

Seasonal variation in the behavior of tailing waste in the southern coastal sea of Sumbawa Island, Indonesia

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Abstract—Seasonal variations of temperature, salinity and sigma-t were observed in the southern coastal sea of Sumbawa Island, Indonesia, related to the dumping activity there. The area of concern is influenced by a tropical monsoon climate with high rainfall from December to February, and an extended dry season from June to September. It was observed that the mixed layer depth (MLD) during January was about 110 m, and that during April around 105 m and that during July and December were around 60 m and 80 m, respectively. MLD variation was closely related to Mean Sea Level (MSL) variation with a negative correlation (MSL rising corresponding to MLD deepening). Moreover, tailing plumes were observed at 150 m depth, then the tailing sank to 3000–4000 m (Java Trench), but a part of them stayed at 150–200 m depth. Distributions of tailings above the bottom showed that seasonal variation of currents played an important role in the spreading of the tailings over the area. In addition, it is recommended that the outlet of discharging pipeline must be below the pycnocline, not at 108 m but 200 m depth.

Key words: Sumbawa Island, dumping, monsoon, downwelling

Introduction

Sumbawa Island, one of the Lesser Sunda Islands which are composed of Bali, Lombok, Sumbawa, Flores, and Sumba, is located in the province of West Nusa Tenggara, the eastern part of Jakarta, Indonesia (Fig. 1). In the southern part of this island, the coastal sea connects to the Indian Ocean. The island and seas are influenced by a tropical monsoon climate with high rainfall during the northwest monsoon (December to February), and an extended arid season during the southeast monsoon (June to September). The character of the tropical monsoonal climate influences the surface currents there because of the change in the prevailing winds.

As part of Indonesian seas, the southern coastal sea of Sumbawa Island is a conduit for the inter-ocean flow of tropical water from the Pacific Ocean to the Indian Ocean, that is, the Indonesian throughflow. The Indonesian throughflow is driven by the Pacific-Indian Ocean pressure gradient, confined to the upper 200 m, with large seasonal and inter-annual variabilities in transport, which are related dynamically to the monsoon winds. The Indonesian throughflow is strong during the southeast monsoon, June to August, and weak during the northwest monsoon, December to February (Gordon et al. 1994).

Regarding to Field et al. (1991, 1996), within the com-

plex pathways towards the Indian Ocean the surface and thermocline waters are of North Pacific origin flowing through the Makassar Strait, while lower thermocline and deeper water masses are of South Pacific origin delivered through more eastern routes. Most of the Indonesian throughflow passes through the Banda Sea where strong vertical mixing modifies the thermocline/pycnocline by transferring surface heat and freshwater to deeper layers before the upper water column is exported to the Indian Ocean via Timor Strait, Ombai Strait and southern coastal sea of Sumbawa Island.

According to Bray et al. (1996), the pycnocline depth (which can be denoted to thermocline depth) is about 120 m near the study area throughout the year. Seasonal variation of the upper layer depth had negatively correlated with the mean sea level. Mixed Layer Depth (MLD) is deeper when the mean sea level (MSL) is higher. The MLD deepening relates to the thermocline/pycnocline deepening as well, so that the MSL rising corresponds to the thermocline/pycnocline deepening. This phenomenon is mainly due to winds blowing and the details will be discussed in the next sections.

Regarding to the previous research that covered the study area of concern, Sachoemar and Yanagi (2002) showed that during the southeast monsoon in July with an intensified strong alongshore southeasterly wind, upwelling indicated by low sea surface temperature, high salinity and high nutrients began to develop in the southern part of Bali-Lombok.

Tailing waste with total amount of about 110,000–

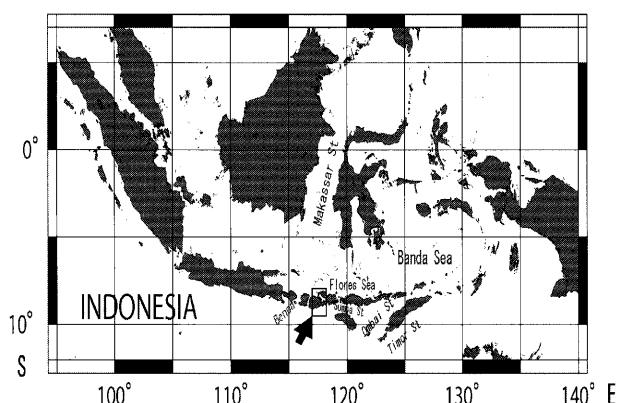


Fig. 1. Indonesia Archipelago and the Sumbawa Island which is shown by an arrow.

