furca...
### Table 3. Taxonomic classification of phytoplankton identified from seven sites around the coats of South Sulawesi

| Class                | Order     | Family                | Species                              |
|----------------------|-----------|-----------------------|--------------------------------------|
| Bacillariophyceae    | Pennales  | Asterionellaceae       | Asterionelopsis sp.                  |
|                      |           | Chaetoceraceae         | Chaetoceros sp.                      |
|                      |           | Fragilariaceae         | Flagillaria sp.                      |
|                      | Naviculales| Amphipleuraceae        | Amphipora sp.                        |
|                      |           | Pleurosigmataceae      | Pleurosigma sp.                      |
|                      |           | Plagiotropidaceae      | Gyrosigma sp.                        |
|                      |           | Naviculaceae           | Plagiotropis sp.                     |
|                      | Centrales | Chaetoceraceae         | Navicula sp.                         |
|                      |           | Biddulphiaceae         | Navicula pupula                      |
|                      |           | Coscinodiscaceae       | Bacteriastum sp.                     |
|                      |           | Hemiaulaceae           | Biddulphia sinensis                  |
|                      |           | Nitzchiaceae           | Ditylum sp.                          |
|                      | Surirellales| Cyanophyceae          | Coscinodiscus sp.                    |
|                      |           | Oscillatoriales        | Hemialus sp.                         |
|                      |           | Rhizosoleniales        | Melosira sp.                         |
|                      | Dinophyceae| Dinophysiales          | Surirella linearis                   |
|                      | Peridiniales| Dinophysiales          | Cymbella minuta                      |
|                      | Gonyaulacales| Dinophysiales         | Oscillatoria sp.                     |
|                      |           | Proteoperidiniae       | Rhizosolenia setigera                |
|                      |           | Ceraticiace             | Rhizosolenia sp.                     |
|                      |           | Gymnodiniceae          | Rhizosolenia imbricata               |
|                      |           | Dinophysiceae          | Ceratium furca                       |
|                      |           | Dinophyceae            | Ceratium fusus                       |
|                      |           | Dinophysiceae          | Ceratium trichoceros                 |
|                      |           | Dinophyceae            | Ceratium triops                      |
|                      |           | Dinophyceae            | Gymnodium sp.                        |
|                      |           | Dinophyceae            | Dinophysis caudata                   |

### Figure 2. Phytoplankton species by class at seven coastal sites around South Sulawesi

(a = Pinrang, b = Pangkep, c = Makassar, d = Takalar, e = Bulukumba, f = Palopo, g = Malili, h = all stations combined)

Legend

- Bacillariophyceae
- Cyanophyceae
- Dinophyceae
Figure 3. Phytoplankton of the class Bacillariophyceae from coastal waters around South Sulawesi, Indonesia: (1) Asterionellopsis, (2) Amphipora, (3) Chaetoceros sp., (4) Surirella linearis, (5) Flagillaria sp., (6) Bacteriastum, (7) Biddulphia sinensis, (8) Ditylum sp., (9) Coscinodiscus, (10) Cymbella minuta, (11) Pleurosigma, (12) Gyrosigma, (13) Hemiaulus, (14) Plagiotrops, (15) Thalassiosira, (16) Thalassionema, (17) Melosira sp., (18) Navicula sp.

Figure 4. Phytoplankton of the class Cyanophyceae from coastal waters around South Sulawesi, Indonesia (19) Oscillatoria sp., (20) Rhizosolenia setigera, (21) Rhizosolenia sp., (22) Rhizosolenia imbricate

