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ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol.53 , No.3, 2021 (373 – 387)
DOI: http://dx.doi.org/10.22146/ijg.40519 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY
RESEARCH ARTICLE

Physical and Chemical Parameters of Estuarine Waters around South Sulawesi

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Received: 2021-08-26
Accepted: 2021-10-03

Key words:
River estuary;
Water quality mapping;
STORET pollution score
Principle Componen Analysis

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Abstract Water quality parameters can be indicators of pollution driving riverine, estuarine and coastal resource degradation. This study evaluated water quality in the downstream, estuarine and surrounding coastal waters of 8 major river estuaries around the western, southern and eastern coasts of South Sulawesi Province, Indonesia. Data on physical and chemical parameters (salinity, temperature, total dissolved solids (TDS), conductivity, turbidity, pH, dissolved oxygen (DO), nitrate and ammonium) were collected during January 2020. These water quality data were interpolated and mapped using the Kriging tool in ArcGIS 9.3 and analysed using the STORET pollution scale and Principle Component Analysis (PCA). STORET scale values indicate moderate to heavy pollution, with the most severe pollution in Makassar City. Dominant defining parameters based on the PCA were nitrate, ammonium and DO at the Malili and Makassar sites, pH, temperature, TDS and salinity at the Palopo, Bulukumba and Pangkep sites, conductivity at the Takalar site and turbidity at the Pinrang site.

1. Introduction

Estuarine areas are often highly productive ecosystems, greatly affected by both marine and riverine environments as well as their interaction (Brandini et al., 2016; Paerl et al., 2014; Seitzinger et al., 2010; Vieillard et al., 2020; Wurtsbaugh et al., 2019). 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 (Mubarak & Nurhuda, 2021; Nasir et al., 2016; Vieillard et al., 2020; Wibisana et al., 2019). 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 (Albert et al., 2020; Horn et al., 2021; Mantyka et al., 2014; Mora et al., 2013; Pauly, 2021; Ullah et al., 2018; Wurtsbaugh et al., 2019). 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 1937 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, 2019). 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. Nasir et al., 2016; Rukminasari & Sahabuddin, 2012; 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. Methods

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 1). Sampling station density (+2 NM) 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).

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.