120,000 metric tons produced every day that are resulted from mining activity, is dumped beneath the sea through the pipeline from the coast along the floor of the continental shelf to 108 m depth (Fig. 2a). The company assumed that the 108 m depth is below the seasonal pycnocline. Then, it is estimated that the tailing would sink to the lower layers until 3000–4000 m depth due to the heavier density of the tailing (1.336 kg/m^3) compared to the sea water density (1.025 kg/m^3).

The tailing waste is in the form of mud. Tailings are resulted from the grinding of the mining sediments to separate gold and/or other precious metal from sedimentary rock. Tailings contain various metals including toxic metal (mercury, arsenic, manganese and others) which would endanger to marine life when they are exposed to the marine environment. It was reported by local media that dead fishes were found nearby the location of the discharging waste; however, it is not clear yet whether it was caused by tailing waste or by crude oil from tankers that passed the passages.

The present research was undertaken in order to understand the influence of the seasonal variability of ocean environment at the dumping site on the fate of the waste there. Discussion on temperature, salinity and sigma-t for seawater movement, on light transmittance related to detecting tailing plumes are conducted.

Observations

The observations were carried out at 11 stations (Fig. 2a) in the study area during January (which represents rainy season), April (transition), July (dry season) and December (rainy season) 2003 and at station 9 every month from January to December 2003 as a control. The bathymetry of the observation area (Fig. 2b) ranged between 25 m and 400 m and station 9 is the deepest station. The data were obtained by using a CTD (Conductivity, Temperature and Depth profiler) for the vertical profiles of water temperature, salinity and light transmittance. Sigma-t and geostrophic current were calculated from water temperature and salinity using

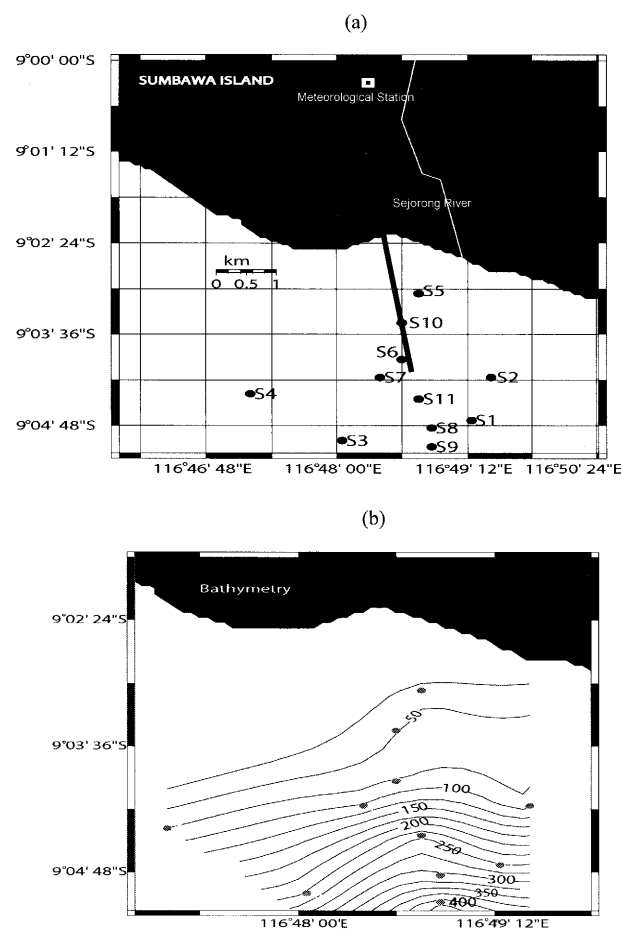


Fig. 2. (a) Observation stations. The thick line across the stations shows the pipeline of the tailing waste. (b) Bathymetry. Numbers in figure show the depth in meters.

the usual state equation and dynamic calculation. Chemical data of dissolved arsenic were obtained by analyzing water samples at various depths (at the surface, middle and bottom) which were withdrawn from Niskin bottles and analyzed by using spectrophotometer.