Figure 5. Phytoplankton of the class Dinophyceae from coastal waters around South Sulawesi, Indonesia: (24) Protoperidinium, (25) Ceratium furca, (26) Ceratium fusus, (27) Ceratium trichoceros, (28) Ceratium triops, (29) Gymnodium, (30) Dinophysis caudata
Table 4. Phytoplankton abundance at seven sites in coastal waters around South Sulawesi, Indonesia

| Station | Bacillariophyceae | Cyanophyceae | Dinophyceae |
|---------|------------------|--------------|-------------|
|         | Mean SD          | Mean SD      | Mean SD     |
| Pinrang | 27,111 29,055    | 6,944 9,375  | 8,722 13,531|
| Pangkep | 2.333 1,886      | 944 1,143    | 849,056 876,135|
| Makassar| 95,389 104,958   | 1,222 1,601  | 42,278 78,511|
| Takalar | 15,611 16,583    | 444 502      | 889 1,544  |
| Bulukumba| 3.333 2,098     | 2,167 2,536  | 3,111 5,456  |
| Palopo  | 2,611 1,512      | 833 753      | 2,778 3,257  |
| Malili  | 32,944 37,693    | 1,111 1,601  | 5,000 4,050  |

Table 5. Ecological indices of phytoplankton community structure at seven sites in coastal waters around South Sulawesi, Indonesia

| Station | Diversity index H' | Evenness index E | Dominance index D |
|---------|---------------------|------------------|-------------------|
|         | Code | Name | Mean SD | Category | Mean SD | Category | Mean SD | Category |
| A Pinrang | A  | 1.066 0.279 | low | - | 0.543 0.171 | moderate | 0.512 0.154 | low |
| B Pangkep | B  | 0.365 0.277 | low | - | 0.176 0.117 | low | 0.849 0.114 | high |
| C Makassar | C  | 0.851 0.512 | low | - | 0.420 0.261 | low | 0.601 0.249 | moderate |
| D Takalar | D  | 1.090 0.231 | low | - | 0.615 0.129 | moderate | 0.451 0.102 | low |
| E Bulukumba | E  | 1.589 0.515 | low | - | 0.824 0.174 | high | 0.268 0.151 | low |
| F Palopo | F  | 1.540 0.258 | low | - | 0.851 0.079 | high | 0.251 0.061 | low |
| G Malili | G  | 1.189 0.471 | low | - | 0.663 0.288 | moderate | 0.453 0.237 | low |

Table 6. Distribution of phytoplankton taxa at seven sites in the coastal waters around South Sulawesi

| Species | Prevalence-number of stations at each site |
|---------|------------------------------------------|
| Name    | Pinrang | Pangkep | Makassar | Takalar | Bulukumba | Palopo | Malili |
| Asterionellopsis | - | - | - | - | 1 | - | - |
| Amphiprora | - | - | - | - | 2 | - | - |
| Chaetoceros sp. | 4 | 2 | 6 | 2 | 1 | 3 | 6 |
| Surirella linearis | 3 | - | - | - | 2 | - | - |
| Flagellaria sp. | - | - | - | - | - | - | - |
| Bacteriastum | 2 | 1 | - | - | - | - | 3 |
| Biddulphia sinensis | - | 5 | 2 | 2 | 2 | 2 | 1 |
| Ditylum sp. | 2 | 1 | - | - | - | - | 1 |
| Coscinodiscus | 2 | 2 | 4 | 6 | 4 | 3 | 4 |
| Cymbella minuta | - | - | - | - | - | - | - |
| Pleurosigma | 1 | 1 | 2 | 4 | 4 | 3 | 1 |
| Gyrosigma | 2 | - | 1 | 1 | 3 | 1 | - |
| Hemiaulus | - | - | - | - | - | - | 1 |
| Plagiotropis | 2 | - | 1 | 1 | 3 | - | - |
| Thalassiosira | 3 | 2 | 3 | 5 | 4 | 4 | 3 |
| Thalassionema | 4 | - | 2 | 2 | 2 | - | - |
| Melosira sp. | - | - | - | - | - | - | - |
| Navicula | 3 | - | 2 | 1 | 1 | 1 | 2 |
| Navicula pupula | 2 | - | - | - | - | - | - |
| Nitzchia sp. | - | 1 | - | - | - | - | - |
| Oscillatoria sp. | 5 | 3 | 5 | 3 | 5 | 5 | 2 |
| Rhizosolenia setigera | 3 | 2 | 1 | 1 | - | 2 | 3 |
| Rhizosolenia sp. | 1 | 3 | 1 | 1 | - | - | 2 |
| Rhizosolenia imbricata | 1 | - | - | 1 | - | - | - |
| Protoperidinium | 1 | 5 | 4 | 1 | - | 4 | 5 |
| Ceratium furca | 4 | 6 | 5 | 1 | 3 | 2 | 5 |
| Ceratium fusus | 2 | 1 | - | - | - | - | - |
| Ceratium trichoceros | 2 | 2 | - | - | 1 | 1 | 2 |
| Ceratium tripos | - | 2 | - | - | - | - | 3 |
| Gymnodium | - | 3 | 5 | - | - | 2 | 5 |
| Dinophysis caudata | - | 3 | 2 | 3 | 1 | 1 | 2 |