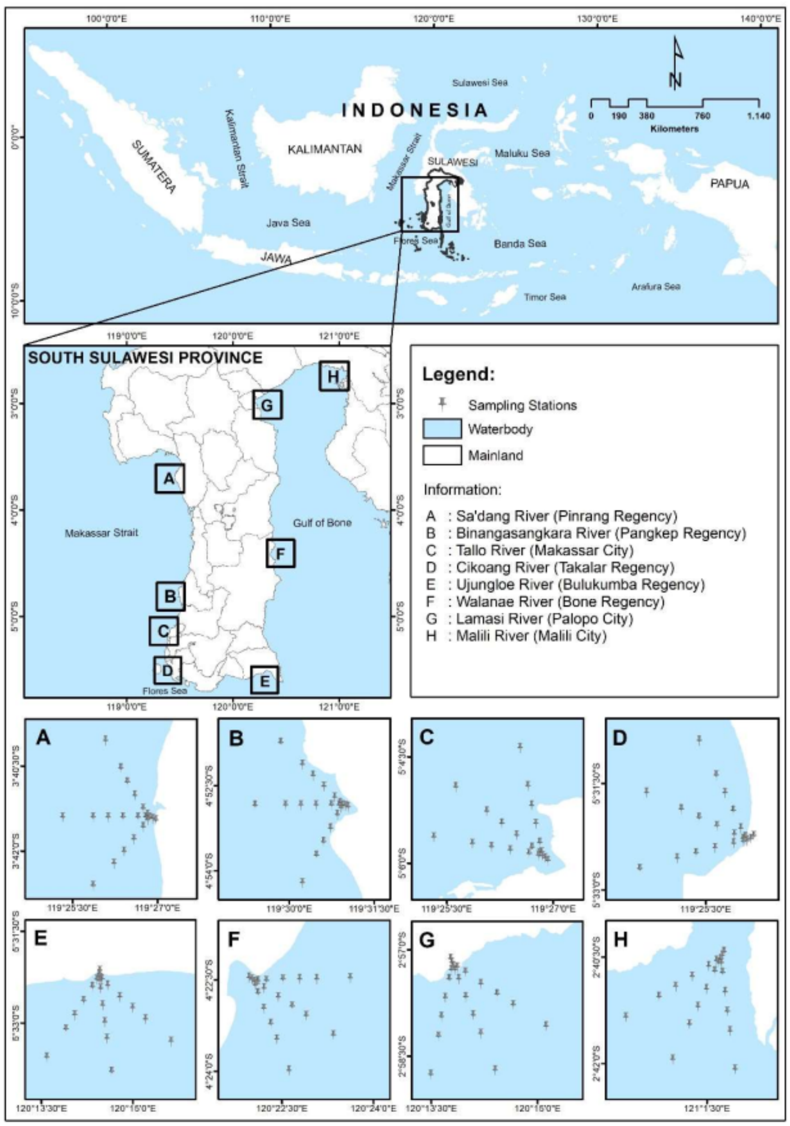

Figure 1. Research sites and sampling stations around South Sulawesi,Indonesia

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. Results and Discussion

Distribution of Physical Parameters

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 2).

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

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

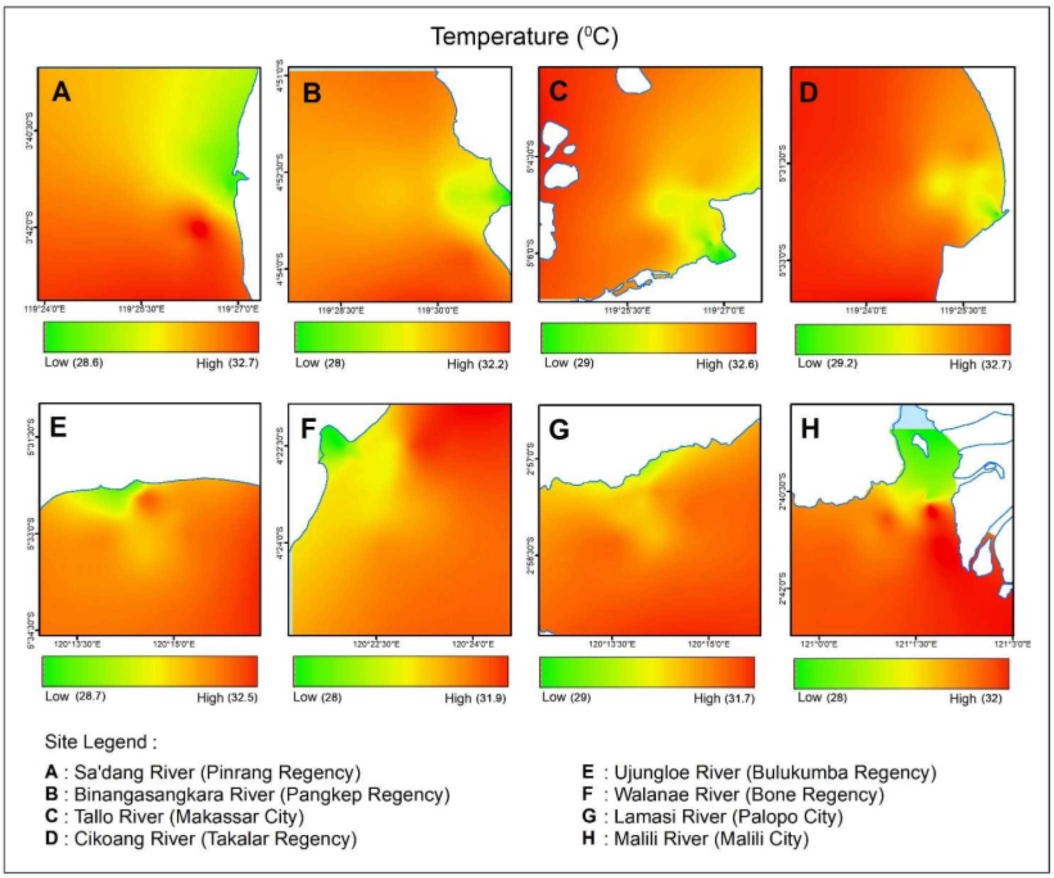

Figure 2. Water temperature distribution at eight sites around South Sulawesi, Indonesia

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; Nababan et al., 2016; Napitu et al., 2015; Sprintall et al., 2019; Wouthuyzen et al., 2018). 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., 2018). In addition to the water of south Sulawesi province, in recent years elevated sea surfaces temperatures have also been reported from other areas of Indonesia including, Kalimantan (Wulandari et al., 2020), Tomini Bay (Ndobe et al., 2020), Tolo Bay and the Banda Sea (Moore et al., 2019)

Data analysis

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 (Boyde, 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 (Boyde, 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.