Meanwhile, monthly mean wind data and solar radiation data were obtained from NOAA-CIRES climate diagnostics center (<http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml>) which covers the study area of 115° – 118° E and 9° – 11° S. River discharge data from Sejong River were got from the meteorology station nearby the study area (See Fig. 2a). In addition, mean sea level data at Benoa-Bali were obtained from National Coordinating Agency for Surveys and Mapping, Indonesia (Fig. 1).

Results and Discussion

Temperature

Seasonal variation of sea surface temperature (SST; Fig. 3) shows that SST was highest (29.0°C) in January and lowest in April (24.2°C). SST in July (25.6°C) was slightly

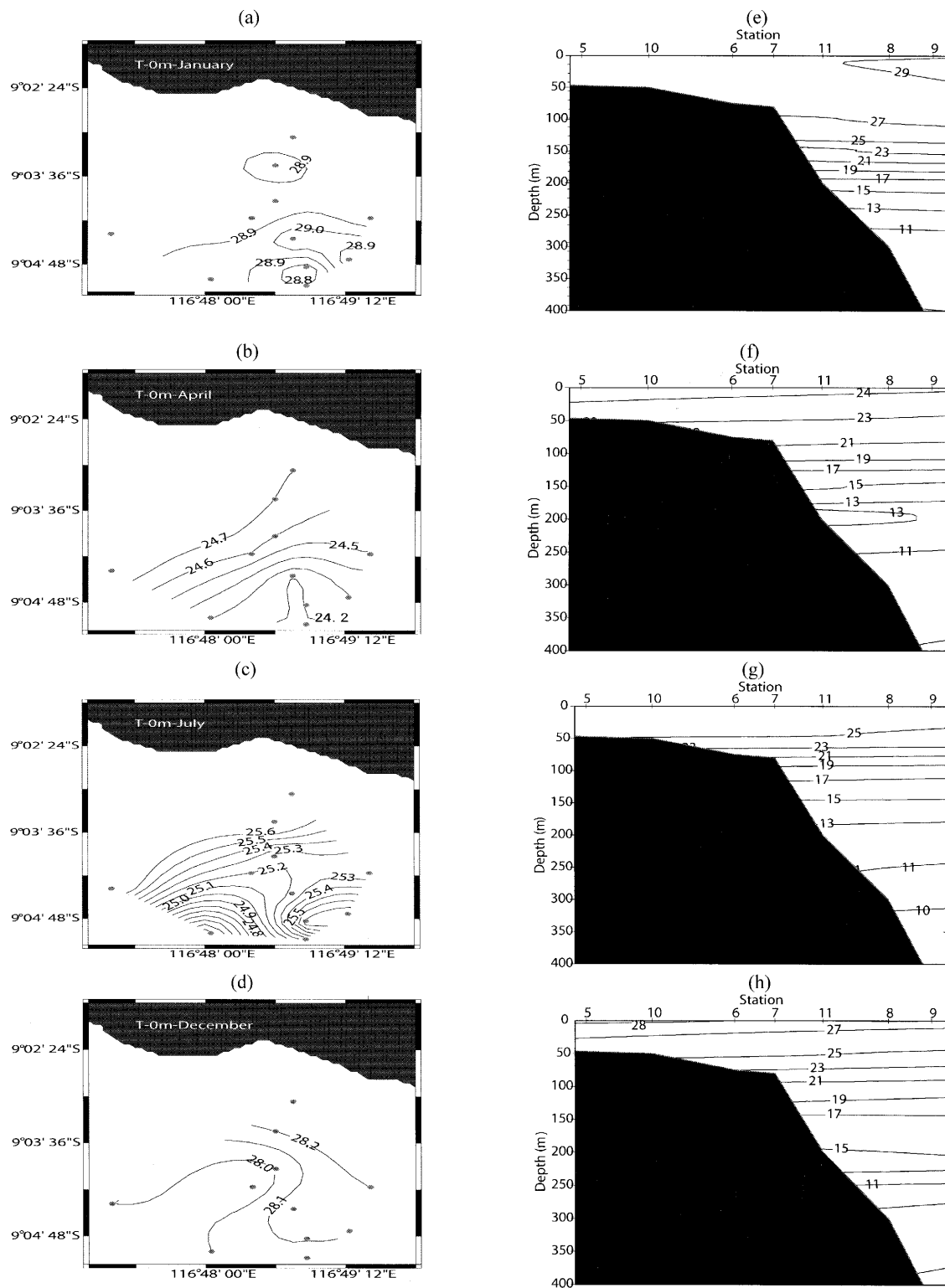


Fig. 3. Left column: horizontal distributions of sea surface temperature in (a) January, (b) April, (c) July and (d) December 2003. Right column: vertical distributions of temperature in (e) January, (f) April, (g) July and (h) December 2003.

higher than that in April, but lower than that in December (28.2°C). The seasonal variation of SST was not related to the solar radiation shown in Fig. 4, because solar radiation in January, April, July and December was nearly the same. Furthermore, horizontal distributions of SST reveal the pattern

with higher SST toward the land and lower SST toward off-shore.

The value of temperature in the lower layer exhibits that water temperature at 100 m depth was approximately 27°C, 20°C, 18°C and 20°C in January, April, July and December,

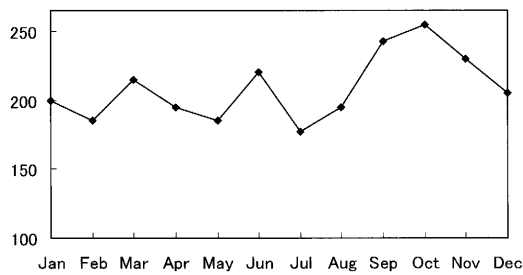


Fig. 4. Monthly mean solar radiation at (Sumbawa Island) 115–118°E and 9–11°S obtained from NOAA-CIRES climate diagnostics center in 2003.

respectively (Fig. 3e–3h). It is interesting that water temperature in July had lower value compared to those in other months at the same depth (100 m). While at 300 m depth, the value of temperature was similar in all months, i.e. approximately 10°C.