Total number of species detected: 21 17 18 17 18 17 18
Number of species/station (mean±SD): 8.7±3.2 7.5±2.9 7.8±1.2 6.0±0.9 6.7±2.1 6.2±1.2 8.7±5.1

*Note: - = not detected
abundance and Dinophyceae species richness, with Malili also having significantly higher Dinophyceae species richness but not abundance. Makassar had significantly elevated Bacillariophyceae abundance and Pinrang had significantly elevated Cyanophyceae abundance. The ecological indices varied significantly between sites, as could be expected from the mean and standard deviation data shown in Table 5. The Diversity Index $H'$ for the Pangkep and Makassar sites differed significantly with each other and with all other sites. The Evenness Index $E$ did not differ significantly between the four Flores Sea and Gulf of Bone sites, but differed significantly between these sites and each of the three Makassar Strait sites as

![Venn diagram of phytoplankton species distribution by seaway](image)

**Figure 6.** Venn diagram of phytoplankton species distribution by seaway

| Table 7. Correlations between phytoplankton community and site/station characteristics (glm function in R) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Horizontal: variables | Phytoplankton abundance | Species richness | Ecological indices |
| Tested | Total Bacillariophyceae | Cyanophyceae | Dinophyceae | $C. furca$ | Total Dinophyceae | $H'$ | $E$ | $D$ |
| Total phytoplankton abundance | *** | *** | *** |*** |*** |*** |
| Bacillariophyceae abundance | *** | ns | ns | ns | ns | ns | ns |
| Cyanophyceae abundance | *** | ns | ns | ns | ns | ns | ns |
| Dinophyceae abundance | *** | ns | ns | ns | ns | ns | ns |
| Ceratium furca abundance | *** | ns | ns | ns | ns | ns | ns |
| Phytoplankton species richness | ns | ns | ns | ns | ns | ns | ns |
| Dinophyceae species richness | ns | ns | ns | ns | ns | ns | ns |
| Site | * | * | *** | ** | ** | ns | * | ** | ** |
| Seaway | * | ns | ns | ns | ns | ns | ns | ns | ns |
| Current flow | ns | * | ns | ns | ns | ns | ns | ns | ns |
| Distance offshore | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| Perceived pollution | (–)* | ns | ns | ns | ns | ns | ns | ns | ns |
| Temperature | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| salinity | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| pH | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| TDS | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| nitrate | ns | ns | ns | ns | ns | ns | ns | ns | ns |

ns = not significant at $\alpha = 0.05$; * = significant at $\alpha = 0.05$; ** = significant at $\alpha = 0.01$; *** = significant at $\alpha = 0.001$
well as between each of the Makassar Strait sites. The Dominance Index D for three sites (Pangkep, Makassar and Malili) each differed significantly with all six other sites, but did not differ significantly between the other four sites. Significant correlations with seaway included total phytoplankton abundance and which were significantly higher in the Makassar Strait. Dinophyceae species richness was significantly lower in the Flores Sea, although Dinophyceae abundance did not differ significantly between seaways. Makassar Strait had significantly lower H' and E and higher D compared to the other two seaways which did not differ significantly from each other.

