DISSERTATION

SPATIAL ANALYSIS OF WATER QUALITY AND THE IMPLICATION FOR SDG TARGET 14.1 IN SOUTH SULAWESI PROVINCE

Analisis Spasial Kualitas Air dan Implikasinya untuk Target Sdg 14.1 di Provinsi Sulawesi Selatan

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Dissertation

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DISERTASI

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Declaration

I certify that this Dissertation is compiled based on the results of research during Doctoral studies at the Faculty of Marine and Fisheries Sciences and does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university.

Makassar, 18 Oktober 2021

Hasriani Ayu Lestari

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Ringkasan

Tujuan utama penelitian ini untuk menganalisa status dan kondisi perairan Provinsi Sulawesi Selatan melalui dinamika parameter fisik-kimia perairan, konsentrasi klorofil-a, serta keanekaragaman dan kelimpahan fitoplankton. Kemudian menginisiasi potensi budidaya rumput laut dalam memperbaiki kondisi perairan Provinsi Sulawesi Selatan. Selain itu sebagai strategi dalam mencapai SDG 14.1.

Penelitian ini dilakukan pada delapan lokasi di seluruh Perairan Provinsi Sulawesi Selatan. Lokasi tersebut antara lain, Kabupaten Pinrang, Kabupaten Pangkep, Kota Makassar, kabupaten Takalar, Kabupaten Bulukumba, Kabupaten Bone, Kota Palopo dan Kota Malili. Pengukuran *insitu* parameter fisik-kimia (Suhu, TDS, konduktifitas, kekeruhan, salinitas, pH, oksigen terlarut, nitrat dan ammonium) dan pengukuran konsentrasi klorofil-a menggunakan Water Quality Checker (Merk TOA DKK Model WQC24-1-2). Pengambilan sampel fitoplankton menggunakan plankton net. No. 25.

Analisis Storet dan PCA dilakukan untuk mengidentifikasi kategori kondisi perairan dan parameter penciri antar lokasi. Analisa Citra Satelit Ocean Color digunakan untuk memetakan dan melihat tren dekade pada konsentrasi klorofil-a. Analisis pada fitoplankton dilakukan melalui perhitungan kelimpahan dan indeks ekologi. Selanjutnya dilakukan analisis R menggunakan general linear model fuction untuk melihat korelasi fitoplankton dengan parameter lingkungan. Kemudian Analisa Citra Landsat-8 dilakukan untuk mengetahui luasan, potensi produksi serta kemampuan absorbs nutrient oleh budidaya rumput laut.

Secara garis besar, Hasil penelitian menemukan bahwa ondisi Perairan Sulawesi Selatan masuk dalam kategori tercemar berat dengan prevalensi 100% kelebihan nutrisi selain faktor lokal. Hal ini ditunjukkan dari 8 lokasi yang ada, 6 diantaranya terkategori Cemar berat, dan 2 terkategori cemar sedang. Pencemaran tertinggi ditemukan pada kota Makassar.

Rata-rata konsentrasi klorofil-a di delapan lokasi berada pada kisaran 0,018 – 0,030 mg/l. Konsentrasi klorofil-a tertinggi ditemukan pada perairan Sungai Cikoang di Kabupaten Takalar. Sebaliknya konsentrasi klorofil-a terendah pada Sungai Tallo di Kota Makassar.

Keanekaragaman fitoplankton di Perairan Sulawesi Selatan secara keseluruhan tergolong rendah. *Ceratium furca* merupakan jenis fitoplankton yang paling melimpah serta merupakan spesies yang menyebabkan pertumbuhan alga berbahaya (HAB). Hasil penelitian menunjukkan bahwa pengaruh negatif aktivitas antropogenik yang tinggi mempengaruhi keanekaragaman dan kelimpahan fitoplankton di Perairan Sulawesi Selatan.

Metode pemanfatan data citra satelit dapat digunakan dalam mengestimasi luas dan volume produksi budidaya rumput. Hasil yang diperoleh dinilai lebih akurat dan efisien dibandingkan dengan metode konvensional. Selain itu metode ini dapat digunakan dalam memperkirakan potensi budidaya rumput laut dalam upaya mitigasi eutrofikasi, sebagai bagian dari strategi untuk mencapai SDG 14.1.

Abstract

The main purpose of this study was to evaluate the status and condition of the coastal waters of South Sulawesi Province through analysing the dynamics of physical-chemical parameters, the chlorophyll-a concentration, and the diversity and abundance of phytoplankton. A further aim was to perform an initial evaluation of the potential of seaweed cultivation for improving the condition of coastal waters around South Sulawesi Province, as well as a strategy to achieve SDG 14.1.

This research was conducted at eight coastal sites around South Sulawesi Province. These sites included Pinrang Regency, Pangkep Regency, Makassar City, Takalar Regency, Bulukumba Regency, Bone Regency, Palopo and Malili City. In situ measurement of physico-chemical parameters (temperature, TDS, conductivity, turbidity, salinity, pH, dissolved oxygen, nitrate and ammonium) and chlorophyll-a concentration was performed using a Water Quality Checker (TOA DKK Brand, Model WQC24-1-2). Phytoplankton were sampled using a No. 25 plankton net.

STORET and PCA analyses were used to categorise water quality conditions and identify the parameters characterizing each site. Ocean Color Satellite Images were analysed to map and elucidate decadal trends in chlorophyll-a concentration. Phytoplankton communities were analysed by calculating abundance and ecological indices. Furthermore, the glm (general linear model) function in R was applied to analyse correlations between phytoplankton and environmental parameters. Landsat-8 satellite data were analysed to determine the seaweed cultivation area, production potential and ability to absorb nutrients.

Generally, the results of the study found that the coastal waters of South Sulawesi were mostly in the heavily polluted category with a 100% prevalence of excess nutrients in addition to local factors. This was evident from the 8 study sites, with 6 categorized as heavily polluted, and 2 as moderately polluted. The STORET pollution index was highest at the Makassar City site.

The mean chlorophyll-a concentration at the eight study sites ranged from 0.018 to 0.030 mg/l. The chlorophyll-a concentration was highest in the estuarine waters of the Cikoang River in Takalar Regency. Meanwhile, the chlorophyll-a concentration was lowest around the Tallo River estuary in Makassar City.

Overall, phytoplankton diversity in the coastal waters of South Sulawesi waters was found to be relatively low. The most abundant phytoplankton species present was *Ceratium furca*, which can cause harmful algal blooms (HABs). The results indicate that the high level of anthropogenic activities had a negative influence on phytoplankton in the coastal waters of South Sulawesi, affecting both diversity and abundance.

Methods using satellite data can be applied to estimate seaweed cultivation area extent and production volume. The results obtained are considered to be more accurate and efficient than conventional methods. Furthermore, this method can be used to estimate the potential of seaweed cultivation in the context of eutrophication mitigation, as a component of strategies to achieve SDG 14.1.

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Chapter I: General Introduction

1. Background

South Sulawesi is one of the provinces in Indonesia which has a coastline of 1,937 km (DKP Sulsel, 2019) and is surrounded by three seaways, namely the Makassar Strait in the west, the Flores Sea in the south and the Gulf of Bone in the east (Ambo-Rappe & Moore, 2018). With a long coastline, it allows coastal communities to carry out various utilization activities including fishing, aquaculture and marine tourism (Dahuri, 2001; Vatria, 2010, Ali, 2015). Various activities in the use of water areas can be seen from the estuary waters to the high seas.

Estuary waters are semi-enclosed coastal waters with an open relationship with the sea and are influenced by fresh water input (Odum, 1993; Ji, 2008). Estuaries have a negative side because they can be sources of waste substances carried by rivers. These wastes can contain pollutants that can affect water quality (Birch et al., 2009). This condition will certainly have an impact on the quality of the aquatic environment, especially in estuaries which are the collection and accumulation of all urban waste, including industry and agriculture (Yogaswara, 2020).

Estuary waters are characterized by the presence of rivers are the main locations for capturing nutrient sources (Viney et al., 2000). The sources of these nutrients/nutrients come from various anthropogenic activities around the estuary waters, including agricultural activities, aquaculture, livestock farming, forestry, industry, settlements, urban and coastal development, fisheries and port development. The source of the waste flows into the waters vary in the form and concentration of compounds; above certain concentration limits these compounds can create conditions that are toxic to aquatic organisms (Susana, 2004). Such events cause pollution which results in a decrease in water quality and have a negative impact on the life of marine biota (Sastrawijaya, 2000).

Cases of marine and coastal pollution underly the birth of the concept of Sustainable Development Goals (SDGs), specifically SDG Goal 14 target 1. By 2025 the target to be achieved is to prevent and significantly reduce all types of marine pollution, especially from land activities, including marine debris and nutrient pollution. (https://www.sdg2030indonesia.org). Therefore, it is important to monitor water quality, specifically the characteristics which can be considered good or bad, related to the purpose for which the water is used (Lamb, 1985). Water quality standards have been developed as a reference to determine whether the water is suitable for certain purposes or polluted. Water quality cannot be detected just by looking with the naked eye. There are several water quality parameters, both physical and chemical, that must be tested and analyzed. The water quality parameters are dynamic and can indicate the environmental condition of a water body (Mahyudin et al., 2015).

Furthermore, one indicators of fertility is the abundance and diversity of phytoplankton communities in a water body (Molleri et al., 2010). Chlorophyll-a is an indicator of water fertility because it reflects the abundance of phytoplankton as primary producers (Rasyid, 2010; Sihombing et al., 2013). Comprehensive identification of the distribution and concentration of chlorophyll-a can be done by utilizing remote sensing technology through analysing different spectral reflection patterns in satellite imagery (Henson et al., 2010) such as Ocean Color satellite imagery from NOAA (National Oceanic and Atmospheric Administration) (Hu, 2009; Xing, 2019).

In addition to measuring water parameters and the concentration of chlorophyll-a, the presence of phytoplankton can also be used as an indicator of the health of an aquatic ecosystem (Hutami et al., 2017). In particular, the abundance of phytoplankton can provide an overview of the fertility and productivity potential of an aquatic ecosystem (Sofarini, 2012; Setyowardani et al., 2021), and can be used as a biological indicator (bioindicator) of water quality (Maresi et al., 2015). Therefore, comprehensive studies on the status and condition of a water body can be done by looking at key indicators in waters, including physical-chemical water parameters, chlorophyll-a concentration and phytoplankton.

However, it should be noted that human activities affecting the condition and quality of coastal waters include aquaculture. For example, the cultivation of fish and shrimp carried out in cages will result in an increase in nutrient sources in the waters and become a source of pollutants (Emerenciano et al., 2011). On the other hand, seaweed cultivation has the potential to absorb pollutants, especially nutrients that can cause eutrophication in waters (Troell et al, 1999; Zheng et al., 2019). In addition, seaweed can also be a bioaccumulator and absorb other pollutants such as heavy metals, so the location of the allotment of seaweed cultivation areas must be appropriate (Sudarshan et al., 2012). Therefore, the management of seaweed cultivation areas is important in relation to water quality issues. This means that the initial basis for management planning is to know the area of the seaweed cultivation area and the volume of seaweed produced.

2. Overview of South Sulawesi Waters

South Sulawesi Province with the capital city Makassar is located between 0° 12' – 8' S and 116° 48' - 122° 36'E longitude with an area of about 45,764.53 Km2, coastline length of 1,937 Km consisting of 24 regencies/cities, 304 sub-districts. With regional boundaries to the north (West Sulawesi), the east (Gulf of Bone and Southeast Sulawesi Province), the south (Flores Sea) and the west (Makassar Strait), (DKP, 2019).