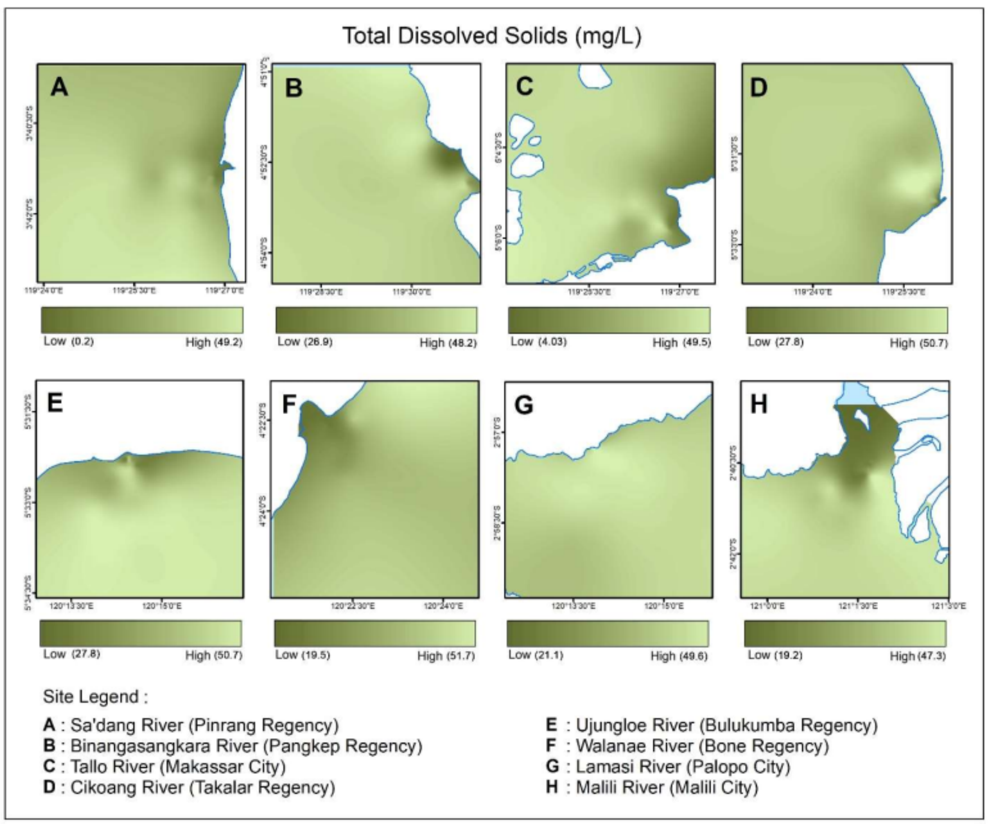

Figure 3. Distribution of total dissolved solids (TDS) at eight sites around South Sulawesi, Indonesia

TDS levels generally correspond with high levels of mineralization, for example in regions with karst and other calcareous formations (Boyde, 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 3), 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.

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 (Allan et al., 2021; Rusydi, 2018; Vineis et al., 2011). Conductivity is generally closely related to TDS, with a site-specific conductivity/TDS linear regression coefficient (Allan et al., 2021; Boyde, 2015; Rusydi, 2018), 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 4).

Conductivity patterns resembled the TDS patterns, albeit with some discrepancies (Figures 3 and 4). 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 2C). Factors which affect conductivity include the quantity and composition of the ions present, while conductivity tends to be positively correlated with water temperature (Allan et al., 2021; Méndez-Barroso et al., 2020; Rusydi, 2018). 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 3 and Figure 4