Total phytoplankton community abundance and species richness had no statistically significant correlation with any water quality parameter or within-site position. However three site characteristics were significantly correlated with some phytoplankton community variables: seawater temperature, the position relative to the river mouth and prevailing currents (current flow on Table 7), and perceived levels of pollution based on qualitative field observations. Dinophyceae abundance correlated with temperature. Mean total species richness was significantly lower upstream, while mean Dinophyceae species richness and Bacillariophyceae abundance were higher downstream from the river mouth. Visible or perceived pollution level was positively correlated with total phytoplankton abundance as well as Dinophyceae abundance and species richness.

Very strong relationships (significant at \( \alpha = 0.001 \)) included positive correlations between abundance of each family and total phytoplankton abundance, indicating that each family had a strong influence on the overall abundance. However, each of the three families appeared to have a different form of relationship with community structure. Cyanophyceae abundance was strongly correlated with total species richness, but had no significant correlation with the ecological indices of community structure (H', E, and D). Conversely, the Bacillariophyceae abundance strongly correlated with all three ecological indices but not with total species richness. The abundance of Dinophyceae as a whole and *Ceratium furca* (the most abundant and prevalent species of this class) in particular were very strongly correlated with all three ecological indices, negatively with H' and E and positively with D. *Ceratium furca* abundance was also very strongly and negatively correlated with total phytoplankton species richness.

### 4. Discussion

The phytoplankton identified from the seven sites around the coast of South Sulawesi belonged to three classes, of which the Bacillariophyceae were the most diverse (Figure 2, Table 6) and the most abundant (Table 4) at six out of the seven sites. The exception was the Pangkep site where the Dinophyceae were by far the most abundant family and contributed an equal number of species to the Bacillariophyceae (Figure 2). The Bacillariophyceae (diatoms) tend to be found in rivers, mostly together with the Chlorophyceae (green algae), and can dominate phytoplankton communities in riverine environments, either all year round or seasonally (Boney 1975; Ozbay 2011; Georg et al. 2012; Ishaq et al. 2013; Farhadian et al. 2015; Allan et al. 2021). Many of the Bacillariophyceae have widespread distributions and play an important role in aquatic food chains, including riverine, estuarine and marine environments (Boney 1975; Farhadian et al. 2015; Kale and Karthick 2015; Allan et al. 2021). The prevalence of these species indicates that the study sites are likely to support coastal and marine food webs.

The ecological indices differed significantly between sites and seaways (Table 7). An H' value over 3 indicates high biodiversity and a relatively stable community (Odum 1998; Morris et al. 2014). Although Table 5 shows that no sites had a high diversity index (H'), values of the evenness and dominance indices (E and D) indicate that the sites on the Flores Sea and Gulf of Bone coasts had relatively stable phytoplankton communities with no excessively dominant species. Meanwhile all three Makassar Strait sites were significantly different and showed signs of communities under stress, with the lowest diversity indices, low to moderate evenness and moderate to high dominance.

The Pangkep site not only had by far the highest phytoplankton abundance, exceeding 5 million cells/l, but also a distinctive species composition with a high proportion (Table 4) and high diversity (Table 6) of Dinophyceae. Of the 7 members of the Dinophyceae present at this site, *Ceratium furca* was the most abundant at all six stations. While present at all sites, *C. furca* was highly dominant at the Pangkep site,
accounting for over 99% of the total phytoplankton abundance at this site. A previous study at the same site (Rashidy et al. 2013) also found a high relative abundance of the genus Ceratium, a genus which is known to have a tendency to population explosions forming blooms which can cause anoxic conditions and thereby result in mass kills of fish and other marine organisms (Mulyani et al. 2012; Ibrahem and Al-Shawi 2015; Yurimoto et al. 2015; Cavalcante et al. 2016). In general, the Dinophyceae tend to have a high capacity for rapid adaptation to environmental change, and can increase rapidly under favourable conditions (Lagus et al. 2004; Cavalcante et al. 2016). This dominance calls for vigilance to detect and, if possible, mitigate potential harmful algal blooms (HABs).