The area of South Sulawesi Province is 46,083.94 Km^2, administratively the South Sulawesi Province government is divided into 21 regencies and 3 cities consisting of 304 sub-districts. North Luwu Regency is the largest district with an area of 7,365.51 Km2 or the area of the district is 15.98% of the entire South Sulawesi region. The number of rivers flowing through the South Sulawesi region is recorded at around 67 rivers. Most of the river flows are in Luwu district, which is 25 rivers. Saddang River is the longest river that flows covering Tator, Enrekang and Pinrang Regencies. Each river is 150 km (DKP, 2019).

The waters of South Sulawesi Province are rich in resources that can be utilized for community life activities, both economic, social and cultural activities. These utilization activities include capture fisheries, aquaculture and marine tourism (DKP, 2019).

3. Physical Water Quality Parameters

3.1. Temperature

Temperature is the heat capacity contained in an object (Sutisna & Sutarmanto, 2015). Temperature is very important for the survival of organisms that exist in waters (Vermeer & Rahmstorf, 2009). Changes in water temperature greatly affect the physical, chemical and biological processes in the water. The temperature in water bodies strongly influenced by the length of sunlight in these waters. The higher the intensity of light that enters the water, the higher the temperature conditions in the waters. The absorption of sunlight that enters the water will change into heat energy (Effendi, 2003) The high temperature will be able to increase the maximum rate of photosynthesis of aquatic plants, while the indirect effect of temperature can change the hydrological structure in the waters which can affect the distribution of phytoplankton (Lv et al., 2014).

3.2. Total Dissolved Solid

Total Dissolved Solid (TDS) is the dissolved solids, either in the form of ions, compounds, or colloids in water. For example, surface water when observed after it rains will cause river or pond water to look cloudy due to the dissolution of suspended particles in the water. While in the dry season the water looks green because of the puddles in the water. The concentration of the solubility of this solid in normal conditions is very low, so it is not visible to the naked eye (Situmorang, 2007). Residue is considered as the total content of dissolved and suspended matter in water. During the determination of this residue, most of the bicarbonate which is the main ion in the waters has been transformed into carbon dioxide, so that carbon dioxide and other gases that disappear during heating are not included in the total solids value (Boyd, 1982).

3.3. Conductivity

Conductivity is a numerical description of the ability of water to carry electricity so that the more dissolved salts that can be ionized, the higher the conductivity value (Khairunnas & Gusman, 2018). Conductivity is expressed in units of mhos/cm.

Measurement of electrical conductivity aims to measure the ability of ions in water to conduct electricity and predict mineral content in water. The conductivity of major rivers is 200-1000 S/cm (mid range conductivity), and saline water is 1000-10000 S/cm (high conductivity). Conductivity values of more than 250 mhos/cm are not recommended because they can precipitate and damage kidney stones (Gasim, 2015; Afrianita et al., 2017).

3.4. Turbidity

Turbidity is a measure that uses the effect of light as a basis for measuring the state of water. Turbidity affects water brightness due to the presence of suspended and dissolved organic and inorganic materials (Efendi, 2003). This makes a real difference in terms of aesthetics as well as in terms of water quality itself. The higher the value of suspended solids, the higher the turbidity value. However, high dissolved solids are not always followed by high turbidity, meaning that high dissolved solids values do not mean high turbidity (Efendi, 2003).

4. Chemical Water Quality Parameters

4.1. Salinity

Salinity is defined as the total weight of all salt (in grams) dissolved in one liter of water, usually expressed in grams per liter. The distribution of salinity in the sea is influenced by various factors such as water circulation, evaporation, rainfall and river flow. The salinity gradient pattern varies depending on the season, estuary topography, tides and the amount of fresh water (Simbolon, 2016). One of the ways to reduce sea surface salinity is the input of fresh water at the mouth of the river. For marine tourism, the sea water quality standard contained in the 2004 Decree of the Minister of Environment is natural, and changes are allowed up to <5% of the seasonal average salinity (Tanto et al., 2018).

4.2. Degree of Acidity

Degree of Acidity (pH) is the negative logarithm of the concentration of hydrogen ions released in a liquid which can then describe the acidity or alkalinity of water. pH (degree of acidity) is expressed in numbers from 1 – 14. In this case the aspect that is measured is the ability of a water solution to provide hydrogen ions (Sutisna & Sutarmanto, 2015). Water pH is one of the chemical factors that is quite important in controlling the stability or balance of waters (Simanjuntak, 2009). Differences in pH values in waters greatly affect aquatic biota. The high and low pH value also greatly determines the presence or dominance of phytoplankton which in turn affects the level of primary productivity of water (Megawati et al., 2014).

The pH of normal or neutral water is between 6 to 8, while the pH of polluted water, for example caused by liquid waste will show different values depending on the type of waste and the way the waste is treated before being disposed of. A high pH will disrupt the balance between ammonium and ammonia in the water column so that it is possible to increase the concentration of ammonia which is toxic to living organisms (Simanjuntak, 2009).

4.3. Dissolved Oxygen

Dissolved oxygen is the total or amount of oxygen gas dissolved in water. Dissolved oxygen in waters is needed by all organisms to carry out respiration, metabolic processes or the exchange of substances that will produce energy for growth and development (Salmin, 2005). Dissolved oxygen in waters usually comes from the photosynthesis process carried out by phytoplankton and the contact between the water surface and the air (Eaton et al., 2005). Waters lose dissolved oxygen naturally through evaporation into the atmosphere, the respiration activity carried out by aquatic organisms, the decomposition of organic matter, the inflow of oxygen-poor underground water and rising temperatures.

4.4. Nitrate (NO3)

Nitrate (NO3) is the main form of nitrogen in natural waters and is the main nutrient for plant and algal growth. Nitrates are very soluble in water and are stable. This compound is produced from the complete oxidation process of nitrogen compounds in the waters. Nitrification which is the oxidation process of ammonia to nitrite and nitrate is an important process in the nitrogen cycle and takes place under aerobic conditions. Nitrates cause water quality to decline, reduce dissolved oxygen, decrease fish populations, foul smell, bad taste (Tresna, 2000). The largest source of nutrients comes from river flows, household waste and anthropogenic activities such as ponds and rice fields. According to the Decree of the Minister of State for the Environment No. 51 of 2004, it is stated that the nitrate content for marine biota is 0.008 mg/l.

4.5. Ammonium

Ammonium is an NH_4^+ ion which is colorless, has a pungent odor and is hazardous to health. Ammonium contributes to total nitrogen and nutrient levels (Statham, 2012). Ammonium (NH_4^+) is an ion, and the relative concentrations of ammonium and ammonia (NH_3^-) can vary with other water quality parameters, particularly temperature, pH and salinity, while nitrate can also be reduced to ammonium, particularly by marine processes. sediments (Vieillard et al., 2020).

5. Chlorophyll -a

Chlorophyll comes from the Greek words chloros which means green and phyllos which means leaves. Chlorophyll is the green pigment in plants, algae and photosynthetic bacteria. These compounds play a role in the process of photosynthesis in plants by absorbing and converting sunlight energy into chemical energy. In the process of photosynthesis, there are 3 main functions of chlorophyll, namely the first to utilize solar energy, the second to trigger the fixation of CO_2 into carbohydrates and the third to provide an energetic basis for the ecosystem as a whole. Carbohydrates produced by photosynthesis through anabolic processes are converted into proteins, fats, nucleic acids, and other organic molecules (Muthalib, 2009).

Chlorophyll-a is one of the tools in measuring the fertility level of a waters which is expressed in the form of primary productivity (Siegel et al., 2013). The concentration of chlorophyll-a in a water is very identical to the presence of phytoplankton which incidentally is a primary food source for marine organisms, especially fish. The concentration of chlorophyll-a in water is highly dependent on the availability of nutrients and the intensity of sunlight. If sufficient nutrients and solar intensity are available, the chlorophyll-a concentration will be high and vice versa (Effendi, 2003).

6. Phytoplankton

Phytoplankton are aquatic organisms that occupy a position as primary producers in the food chain and the bottom of food webs (Harris et al., 2000). Phytoplankton can carry out photosynthesis because it has chlorophyll so it can absorb sunlight. The results of phytoplankton photosynthesis in the form of organic matter are utilized by zooplankton, fish larvae, and other organisms as a natural food source (Andriani & Hartini, 2017). Phytoplankton is also an organism that can be used as a biological indicator in determining water quality through a species indicator approach or species diversity. This is also because phytoplankton have a short life cycle and have a very fast response to environmental changes (Siegel et al.2013).

The survival of phytoplankton is highly dependent on the physical and chemical conditions of the waters. Phytoplankton with high abundance is generally found in waters around river mouths or in offshore waters where upwelling occurs. In this location zone, the fertilization process occurs due to the entry of nutrients into the environment (Sediadi et al., 1999). This happens because of the entry of nutrients from the land that enter the river and flow into the sea. The large abundance of phytoplankton of certain types can cause HABs to occur in the waters.

There are five classes of Fitoplankton; (1) Bacillariophyceae is a class or component of phytoplankton that is most often found in various kinds of waters. The size of diatoms in general is in the range of 5 m–2 mm. Bacillariophyceae are generally single cells that are solitary, but there are some that live connected to each other and form a colony like a chain. Bacillariophyceae have cells with shapes that vary from species to species and vary in size within one species (Grahame, 1987; Nontji, 2008); (2) Dinophyceae, a group of phytoplankton classes that are very common in waters after the Bacillariophyceae class. Dinoflagellates generally measure 5 - 200 m (Kennish, 1990). The characteristics of this class of Dinoflagellates are single-celled, do not have a light brown outer shell, and have a pair of flagella that are used for movement in the water (Nybakken, 2005). Dinoflagellates that have an important role for fisheries, because they are food for many types of fish that have economic value (Nontji, 2008); (3) Cyanophyceae, phytoplankton class with special characteristics, namely the presence of a bluish green dye (Cyanophysin) or commonly called phycocyanin pigments. Cyanophyceae do not have flagella as a means of locomotion so that their movement is only by gliding (Kabinawa, 2006). The Cyanophyceae class or commonly called the blue green algae group is generally found in shallow waters, tropical coastal waters, but with low abundance (Kennish, 1990). Cyanophyceae can tolerate a higher temperature range (above 30°C) than the Chlorophyceae and diatom groups (Effendi, 2003); (4) Chlorophyceae, generally find in fresh water and this type of phytoplankton is the most commonly found in freshwater waters of Indonesia. Chlorophyceae have green chloroplasts, contain the pigments chlorophyll a and b and carotenoids. The most abundant pigment found is chlorophyll a, which causes it to have a dominant green color. Chlorohyceae have food reserves in the form of pyrenoids and cell walls consisting of cellulose (Effendi, 2003). (5) Euglenophyceae class are single-celled organisms, have chlorophyll and are able to carry out the process of photosynthesis, generally living in fresh water rich in organic matter. Euglenophyceae has an elongated oval cell shape and has eye spots that are very sensitive or sensitive to light and are found on the upper part of the body. On calm water surfaces, several genera in this group are able to form cysts that cover the entire surface of the water with red, green, yellow or all three colors (Wetzel & Likens, 1990).

7. Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) agreed in 2015 are a continuation of the Millennium Development Goals (MDGs) (Figure 1). The SDGs have become a new history in global development, because the agreement on the SDGs at the 70th General Assembly of the United Nations (UN) has a new universal development goal starting in 2016 until 2030. The SDGs bring 5 fundamental principles that balance the economic dimension, social and environmental, namely 1) People (humans), 2) Planet (earth), 3) Prosperty (prosperity), 4) Peace (peace), and 5) Partnership (cooperation). The SDGs were agreed upon by 193 heads of state and government who are members of the United Nations and include the State of Indonesia (Panuluh & Fitri, 2016).