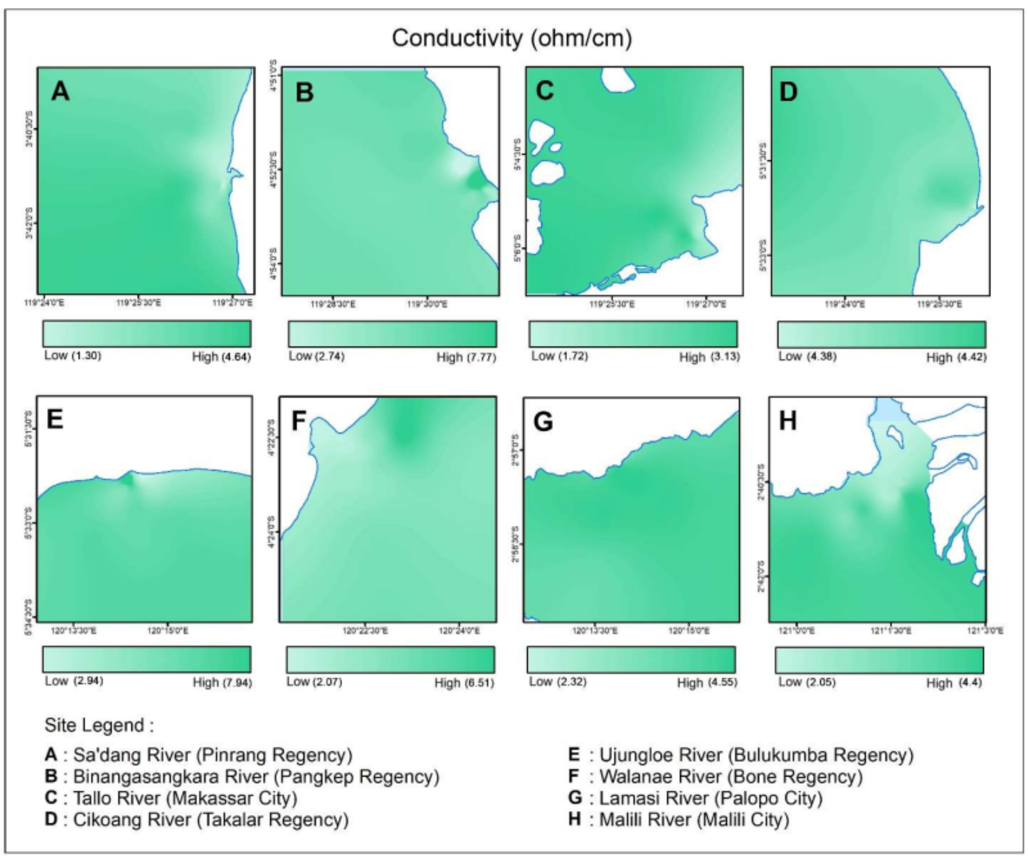

Figure 4. Distribution of conductivity at eight sites around South Sulawesi, Indonesia

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.

Turbidity

Turbidity was generally higher in and/or around the river mouth at each of the eight estuaries studied (Figure 5). In addition to suspended sediments and other particulate matter carried by the rivers, at the Pinrang site wave action had 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.

Chemical Parameters

Salinity and pH

Salinity was generally lowest in the river mouth, increasing along the outflow plume to ambient seawater levels (Figure 6) 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 7).

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.