The high phytoplankton population abundance as well as the high proportion of Dinophyceae at the Pangkep site could be related to anthropogenic activities, including nutrients in the water. Nutrient levels (nitrate and ammonium) were relatively high at all the study sites, exceeding the Indonesian water quality standards for aquatic (marine) organisms under Decree of the Minister for the Environment of the Republic of Indonesia No. 51/2004 (nitrates <0.008 mg/l and ammonium <0.3 mg/l). The nutrients present and the patterns of nutrient release can influence phytoplankton abundance and community composition (Hallegraeff 2010; Ozbay 2011; Paerl and Paul 2012; Ibrahem and Al-Shawi 2015). Although concentrations of the nutrients measured (nitrate and ammonia) at the Pangkep site were similar to those at the other sites surveyed, there may have been other nutrients (e.g. phosphates) not measured in this study. Potential sources of nutrients observed in the area around this site included brackish-water aquaculture ponds (fish and shrimps), poultry farming (chickens and ducks), and the direct discharge of sewage and other human wastes. Furthermore, the temperatures recorded at this and other sites were sufficiently elevated that they could have enabled or contributed to accelerated phytoplankton reproduction (Zohary et al. 2021).

Although river discharge and related physical and chemical parameters can significantly influence the distribution and composition of phytoplankton communities (Bharathi et al. 2018), this was not supported by any strong correlations between the water quality parameters measured and phytoplankton community characteristics recorded in this study. There were indications that phytoplankton communities may differ upstream and downstream (relative to prevailing currents) of river plumes, and may be influenced by water temperature, but the correlation was weak. This lack of a clear signal related to water quality parameters could be due to a combination of several factors. One of these is time; while the phytoplankton communities and seawater properties were sampled at the same time, the observed phytoplankton communities would have been influenced by conditions in the period preceding the sampling, which might have changed over time. For example, although nitrate concentrations were similar (and quite high) at all sites, there may have been peaks in concentration (e.g. releases of effluent from brackish-water tambak aquaculture ponds) which had been used up by phytoplankton and other photosynthetic organisms or dispersed by the time of sampling at the Pangkep site. Conversely, the high nutrients at some other sites could be recent, for example due to flooding during recent severe weather events, and the phytoplankton communities might not yet have reacted to the conditions measured. Another possibility is that one or more main driving factors were not measured. For example, phosphate is also a nutrient which can influence phytoplankton abundance and community composition (Mackey et al. 2007). However, despite the limitations of this study, the results provide an overview of phytoplankton abundance and diversity in this region. They also raise a warning that coastal waters around South Sulawesi may be at risk of experiencing HABs, with a potentially higher risk in the Makassar Strait compared to the Flores Sea and Gulf of Bone coasts.

5. Conclusion

Phytoplankton communities at the seven study sites around the coast of South Sulawesi, Indonesia comprised a total of 31 identified species belonging to three classes (Bacillariophyceae, Cyanophyceae, and Dinophyceae). Six species were found at all seven sites, including Ceratium furca, a member of the Dinophyceae which can cause harmful algal blooms (HABs) as well as Bacillariophyceae thought to be important in aquatic food webs (e.g. Chaetoceros sp). Diversity was low overall, but highest at the Bulukumba site. The Pangkep District site phytoplankton community was the most abundant
but had the lowest diversity and evenness, with strong dominance by *C. furca*. The results indicate that negative influence of anthropogenic activities is higher in the Makassar Strait where estuarine and coastal phytoplankton communities are more likely to produce HABs than at the sites in the Flores Sea and Gulf of Bone. However, the ubiquity of high nutrient (nitrate and ammonium) concentrations calls for further research and efforts to reduce the flow of nutrients into the coastal waters all around this province.

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