Figure 1. Sustainable Development Goals (http://www.sdg2030indonesia.org)

The Agreement on the Implementation of Sustainable Development Goals in Presidential Regulation Number 59 of 2017 contains 17 main goals. In the 14th goal of the SDGs which is a special program in the marine sector, namely to conserve and sustainably utilize marine, oceanic and maritime resources for sustainable development with the following targets (https://www.sdg2030indonesia.org):

1) By 2025, prevent and significantly reduce all types of marine pollution, especially from land activities, especially nutrient pollution and marine debris.
2) By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and taking restoration actions in order to achieve healthy and productive marine
3) Minimize and overcome the impact of increasing acidity of seawater, including increasing scientific cooperation at every level
4) By 2020, effectively regulate harvesting and overfishing, illegal, unreported and unregulated fishing, as well as destructive fishing practices and implement scientific-based management planning in order to restore fish

stocks as quickly as possible, at least to a level where it can be produce maximum sustainable yields as per the biological characteristics of each fish

5) By 2020, conserve at least 10 percent of the marine coastal area, consistent with national and international law and based on the best available scientific information
6) By 2020, prohibit certain forms of fisheries subsidies that contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing such forms of subsidies, with awareness that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of WTO subsidies negotiations2
7) By 2030, increase economic benefits for small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture, aquaculture, and tourism.
8) Increase scientific knowledge, develop research capacity and transfer marine technology, by referring to the Criteria and Guidelines of the Intergovernmental Oceanographic Commission on the Transfer of Marine Technology, in order to improve marine health and increase the contribution of marine biodiversity to the development of developing countries, especially developing countries. developing small islands and less developed countries
9) Provide access to marine resources and markets for small fishermen
10) Promote the conservation and sustainable use of the ocean and its resources, as stated in paragraph 158 of “The Future We Want”.

8. Seaweed in South Sulawesi

Seaweed is a macroalgae which is a low-level plant and belongs to the thallophyta division (Alam, 2011). Seaweed is a low-level plant that does not have different skeletal structures such as root-stem-leaves (Kadi & Admadja, 1988). Seaweed is classified as a low-grade plant, generally grows attached to a certain substrate, does not have true stems, roots or leaves; but only resembles a rod called a thallus (Duma, 2012).

Since the year 2000, seaweed farming has expanded rapidly across coastal Indonesia. Production is concentrated in Eastern Indonesia, particularly in Sulawesi, NTB and NTT. Seaweed as a plant has high cultivation potential and is growing rapidly, especially in South Sulawesi. Types of commercial seaweed cultivated in South Sulawesi Province include *Gracillaria* and *Euchema*. South Sulawesi alone produces 3.66 million tonnes of seaweed a year – over a third of Indonesia's total seaweed supply and 11 per cent of global supply. South Sulawesi has been named a priority region for seaweed farming expansion, with up to 250,000 ha of farms possible (Presidential Decree 33- 2019).

9. Research Framework

South Sulawesi waters are directly connected to Makassar Strait in the west, the Flores Sea in the south and Gulf of Bone in the east. The waters of South Sulawesi are utilized by various activities by the community. Existing utilization can be seen from various activities in river mouths to open waters. Various existing uses and activities have an impact on water quality. If this continues, it can have a fatal impact on aquatic ecosystems. Therefore, it is important to evaluate and manage integrated in improving water quality. Indicators for assessing the quality and fertility of a waters can be seen from the suitability of water parameters, chlorophyll-a concentration and the presence of phytoplankton. In addition, a strategy is needed to minimize and reduce the impact that can be caused. Comprehensively, it can be explained through the research concept framework in Figure 2.

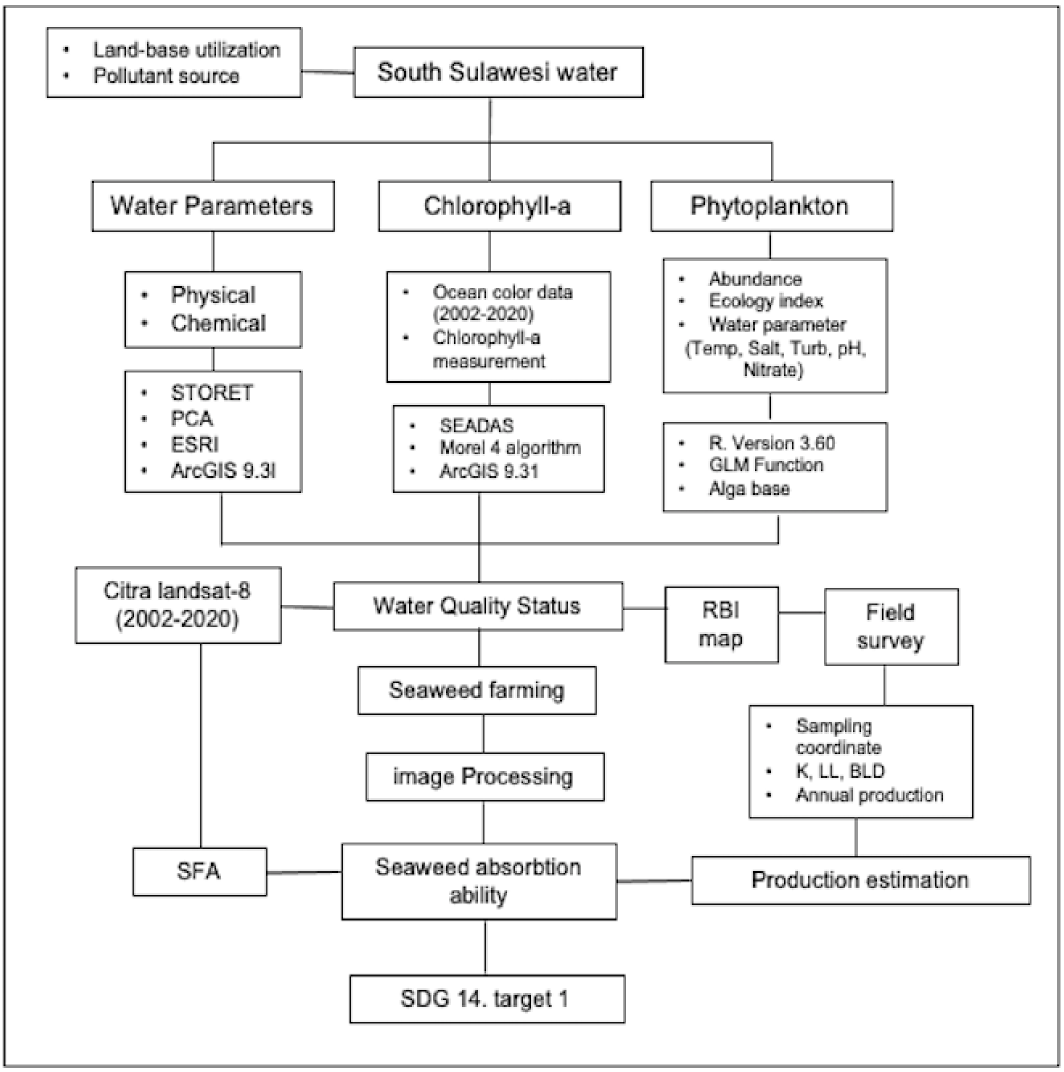

Figure 2. Reasearch Framework

10. Research Questions

Based on the background described above, this research is limited and studied in depth on the following problems:

1. How are physico-chemical parameters distributed and what are the implications for water quality in South Sulawesi Province?
2. What are the decade trends in chlorophyll-a concentration and distribution in the waters of South Sulawesi Province?
3. What is the condition of the diversity and abundance of phytoplankton in the waters of South Sulawesi Province?
4. What are the temporal dynamics of the area and the estimation of the potential for seaweed aquaculture production to contribute to mitigating eutrophication in South Sulawesi waters?

11. Research Goals

This research aims to:

1. Determine the distribution, status and quality of water parameters in South Sulawesi Province.
2. Analyse the decadal changes in the distribution and concentration of chlorophyll-a in the waters of South Sulawesi during the period 2002-2020.
3. Analyse the diversity and abundance of phytoplankton in the waters of South Sulawesi.
4. Analyse the temporal fluctuations in seaweed cultivation area, evaluate the phytoremediation potential for seaweed cultivation to mitigate eutrophication and produce an improved estimation of the potential for seaweed production in South Sulawesi.
5. Provide recommendations regarding strategies for achieving SDG 14 targets to reduce marine pollution in the waters of South Sulawesi.

12. Novelties

Generally, this research has been widely carried out in Indonesia, especially South Sulawesi. However, existing research has only been carried out on a small scale and scope area and with improvised technology. In Indonesia, especially South Sulawesi Province, further research is needed using more advanced technology in order to obtain results on a larger and wider scale and to obtain more valid and efficient results. This research can contribute to achieving SDG 14 targets in South Sulawesi, in particular through the following novelties:

1. Provide new knowledge on the status and quality of waters throughout the waters of South Sulawesi
2. Provide new potential approach on water quality Improvement (reducing eutrophication) through seaweed cultivation.

13. Hypotheses

Based on the background, formulation or research questions, research objectives, the following research hypotheses can be formulated:

1. Status and water quality in estuarine areas around South Sulawesi Province is polluted.
2. There were changes in the concentration of chlorophyll-a in the waters of South Sulawesi Province during the period 2002-2020.
3. Diversity and abundance of phytoplankton in the waters of South Sulawesi is low.
4. Seaweed cultivation and potential production can be estimated and monitored efficiently using remote sensing methods and used to estimate the potential to contribute to mitigating eutrophication.

Chapter II: Physical-Chemical Parameters in Estuarine Waters of South Sulawesi

1. Introduction

Estuarine areas are often highly productive ecosystems, greatly affected by both marine and riverine environments as well as their interaction (Seitzinger et al., 2010; Paerl et al., 2014; Brandini et al., 2016; Wurtsbaugh et al., 2019; Viellard et al., 2020). Such interactions can affect the distribution and characteristics of biotic communities and abiotic features in these waters (Jiang et al., 2010; Paerl et al., 2014; Vieillard et al., 2020). Nutrients are an indispensable element in aquatic energy cycles, supporting living organisms and productive ecosystems; however, excessive nutrients can have many adverse effects (Jiang et al., 2010; Wurtsbaugh et al., 2019). Estuarine areas often become traps for nutrients and a wide variety of pollutants originating from land-based anthropogenic activities as well as from activities and processes in aquatic environments (marine, brackish and freshwater) including plastics (Faizal et al., 2020), sediment (Mubarak & Nurhuda, 2021), particulate matter (Nasir et al., 2016) and nutrient loading (Paerl et al., 2014; Wurtsbaugh et al., 2019).

Coastal areas with river mouths each have their own characteristics. Hydrodynamic factors and processes such as currents, tides and bathymetry interact with other factors such meteorological conditions to influence the distribution patterns and concentration of suspended particles and pollutants (Nasir et al., 2016; Wibisana et al., 2019; Vieillard et al., 2020; Mubarak & Nurhuda, 2021). It is important to monitor water quality by checking physical and chemical parameters, especially in coastal and estuarine areas which tend to be particularly vulnerable to pollution (Saraswati et al., 2017; Vieillard et al., 2020). The effects of climate change combined with localised anthropogenic impacts are already altering conditions in aquatic ecosystems from upland springs and streams to the ocean, with mostly negative impacts projected to become more severe (Mora et al., 2013; Mantyka-Pringle et al., 2014; Ullah et al., 2018; Wurtsbaugh et al., 2019; Albert et la., 2020; Horn et al., 2021; Pauly, 2021). In particular, changes in the hydrological regimes and physical–chemical parameters are considered likely to increase the likelihood of population explosions or biomass of opportunistic nuisance microalgae and cyanobacteria (Paerl et al., 2014), the extensive loss of freshwater and marine biodiversity (Albert et al., 2020), and seriously impact fisheries, especially in tropical regions (Sumaila et al., 2011). There is a need for data on current conditions to evaluate threats and monitor change; however, studies tend to be biased towards temperate rather than tropical estuarine ecosystems (Vieillard et al., 2020).