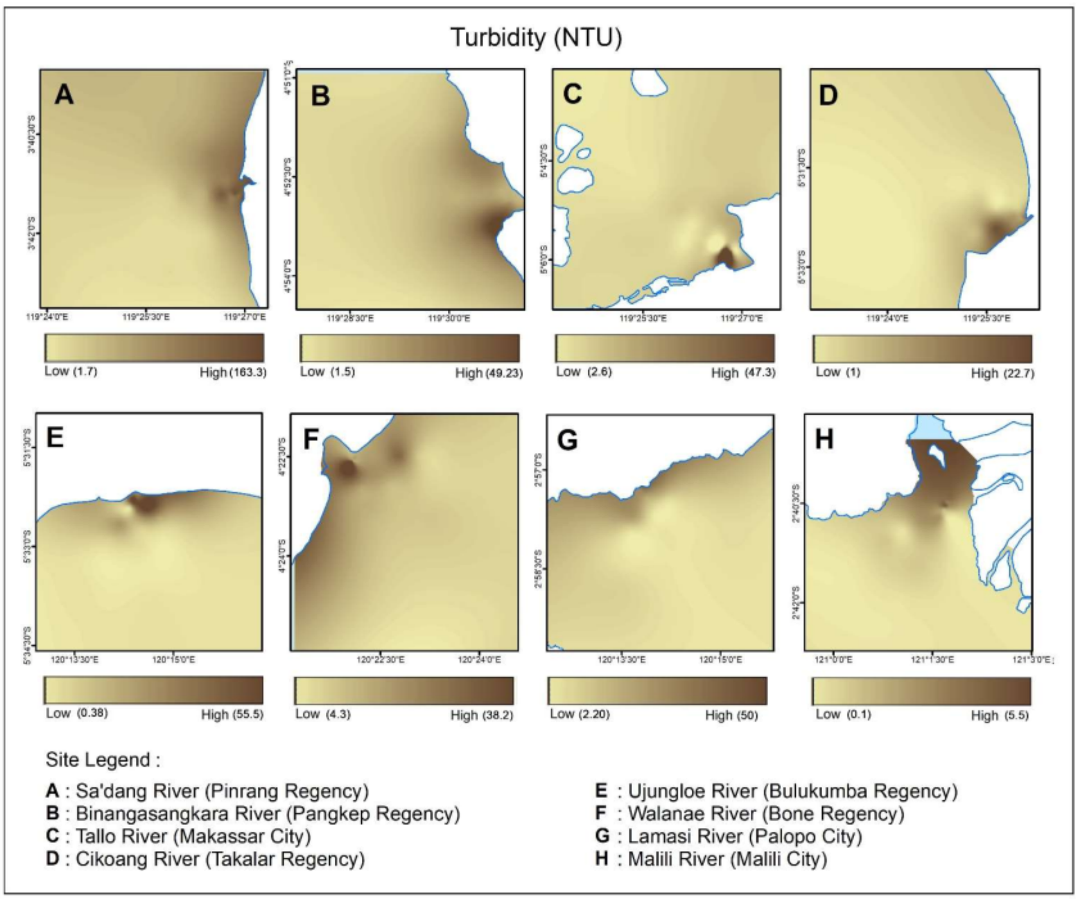

Figure 5. Turbidity distribution (NTU) at eight sites around South Sulawesi, Indonesia

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).

Dissolved Oxygen

Dissolved oxygen concentrations at the eight estuarine sites in this study were generally low, with no consistent pattern across sites (Figure 8). 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.

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 a nd 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, 2000; Gobler et al., 2014; Harley et al., 2006; 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 (Boyde, 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