South Sulawesi is an Indonesian Province with a 1,937 km coastline (DKP Sulsel, 2019) facing three seaways: Makassar Strait to the west, the Flores Sea to the South and the Gulf of Bone to the east (Ambo-Rappe & Moore, 2018). At least 20 large rivers and many smaller streams flow into the sea along these coasts. In the case of the coastal and estuarine waters around South Sulawesi, water quality research has generally been carried out at small spatial scales and studies have used a wide variety of instruments (e.g Rukminasari & Sahabuddin, 2012; Nasir et al., 2016; Rustiah et al., 2019; Samawi et al., 2020), making inter-site or temporal comparisons difficult or inappropriate. As in many tropical regions (Vieillard et al., 2020), there is a dearth of comprehensive, large scale data on water quality for estuarine ecosystems in this area using standardised up-to-date instruments. Therefore, this study was conducted to gain a wide overview of the water quality in estuarine waters around South Sulawesi Province, and to determine the factors and parameters that characterise the region as well as specific sites.

2. Material and Methods

2.1. Study Sites and Data Collection

This research was conducted in estuarine waters around South Sulawesi Province, Indonesia in January 2020. Eight sites were selected through purposive sampling, based on the presence of major rivers in cities/regencies representing the western (Makassar Strait), southern (Flores Sea) and eastern (Gulf of Bone) coasts of South Sulawesi (Figure 3). Sampling station density (was selected to enable contours to be produced for each parameter from the *in situ* measurements made through the application of the kriging method (Oliver & Webster, 1990).

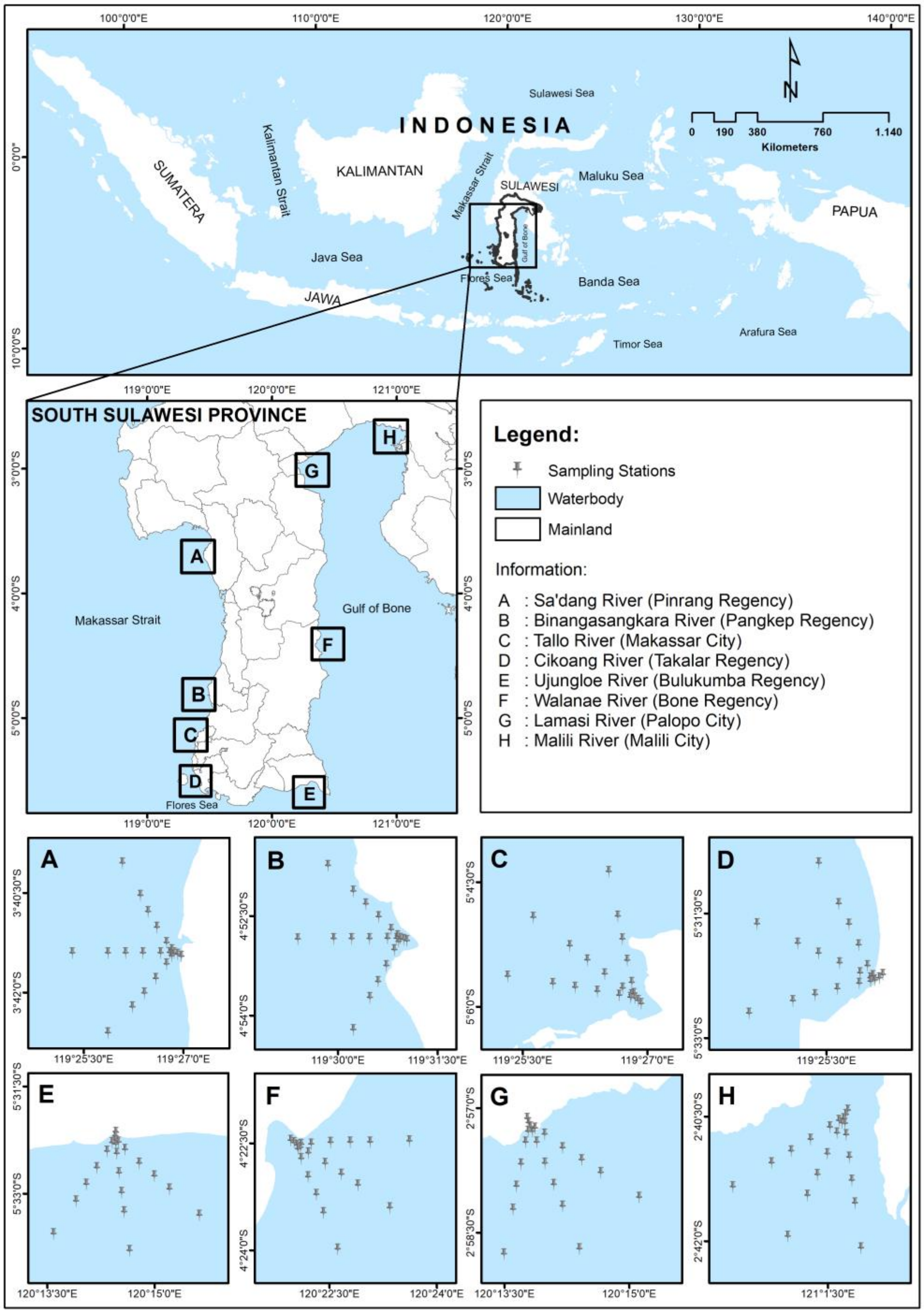

Figure 3. Research sites and sampling stations around South Sulawesi, Indonesia

Data on physical and chemical water parameters (salinity, pH, temperature, dissolved oxygen (DO), depth, nitrate and ammonium concentrations, conductivity and turbidity) were obtained through *in-situ* measurements using a calibrated Water Quality Meter (TOA DKK Brand Model WQC24-1-2). At each site, data were collected at 20 sampling stations along an inshore-offshore gradient in estuarine waters starting with three points in the lower (tidal) reaches of the major river at each station with seven points radiating in each of three directions seawards. Data were tabulated in Microsoft Excel 2010.

2.2. Data Analysis

The data collected in the field were plotted on a base map using the field sampling coordinates. The point data for each water quality parameter were interpolated using the kriging interpolation method (Oliver & Webster, 1990) and mapped as contours. Kriging, also known as Gaussian process regression, is a type of geostatistical interpolation based primarily on empirical observations (observed sample data points) and is widely used in spatial analysis (Ikechukwu et al., 2017). The contours were generated using the Kriging interpolation tool (ordinary kriging method) in the ESRI ArcGIS Version 9.3 Geographic Information System (GIS) (ESRI, 2009).

Water quality status was evaluated using the Storage and Retrieval of Water Quality data System (STORET) Index of pollution developed by the US-EPA (United States Environmental Protection Agency) (Barokah et al., 2017). This Index classifies water quality based on four classes: (1) Class A: very good, score = 0 meets the quality standard; (2) Class B: good, score = -1 to -10 lightly polluted; (3) Class C: moderate, score = -11 to -30 moderately polluted; (4) Class D: poor, score below -31, heavily polluted. Principle Component Analysis (PCA) was used identify the defining water quality parameters that characterised each site. The STORET and PCA analyses were implemented in Microsoft Excel 2010.

3. Result and Discussuion

3.1. Distribution of Physical Parameters

3.1.1. Temperature

The temperature ranges and distribution patterns differed substantially between sites. However, at all eight sites the data show an overall pattern of lower water temperatures in the lower reaches of rivers and their outflow plumes than in the surrounding seas (Figure 4).

This pattern of lower riverine water temperature was most marked in terms of the extent of cooler waters around the Malili River in Malili City (H) followed by the Binangasangkara River in Pangkep Regency (B). The pattern was least marked at the Lamaso River in Palopo City (G), which had a the smallest range with the lowest maximum (offshore) temperature and a relatively high minimum temperature, while the coastal waters around the Ujungloe River in Bulukumba Regency (E) had the lowest extent of river-related cooling.

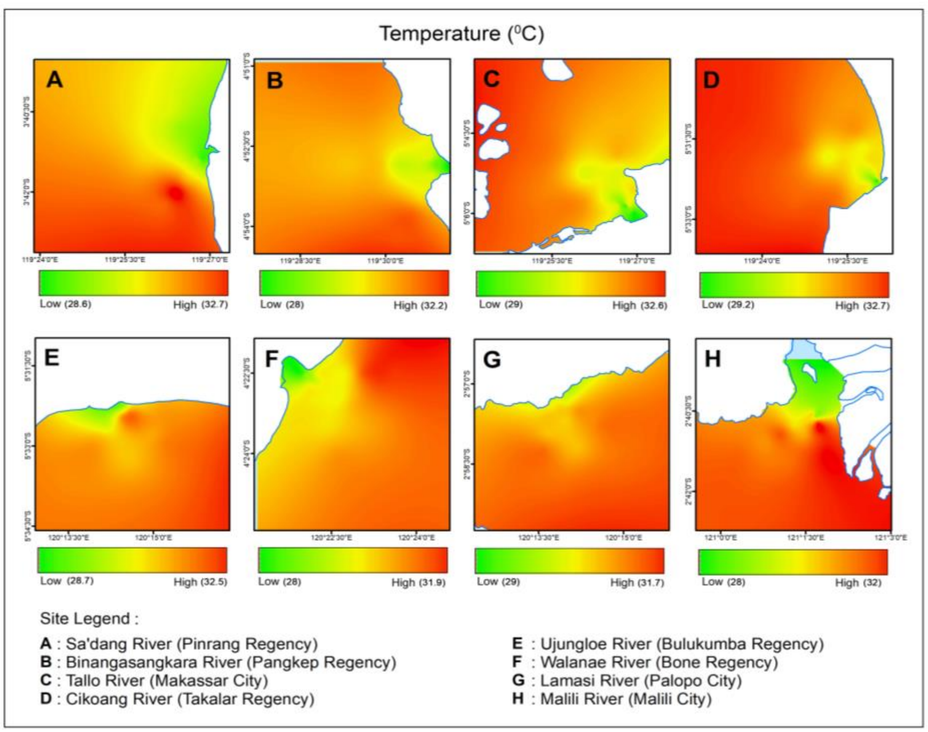

Figure 4. Water temperature distribution at eight sites around South Sulawesi, Indonesia

The patterns of generally higher water temperatures further from the river plumes and further offshore indicate that all three seaways (Makassar Strait, Flores Sea and Gulf of Bone) were experiencing relatively high sea surface temperatures at the time of the surveys. The patterns at certain sites also indicate that some shallow inshore waters were warmer than the offshore or main seaway temperature. For example, to the south of the Binangasangkara River in Pangkep Regency (B), southeast of the Malili River in Malili City (H), and north of the Walanae River in Bone Regency (F), sites with potential inflow from extensive brackish-water aquaculture ponds (called *tambak* in Indonesia) and/or other coastal wetlands with possibly elevated water temperatures. The highest temperatures in Makassar (C) were offshore from the Tallo River, around the reclamation site. At the Cikoang River in Takalar Regency (D), the water temperature was relatively even outside of the well-marked cooling effect of the river plume.

Compared to temperature data from previous decades for the Makassar Strait and Flores Sea (Kinkade et al., 1997; Nababan et al., 2016), the water temperatures recorded from the offshore stations at the eight study sites were, in general, relatively high. Furthermore, the maximum temperatures can mostly be considered high compared to recent studies at the same or nearby sites. In 2016 water temperature in Takalar during the west monsoon season ranged from 28.8 to 32.2 °C (Rahadiati et al., 2017), similar to (albeit slightly lower than) the range in this study (29.2-32.7 °C). A study in 2018 (Rustiah et al., 2019) reported temperatures of 29-31°C at the Pangkep site, a smaller range than the 28.0-32.2 °C measured in this study with a substantially lower maximum value. Meanwhile, sea surface temperatures in 2018 were reported as slightly higher in the Gulf of Bone (29.7 - 31.2 °C) than the Makassar Strait (29.2 - 30.3) (Hidayat et al., 2019), indicating similar average values but lower maximum values compared to the higher resolution data for coastal waters from this study.