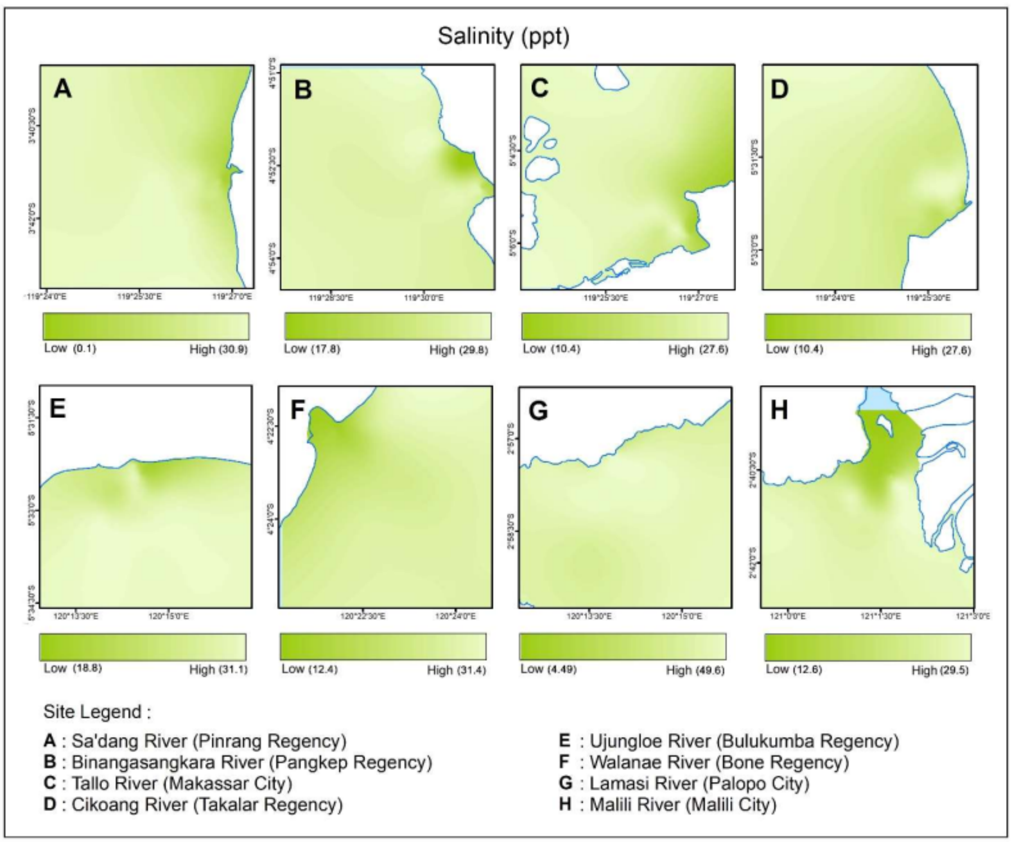

Figure 7. Distribution of pH at eight sites around South Sulawesi, Indonesia

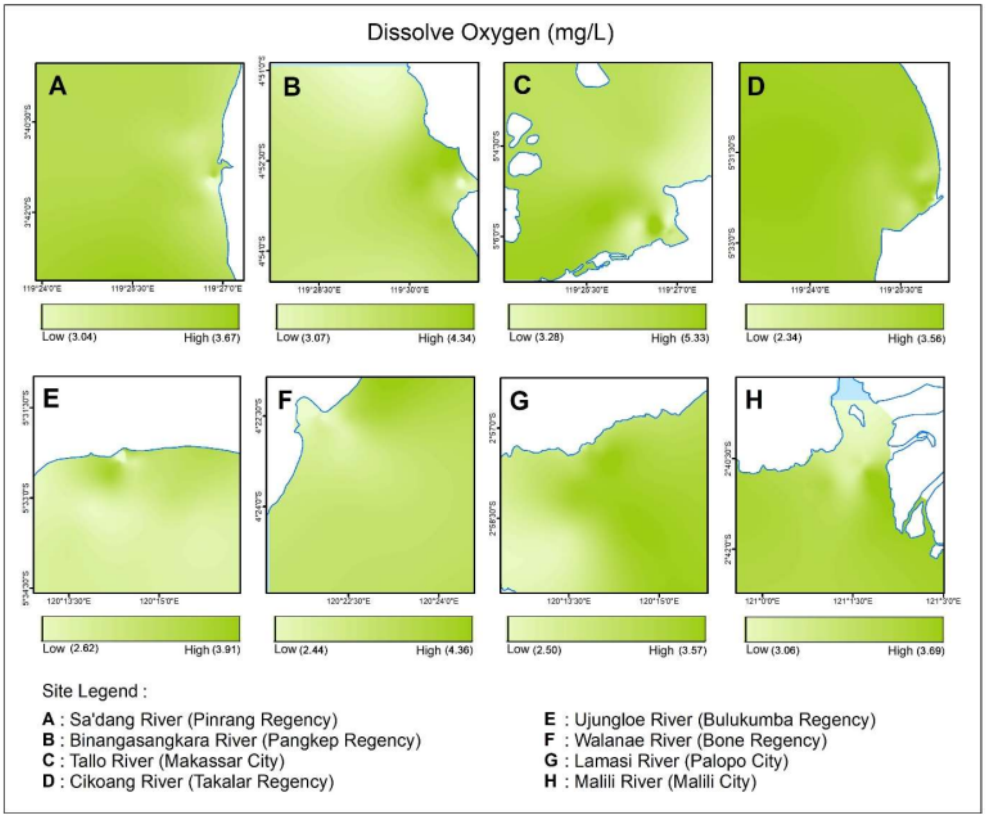

Figure 8. Dissolved oxygen (DO) distribution at eight sites around South Sulawesi, Indonesia

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, 2021; Pauly & Cheung, 2017) and turbidity also tends to reduce DO in estuarine environments (Schmidt et al., 2017).

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 9). 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 10). 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 concentration (especially nitrate) affecting water quality in estuarine and coastal enviroments. These include the Banda Strait (Gaol et al., 2017), Benoa bay, Bali (Suteja & Purwiyanto, 2018; Suteja & Dirgayusa, 2018) and Lampung (Barokah et al., 2017) in Indonesia, as wel; as other countries including Malaysia (Er et al., 2018; Kaniz et al., 2014), Philippines (Sotto et al., 2014) and Thailand (Cheevapron & Menasveta, 2003).

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).