Sea surface temperature in the Indonesian seas, including the seas around South Sulawesi, tend to vary with the seasons as well as with longer cycles, especially the El Niño-Southern Oscillation, and other factors affecting water mass transport in the Indonesian Throughflow (ITF) (Kinkade et al., 1997; Napitu et al., 2015; Nababan et al., 2016; Wouthuyzen et al., 2018; Sprintall et al., 2019). Nonetheless, the data from this study are consonant with the overall trend of rising sea surface temperatures associated with global climate change (Gattuso et al., 2015; IPCC, 2021), and detected at the local scale (Putri et al., 2021). In addition to the waters of South Sulawesi province, in recent years elevated sea surface temperatures have also been reported from other areas of Indonesia including Kalimantan (Wulandari, 2009) Tomini Bay (Ndobe et al., 2020), Tolo Bay and the Banda Sea (Mora at al., 2013).

3.1.2. Total Dissolved Solids (TDS) and Conductivity

Total dissolved solids (TDS) represents the inorganic salts, organic matter and other materials dissolved in water or in particles so small that they are considered to be in true solution (Boyd, 2015). Sources of abiotic TDS include the dissolution and suspension of minerals from soils and other geological formations, while biotic sources include organic matter in soils, living aquatic organisms (especially microorganisms) and their decaying remains (Boyd, 2015) as well as wastewater and other types of organic pollution (Allan et al., 2021). Solids contributing the most to TDS in inland waters are generally of inorganic origin, where high TDS levels generally correspond with high levels of mineralization, for example in regions with karst and other calcareous formations (Boyd, 2015) such as the karst formations found in several regions of South Sulawesi (Brumm et al., 2021). However, TDS levels in excess of salinity can also be an indicator of pollution (Allan et al., 2021).

Concentrations of total dissolved solids (TDS) concentrations were lower in and around the river mouth at all eight stations (Figure 5), indicating that the river waters carry fewer dissolved solids than the three seaways they flow into, i.e. the Makassar Strait, Flores Sea and Gulf of Bone. TDS levels were highest offshore from the Walanae River in Bone Regency followed by the Bulukumba Regency site (E). Maximum values were lowest at the Makassar City site (C). At the Palopo site (G) the lower riverine TDS did not extend beyond the lower reaches of the Lamasi River, while at the Takalar site (D) there was very little difference between the lower reaches of the Cikoang River and surrounding seawater.

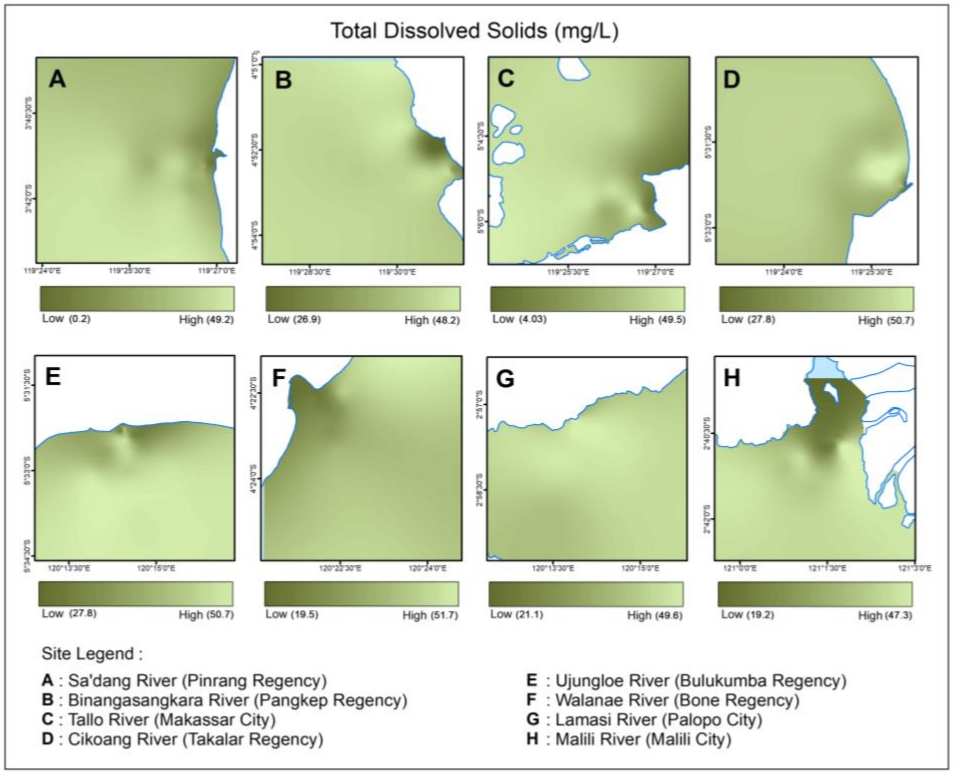

Figure 5. Distribution of total dissolved solids (TDS) at eight sites around South Sulawesi, Indonesia

The electrical conductivity of water, commonly referred to as conductivity in water quality analyses, is a measure of the conductance of water, in other words the ability of water to transmit electrical charge (Allan et al., 2021). Conductivity is extremely low in pure water and increases with the concentrations of ions and thus with salinity and TDS (Vineis et al., 2011; Rusydi, 2018; Allan et al., 2021). Conductivity is generally closely related to TDS, with a site-specific conductivity/TDS linear regression coefficient (Boyd, 2015; Rusydi 2018; Allan et al., 2021), and has been used as an indicator of pollution (Allan et al., 2021) or saline intrusion (Vineis et al., 2011). However, the value of the regression coefficient tends to be site-specific and must be determined empirically (Allan et al., 2021); in some cases the relationship is not easy to determine and may not be linear (Rusydi, 2018). Mostly, conductivity values were relatively low in the lower reaches of the river and river plume compared to the surrounding waters (Figure 6)

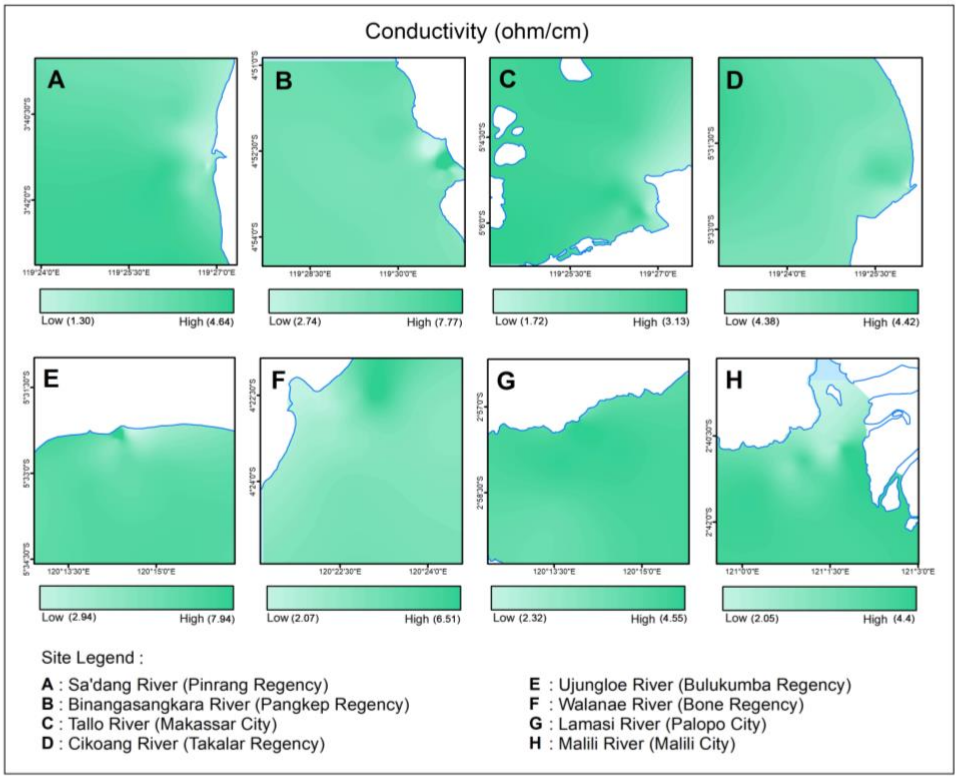

Figure 6. Distribution of conductivity at eight sites around South Sulawesi, Indonesia

Conductivity patterns resembled the TDS patterns, albeit with some discrepancies (Figures 5 and 6). For example, at the Makassar site [C], an area in the central outflow of the Tallo River has relatively low TDS but high conductivity compared to surrounding waters, as well as a relatively low temperature (Figure 4). Factors which affect conductivity include the quantity and composition of the ions present, while conductivity tends to be positively correlated with water temperature (Rusydi, 2018; Mendez-Barroso et al., 2020; Allan et al., 2021). This apparent anomaly, where elevated conductivity was associated with lower TDS and temperature, could be due to the composition of polluting elements present, as it would be possible to have a relatively low concentration of solids but a high proportion of ions with a relatively high capacity to conduct electricity. Other sites where discrepancies between Figure 5 and Figure 6 indicate potential non-linearities include the western side of the Ujungloe River estuary in Bulukumba (E) and the southern side of the Binangasangkara River estuary in Pangkep Regency where there are areas of high conductivity associated with low TDS, although the other sides of these estuaries follow the expected pattern. The area of high conductivity to the north of the Walanae River in Bone Regency also seems more pronounced than a linear relationship with the TDS levels would suggest.

3.1.4. Turbidity

Turbidity was generally higher in and/or around the river mouth at each of the eight estuaries studied (Figure 7). In addition to suspended sediments and other particulate matter carried by the rivers, at the Pinrang site wave action had visibly re-suspended fine sediment from the substrate, resulting in very high turbidity. The upper limit of the water standard for marine ecosystems under Decree of the Minister for the Environment of the Republic of Indonesia No. 51/2004 is 5 NTU. This level was exceeded at some or most stations at all sites, although at the Malili River site in Malili Regency it was only exceeded at one station in the lower reaches of the river.

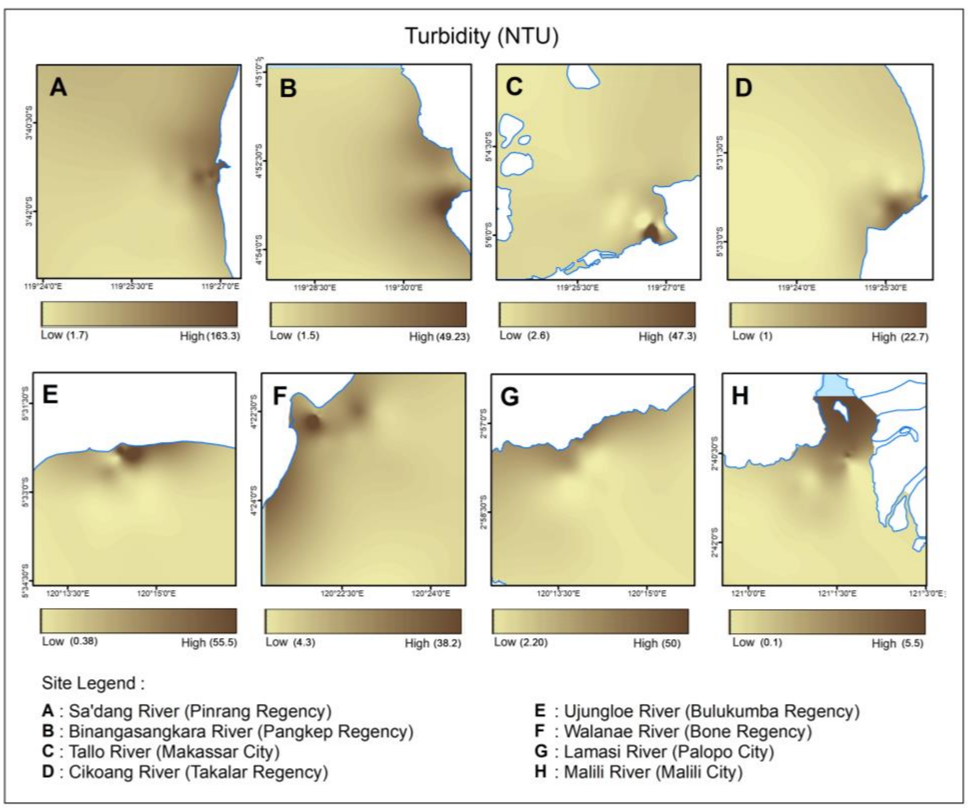

Figure 7. Turbidity distribution (NTU) at eight sites around South Sulawesi, Indonesia

3.2. Chemical Parameters

3.2.1. Salinity and pH

Salinity was generally lowest in the river mouth, increasing along the outflow plume to ambient seawater levels (Figure 8) in a manner similar to TDS. The extent of low salinity was very limited at the Palopo site (G) and at the Takalar site no stations were below 29 ppt. A reverse pattern for pH occurred at most sites, with riverine waters mostly having lower pH than the surrounding seawater (Figure 9).

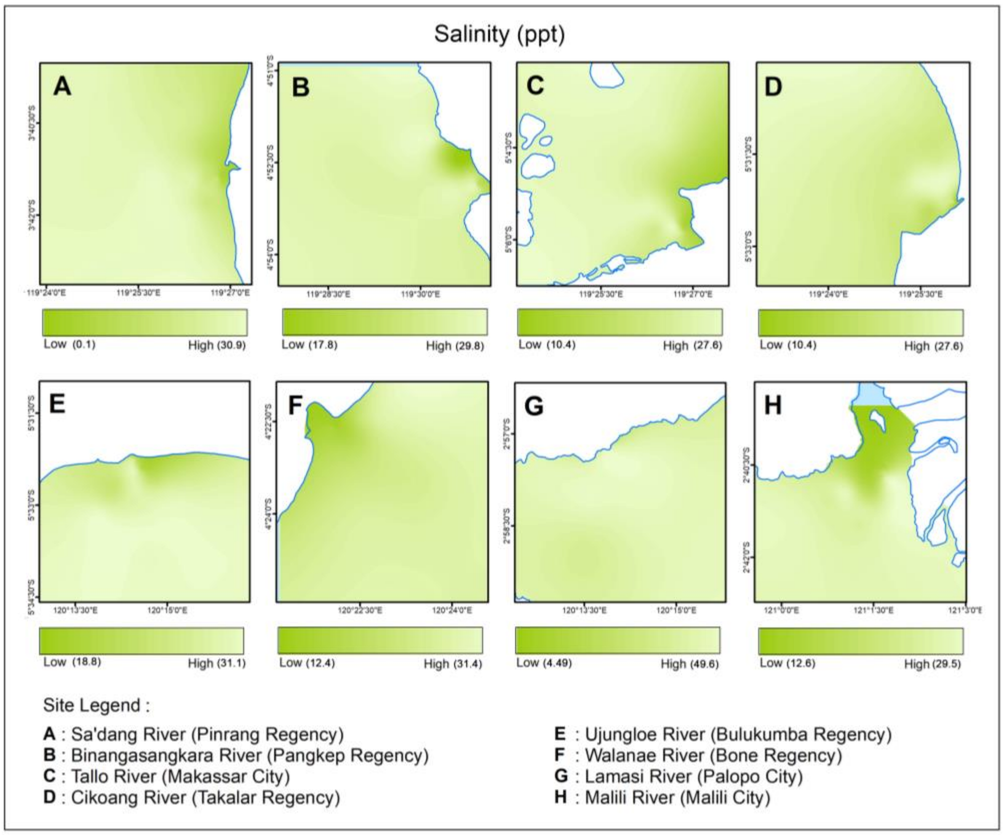

Figure 8. Distribution of salinity at eight sites around South Sulawesi, Indonesia

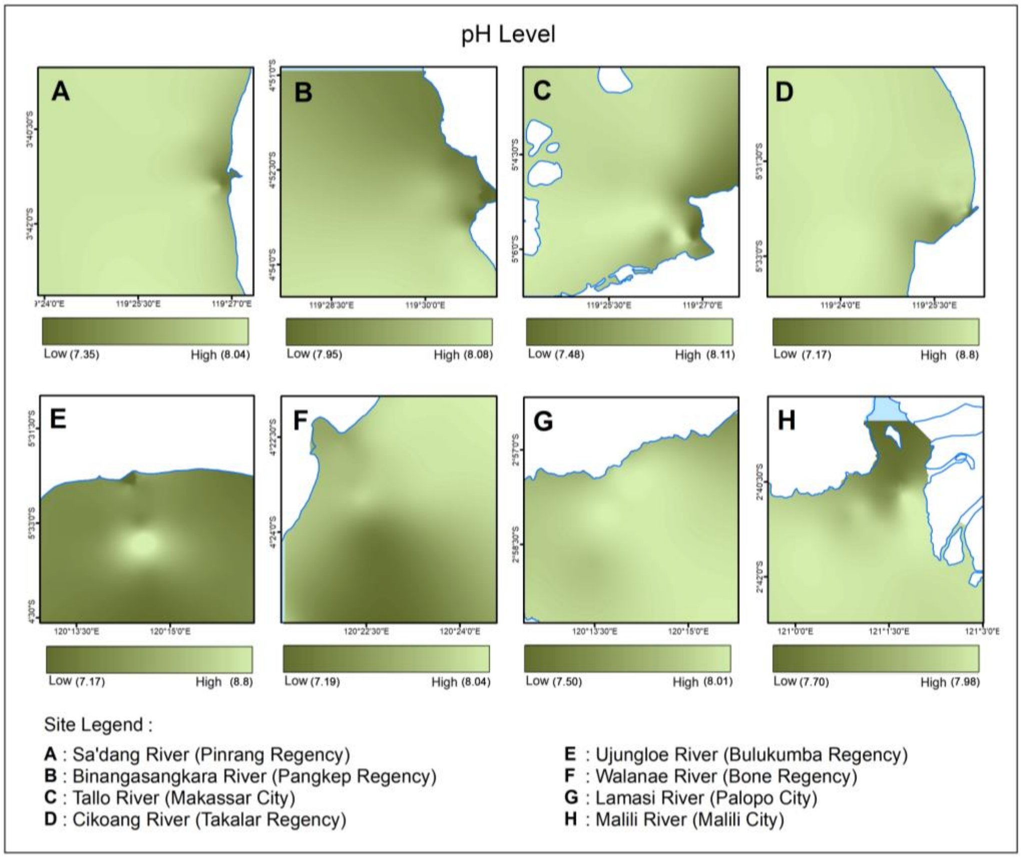

Figure 9. Distribution of pH at eight sites around South Sulawesi, Indonesia

The Bulukumba site (E) had the lowest salinity each side of the river mouth rather than in the centre of the river discharge plume, and an unusual pH distribution. At this site there were extensive seaweed farms in the shallow offshore waters. Eucheumatoid seaweeds are influenced by quality parameters (Hurtado et al., 2019; Ndobe et al., 2020). Conversely, the metabolic processes of seaweeds can influence water quality parameters; in particular, growing seaweeds can raise pH at a local scale, as reported for both tropical and temperate seaweeds (Krause-Jensen et al., 2015; Page et al., 2016; Xiao et al., 2021). However, the pH was low around the seaweed farming area. One reason for this could be an outbreak of ice-ice disease observed during the data collection. This disease results in the disintegration and detachment of decomposing seaweed thalli (Hurtado et al., 2019). This decomposing material would have been present in the surface waters and the water column as well as on the sea bed, and could have released compounds capable of reducing pH (Page et al., 2016).

3.2.2. Dissolved Oxygen

Dissolved oxygen concentrations at the eight estuarine sites in this study were generally low, with no consistent pattern across sites (Figure 10). Dissolved oxygen concentrations at the eight estuarine sites in this study were generally low compared to the recommended range (>5 mg/l) for marine life in the water quality standard under Decree of the Minister for the Environment of the Republic of Indonesia No. 51/2004.

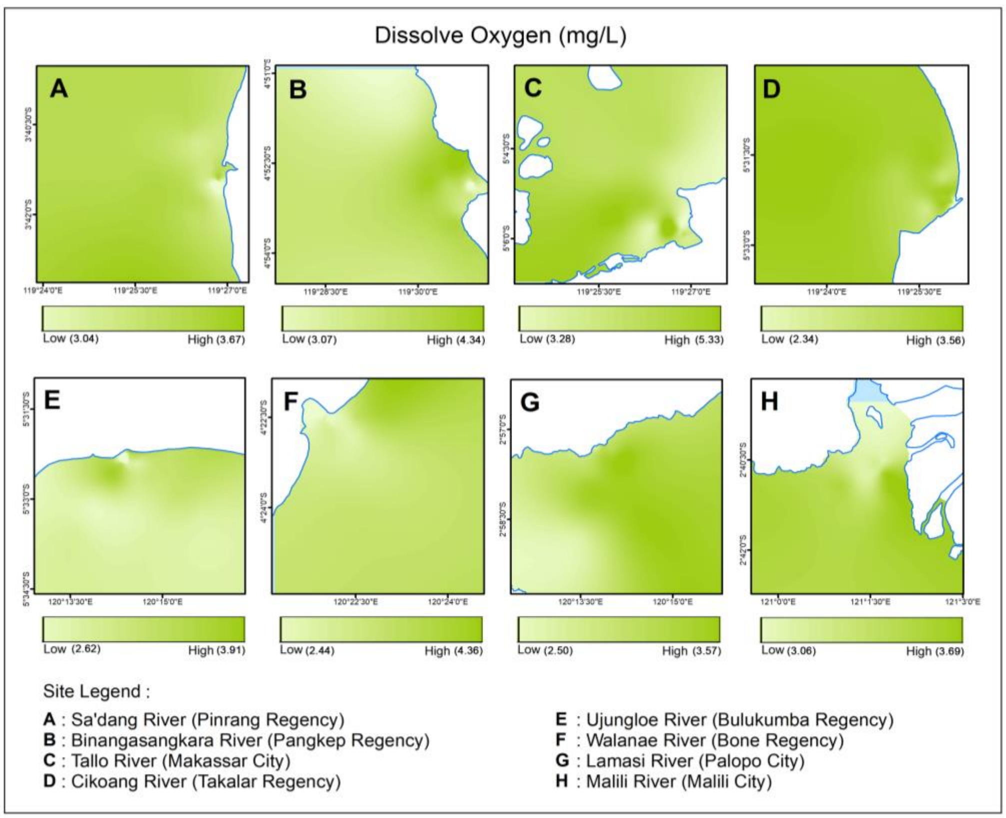

Figure 10. Dissolved oxygen (DO) distribution at eight sites around South Sulawesi, Indonesia

A comprehensive study on a wide variety of taxa by the U.S. Environmental Protection Agency (EPA, 2000) found that tolerance of below optimal oxygenation levels decreases over time, with exposure time tolerance highly variable between life stages as well as taxa, with continuous exposure having a greater or more rapid effect than cyclic (e.g. tide-related) exposure. Fairly short exposures to hypoxic conditions below around 2.3 mg/l was found to cause high or even 100% mortality in most juvenile and adult fish and invertebrates, although some showed high mortality at higher levels (between 4.5 and 2.3 mg/l) while others survived extremely hypoxic environments below 2.3 mg/l. Larval stages were found to be more susceptible, with high mortality in many taxa at DO levels below 4.5 mg/l, with survival decreasing exponentially to close to zero around 3 mg/l. In almost all taxa (but especially fishes) growth was increasing reduced below around 5 mg/l. Therefore, non-lethal hypoxic conditions such as those recorded at the study sites may still comply with the Indonesian water quality standard (minimum 3 mg/l) but can still have serious negative effects on biotic communities and fish stocks, including through reduced larval survival and growth, alone or in synergy with other stressors such as elevated temperatures or reduced pH (EPA, 200; Harley et al., 2006; Gobler et al., 2014; Jorissen & Nugues, 2021; Sampaio et al., 2021).