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 (Brandini et al., 2016; Jiang et al., 2010; Suteja & Purwiyanto, 2018; Vieillard et al., 2020; Wurtsbaugh et al., 2019) as well as potentially arising from some natural processes and sulphate concentrations (Wurtsbaugh et al., 2019). While healthy mangrove forests can mitigate many

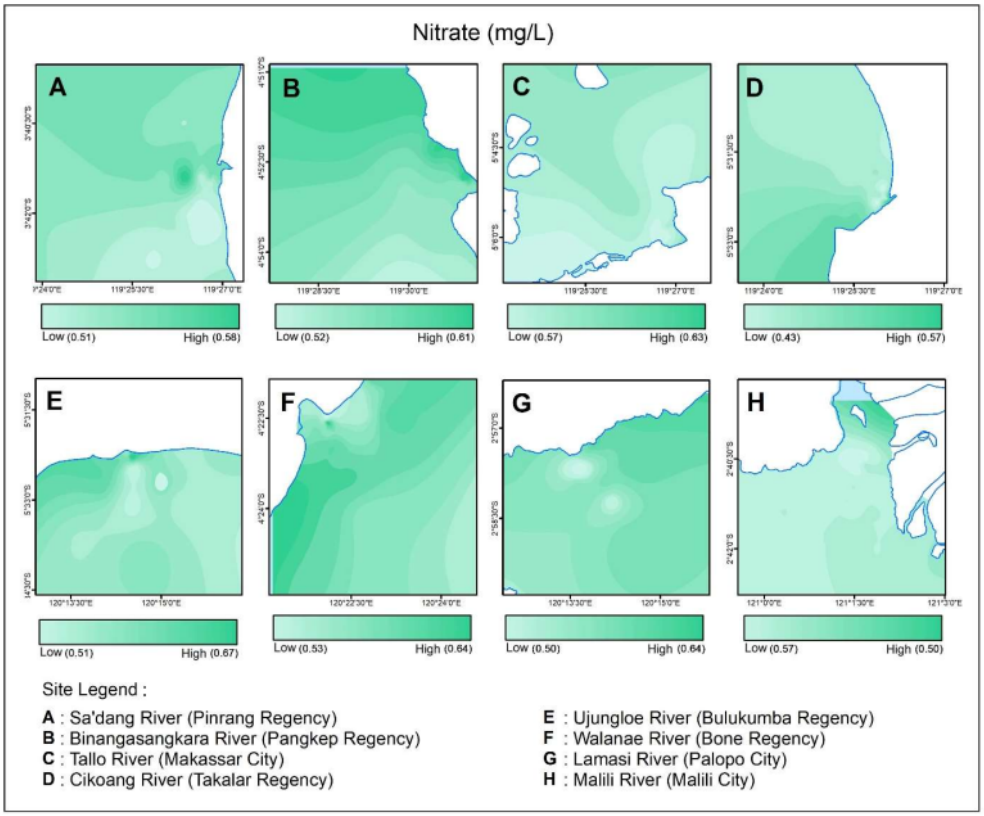

Figure 9. Distribution of nitrate concentration at eight sites around South Sulawesi, Indonesia

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).

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 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. Two sites were in the moderately polluted category: Malili (-24) and Bone (-28). The other six sites were categorised as heavily polluted: Pangkep (-35); Pinrang, Takalar, and Palopo stations (all -36), Bulukumba (-41); and Makassar which had the lowest (most negative) score (-53).