Data for some sites indicate that DO values may be higher in the past or under different weather conditions. For example, in 2012, the Tallo River estuary in Makassar had DO concentrations of around 5 mg/l (Rukminasari & Sahabuddin, 2012). Wave action tends to increase DO in surface waters (Boyd, 2015). However, at the Pinrang site, where weather conditions were rough with wind and large waves at the time of the data collection, DO levels were also low, indicating other factors affecting oxygen levels. Two likely factors across sites are temperature and nutrient levels. The study was conducted during a period of unusually hot and unsettled weather with calm dry spells interspersed with severe storms. Higher temperatures increase biological oxygen demand as well as reducing the solubility of oxygen in water, while various processes tend to reduce DO when nutrient levels (e.g. nitrate and ammonium) are high (EPA, 2000; Pauly & Cheung, 2017; Pauly, 2021) and turbidity also tends to reduce DO in estuarine environments (Schmidt et al., 2017).

3.2.3. Nitrate and Ammonium

The range of nitrate values recorded at the eight South Sulawesi sites was predominantly in the range 0.5–0.6 mg/l, mostly with a seawards decreasing gradient from the mouth of the estuary and/or the shore (Figure 11). Although the patterns differed, ammonium concentrations were also high at almost all stations and predominantly in the range 0.4-0.6 mg/l (Figure 12). These values exceed the standards for nitrate in aquatic/marine ecosystems (< 0.008 mg/l) and for ammonium in aquatic ecosystems and ports (<0.3 mg/l) set by the Decree of the Minister for the Environment of the Republic of Indonesia No. 51/2004. Such conditions are not an isolated occurrence particular to the study area in South Sulawesi. Studies in other areas of Indonesia and Southeast Asia have also reported similarly high nutrient concentrations (especially nitrate) affecting water quality in estuarine and coastal environments. These include the Bangka Strait (Gaol & Sadhotomo, 2007), Benoa Bay, Bali (Suteja & Purwiyanto, 2018), and Lampung (Barokah et al., 2017) in Indonesia.

Nutrient plumes were observed for most rivers with the highest mean nitrate concentrations were found at the Pangkep and Bone sites, both of which are areas where extensive conversion of coastal mangrove forests have been converted to *tambak* brackish water aquaculture ponds, while intensive poultry and livestock farming and direct discharge of sewage and domestic waste were also observed during the data collection in the field. In the context of coastal and estuarine water quality and eutrophication, ammonium ($NH4^{+}$) appears to be less frequently measured or mentioned compared to nitrate ($NO3^{-}$). Nonetheless, ammonium contributes to total nitrogen and nutrient levels (Statham, 2012). Ammonium ($NH4^{+}$) is an ion, and the relative concentrations of ammonium and ammonia ($NH3^{-}$) can vary with other water quality parameters, in particular temperature, pH and salinity, while nitrate can also be reduced to ammonium, especially by processes in marine sediments (Vieillard et al., 2020).

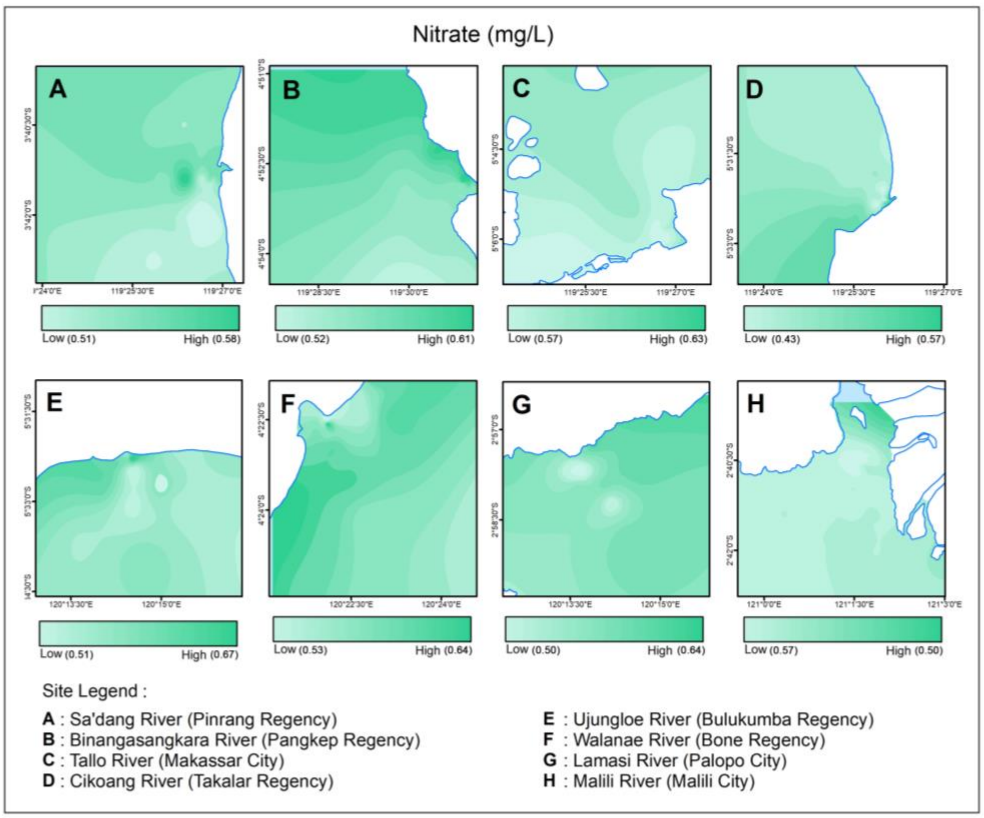

Figure 11. Distribution of nitrate concentration at eight sites around South Sulawesi, Indonesia

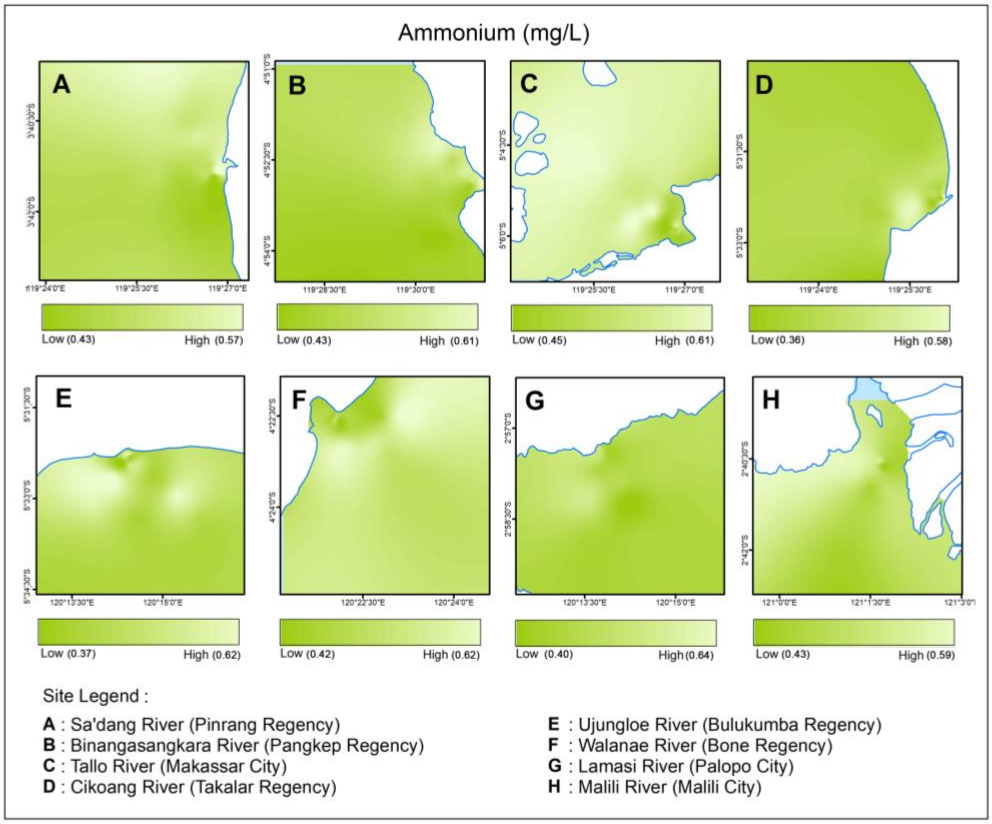

Figure 12. Distribution of ammonium concentration at eight sites around South Sulawesi, Indonesia

Rivers are widely perceived as the main source of nitrate in most estuarine and surrounding coastal waters, with nutrient input typically arising from agriculture, aquaculture, industry and household or residential waste (Jiang et al., 2010; Brandini et al., 2016; Suteja & Purwiyanto, 2018; Wurtsbaugh et al., 2019; Vieillard et al., 2020) as well as potentially arising from some natural processes and sulphate concentrations (Wurtsbaugh et al., 2019). While healthy mangrove forests can mitigate many forms of pollution, degraded mangroves can release many stored compounds; when converted for aquaculture, the release of *tambak* water to the sea can be a source of nutrients as well as various pollutants and a vector for pests and diseases (Cochard, 2017). By 2003, over two-thirds of the mangrove forests of South Sulawesi had been converted to *tambak* ponds for coastal aquaculture (Malik et al., 2017).

Nitrogen compounds in general promote the production of organic matter (Wurtsbaugh et al., 2019). High levels of nitrogenous compounds in water, especially nitrate ($NO3^-$) but also ammonium ($NH4^+$) and other nitrogenous compounds, can cause eutrophication (Vargas-González et al., 2014). Run-off from urban landscapes generally contains much higher levels of both nitrate and ammonium compared to forested areas, while fertilised croplands tend to yield high amounts of nitrate and moderate amounts of ammonium (Wurtsbaugh et al., 2019).

3.3. STORET Pollution Index and Principle Component Analysis

The STORET scale indicates the overall level of pollution based on the combination of several parameters with reference to water quality standards. The full data set used for the STORET analysis is provided in Appendix I. The mean values for the nine water quality parameters measured vary between sites (Table 1), with the least variation in the nitrate ($NO3^-$) and ammonium ($NH4^+$) concentration parameters. The STORET Pollution Index values ranged from -24 to -54 (Table 2).

Table 1. Mean values of physical and chemical parameters in estuarine waters at eight sites around South Sulawesi, Indonesia used in STORET analysis

Station (Regency/ City)	Parameter (unit)								
	Salinity (ppt)	Temperature (°C)	Turbidity (NTU)	Conductivity (ohm/cm)	TDS (mg/l)	pH	DO (mg/l)	$NO3^-$ (mg/l)	$NH4^+$ (mg/l)
Pinrang	16.11	29.6	77.277	5.119	24.79	7.790	3.43	0.532	0.476
Pangkep	26.59	30.2	13.725	4.194	42.42	8.012	3.78	0.565	0.517
Makassar	20.25	34.0	8.343	4.495	29.50	7.852	3.99	0.595	0.530
Takalar	29.87	32.8	8.124	6.445	48.38	7.835	3.28	0.503	0.463
Bulukumba	26.86	31.0	18.131	4.228	38.11	7.960	3.51	0.563	0.493
Bone	20.14	30.0	13.362	3.213	32.23	7.727	3.19	0.569	0.516
Palopo	27.95	32.1	19.657	4.186	43.10	7.894	3.15	0.596	0.482
Malili	21.51	30.8	1.862	3.230	33.89	7.867	3.37	0.590	0.518

Table 2. Storet Pollution Index values at the eight study sites around South Sulawesi

Station	Scale	Indication
Pinrang	-36	Heavily Polluted
Pangkep	-35	Heavily Polluted
Takalar	-36	Heavily Polluted
Makassar	-53	Heavily Polluted
Bulukumba	-41	Heavily Polluted
Bone	-28	Moderated Polluted
Palopo	-36	Heavily Polluted
Malili	-24	Moderated Polluted

Field observations showed the Tallo River estuary in Makassar City as having more visible signs of activities potentially affecting water quality than the other sites. These included the discharge of industrial wastes such as factory and food industry waste, pollution from docks and associated activities, domestic waste and sedimentation visible along the Losari Beach coast south of the river mouth. The heavily polluted category for this site is also consonant with several other studies in this area reporting high levels of marine debris (Faizal et al., 2020), elevated temperatures and phytoplankton with the potential to cause harmful algal blooms (Tambaru et al., 2019), high phosphate concentrations, especially during the west monsoon (Rastina et al., 2020), high levels of riverborne organic and inorganic particulate matter (Nasir et al., 2016), low pH (Rustiah et al., 2018; Tambaru et al., 2019), moderately elevated high total suspended solids (Rustiah et al., 2018), and heavy metal contamination (Rukminasari & Sahabuddin, 2012). Furthermore, a major reclamation project has been joining the offshore islands to one another. Visible impacts include increased sedimentation during construction; increased protection from wave action in this already comparatively sheltered area; and reduced water circulation. These impacts are likely to increase the retention of all pollutants, including nutrients, while reducing the processes which can replenish oxygen used in biotic or abiotic (chemical) processes.

Although the other seven estuarine sites had lower STORET pollution Index values than the Tallo River in Makassar City, nitrate and ammonium levels were high at all sites. A study in February 2018 included a station within the Pangkep site in this study (Rustiah et al., 2019) where the water column nitrate and ammonium values were an order of magnitude lower than the values in Table 1; however, sediment samples had similar (albeit slightly lower) nitrate and ammonium levels to those in Table 1. This indicates potential cycling between the water and sediment, with short-term storage in and release of nutrients from the sediment, and/or the accumulation of organic matter with subsequent decomposition and release of regenerated ammonium from the sediment, as reported *inter alia* by Wurtsbaugh et al. (2019). Such processes could occur not only at the Pangkep site but also at other sites with high nutrient and organic matter inputs either permanently or seasonally and sediment which is vulnerable to disturbance by wave action or other factors.

Principal component analysis (PCA) yielded seven axes with the first two axes (Figure 13) explaining 77.52% of the between-site variability. The position of the Malili and Makassar sites indicates that higher nutrient and dissolved oxygen concentrations characterise these sites, although nutrient concentrations were high and dissolved oxygen levels were low at all sites. Palopo, Bulukumba and Pangkep were all characterised by pH, temperature, TDS and salinity, while Takalar was characterised by conductivity. The elevated turbidity characterising the Pinrang site was likely at least partly due to the strong wave action at the time of the survey, combined with the predominantly fine sediment observed at this site, and reported along much of the west coast of South Sulawesi (Nasir et al., 2016; Rustiah et al., 2019). This sediment is to some extent a natural phenomenon but has been exacerbated by upland and mangrove degradation and associated increases in sedimentation (Nasir et al., 2016; Malik et al., 2017).

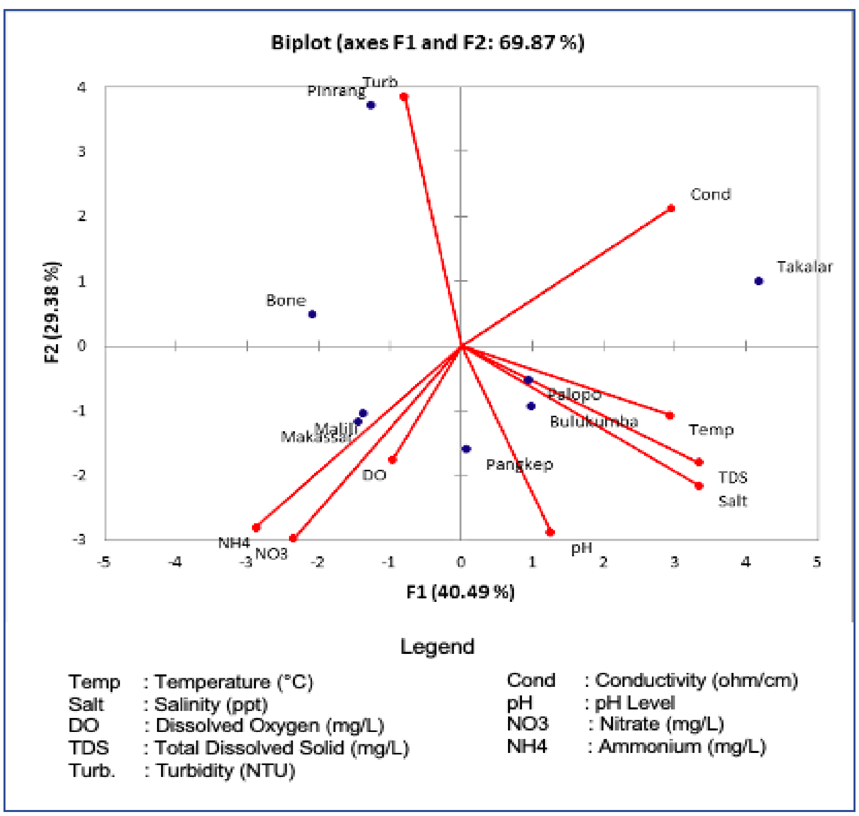

Figure 13. Principal component analysis (PCA) plot of (F1 and F2) of water quality parameters characterizing eight sites around South Sulawesi, Indonesia

Over time, elevated nutrient levels can lead to a shift in phytoplankton communities, with a reduction in beneficial phytoplankton such as diatoms and increased abundance of potentially harmful taxa such as some dinoflagellates (Jiang et al., 2010). Furthermore, while nitrates tend to favour the growth of diatoms and green algae, ammonium tends to promote the growth of dinoflagellates and non-nitrogen-fixing cyanobacteria and the release of ammonium from disturbed sediments can trigger the development of harmful algal blooms (HABs) (Wurtsbaugh et al., 2019).

Temperature affects the rate of photosynthesis and reproduction of eukaryotic phytoplankton and cyanobacteria, with maximum growth peaks differing between class (Paerl et al., 2014) as well as lower taxonomic divisions. According to (Paerl et al., 2014), given sufficient light and nutrients, the growth rate of chlorophytes tends to peak around 30°C and decline sharply around 35°C, while diatoms and dinoflagellates peak at much lower temperatures (typically around 15-25°C) and cyanobacteria peak at higher temperatures (typically 25-35°C, declining around 40°C). Furthermore, a strong association between elevated temperature and the occurrence of harmful algal blooms (HABs) has been reported (Ansari & Gill, 2014; Paerl et al., 2014; Tambaru et al., 2019; Wurtsbaugh et al., 2019). The changes in planktonic communities under elevated temperatures, especially when combined with lowered pH, tend to reduce the energy flow from primary producers to higher trophic levels (Ullah et al., 2018; Horn et al., 2021). There fore temperature can significantly affect the abundance and composition of phytoplankton communities at the base of the food chain, and hence the organisms of particular interest human populations (e.g. for fisheries, aquaculture, and tourism) as well as overall ecosystem productivity.

Temperature also directly affects the metabolism and behaviour of marine vertebrates and invertebrates, including fish. Above optimum temperatures lower the ability of oxygen to remain dissolved in water while increasing oxygen demand for metabolism, thereby limiting growth and maximum size (Pauly & Cheung, 2017; pauly, 2021). Furthermore, especially when combined with other stressors, temperatures exceeding their thermal tolerance niche can directly threaten the survival of many marine, freshwater and diadromous organisms (Paerl et al., 2014; Ullah et al., 2018; Albert et al., 2020). The relatively high temperatures (in excess of 32°C) recorded from some stations at most sites were associated with hot weather, especially in Bulukumba. The prevalence of ice-ice at this site, may well be related to the low DO and relatively high temperature, similar to conditions associated with ice-ice at other sites (Ndobe et al., 2020). This outbreak is one indication of the vulnerability of these estuarine ecosystems to the effects of climate change, in particular increases in both mean temperatures and extreme peaks.

The prevalence (100%) of elevated nutrient levels at the eight study sites around the province indicates the need for spatially integrated measures throughout the watersheds of South Sulawesi to mitigate nutrient enrichment. This should address domestic sewage and waste treatment and disposal, agricultural practices including livestock farming and aquaculture (e.g. *tambak* brackish water aquaculture), as well as industrial sources. As advocated by (Paerl et al., 2014), these measures should consider both present and future conditions, taking into account likely changes in precipitation and hydrology as well as temperature, and aim to control both nitrogen and phosphorus.

Regulations could be developed to “curb nutrient loading from point-, and especially nonpoint sources” as proposed by (Wurtsbaugh et al., 2019), including building regulations for residential, commercial, industrial and infrastructure development (Lasut et al., 2008). The adoption of sustainable approaches to agriculture, forestry and agroforestry should be accelerated, while maintaining riparian buffer zones (Jose, 2009; Wurtsbaugh et al., 2019). In larger conurbations and cities with residential and industrial estates, as elsewhere (Lasut et al., 2008; Vargas-González et al., 2014), strategies are needed to reduce nutrient inputs from urban wastewater. In this context, waste water treatment plants should be installed and/or upgraded, and could use various technologies, including physical, chemical or biological nutrient removal (Lasut et al., 2008; Wurtsbaugh et al., 2019). Meanwhile, restoring coastal wetlands such as swamps, seagrass beds and mangrove forests could also play a role (Barbier et al., 2011; Day et al., 2012). In addition to improved practices in monoculture, coastal pond and cage aquaculture of fish and crustaceans could adopt polyculture or integrated multi-trophic aquaculture (IMTA) practices (Hughes & Kenneth 2021). These could include algae for phytoremediation and/or invertebrates as polycultured species to convert wastes and nutrients into valuable products (Ansari & Gill, 2014; Namukose et al., 2016). The role of farmed seaweeds in phytoremediation of coastal waters also appears to be worth investigating (Xiao et al., 2017; Zheng et al., 2019)), especially as South Sulawesi is a major seaweed farming region (Nuryartono et al., 2021).

4. Conclusion

The estuarine ecosystems of eight major rivers around South Sulawesi are at risk from pollution, with a 100% prevalence of excessive nutrients in addition to localised factors. Six of the eight study sites were categorized as heavily polluted (Pinrang, Pangkep, Makassar, Takalar, Bulukumba, and Palopo), with the most severe pollution at the Tallo River estuary in Makassar City, while two were moderately polluted (Bone and Malili). Principle component analysis grouped the eight sites into four groups based on the most prominent defining parameters. These were pH and temperature at the Palopo and Bulukumba sites; nitrate and ammonium at the Makassar and Malili sites; DO, turbidity and conductivity at the Pinrang site; and salinity and TDS at the Pangkep and Takalar sites.

The consistently low dissolved oxygen levels recorded are a cause for concern and call for regular monitoring of this parameter in the waters around South Sulawesi and may be related to the nutrient levels as well as meteorological conditions, calling for research to better understand and potentially mitigate the occurrence of hypoxic conditions. Based on the findings climate change mitigation and adaptation should be considered, in particular with respect to elevated water temperature and nutrient loading to reduce the risks to the socio-ecological systems including biodiversity as well as fishing and aquaculture livelihoods. A key factor in risk mitigation should be watershed-wide strategies to reduce nutrient loading of riverine and coastal waters, thereby reducing the risk of harmful algal blooms and anoxic conditions in estuarine and coastal waters.