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

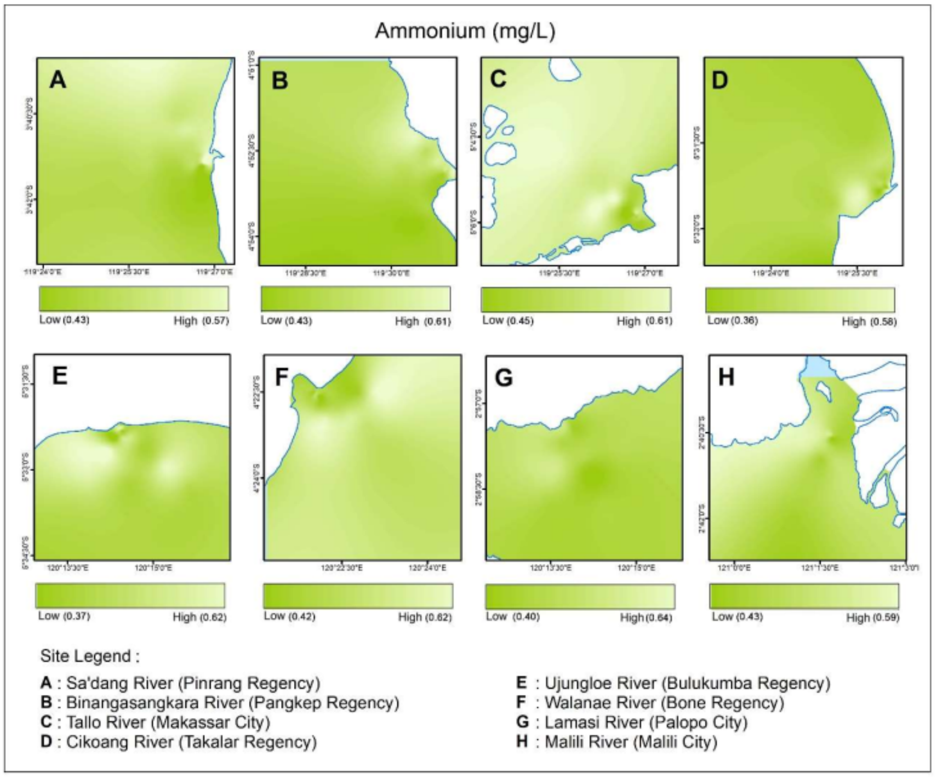

Figure 10. Distribution of ammonium concentration at eight sites around South Sulawesi, Indonesia

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

Station	Parameter (unit)								
(Regency/ City)	Salinity (ppt)	Temperature (ºC)	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

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 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 11) explaining 77.52% of the between-site variability. The position of the Malili and Makassar sites indicates that high nutrient and dissolved oxygen concentrations characterise these sites. Palopo, Bulukumba and Pangkep were all characterised by pH, temperature, TDS and salinity, while Takalar was characterised by conductivity. The strong wave action, 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), was likely responsible for the elevated turbidity characterising the Pinrang site. This sediment is to some extent a natural

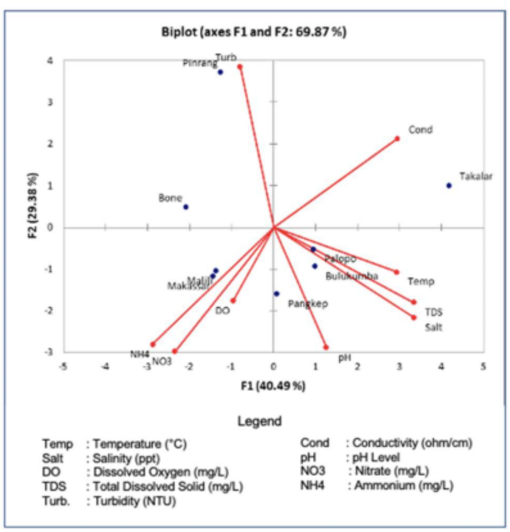

Figure 11. Principal component analysis (PCA) plot of (F1 and F2) of water quality parameters characterizing eight sites around South Sulawesi, Indonesia

phenomenon but has been exacerbated by upland and mangrove degradation and associated increases in sedimentation (Malik et al., 2017; Nasir et al., 2016).

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 (Horn et al., 2021; Ullah et al., 2018). Therefore 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, 2021; Pauly & Cheung, 2017). 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 (Albert et al., 2020; Horn et al., 2021; Paerl et al., 2014; Ullah et al., 2018). 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 form point-, and especially nonpoint source" as proposed by (Wurstsbaugh et al., 2019), including building regulation for residential, commercial, industrial and infrastructure development (Lasut, Jensen, & Shivakoti, 2008). The adoption of sustainable approaches to agriculture, forestry and agroforestry should be accelerated, while maintaining riparian buffer zones (Jose, 2019; Wurstsbaugh 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; Wurstsbaugh et al., 2019). Meanwhile, restoring coastal wetlands such us swamps, seagrass beds and mangrove forest 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-tropic aquaculture (IMTA) practices (Hughes, 2021; Soto 2009). These could include algae for phytoremediation and/or invertebrates as polyculture 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 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.

Acknowledgement

This research was funded by a Master Program of Education Leading to Doctoral Degree for Excellent Graduates (PMDSU) Scholarship from The Ministry of Research, Technology, and Higher Education (grant number SP DIPA-042.06.1.401516/2018). We would also like to thank the Marine Science and Fisheries Faculty of Hasanuddin University for in-kind support.

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