It was shown by several scientists (Sachoemar and Yanagi, 2002, Purba, 1995, Schalk, 1987, Wyrтки, 1961) that during the southeast monsoon (June–September) upwelling events occur in some regions of Indonesian waters, including the southern coastal sea of Sumbawa Island where SST reached 25°C. The reports mentioned that upwelling occurrence began to develop in July though this phenomenon was not clearly observed in the upper layer from the vertical distributions of water temperature in the present research (Fig. 3g).

An intensified eastward wind parallel to the coastline in the southern hemisphere could generate a downwelling phenomenon. This results in the Ekman transport towards the coast (left hand side of the wind direction in the southern hemisphere) to pump underlying layers downward. A little downwelling event was clearly identifiable in the present research as shown in Fig. 3h during December with an indication of downward isotherms toward the coast in the upper layer.

Salinity

Sea surface salinity (SSS) distributions in the study area (Fig. 5a to 5d) were in the range of 32.0–34.5 psu. SSS was highest in December (34.38 psu) followed by July (34.1 psu), April (33.3 psu) and lowest in January (32.4 psu). The lowest SSS in the region nearby the coast during January was corresponding to the freshwater discharge from river shown in Fig. 6. SSS values are still in the range that were observed by previous scientists, e.g., Tomascik et al. (1997) mentioned that SSS in Indonesian waters ranged between 31.20–34.50 psu. While, Wyrтки (1962) reported that the maximum SSS in the region of concern in the period of 1950–1955 was 34.8 psu and minimal reached 32.5 psu.

Vertical distributions of salinity can be quite variable. The salinity distributions in January and April were highly stratified compared to those in July and December (Fig. 5e to

5h). The value of salinity at 100 m depth was 33.8 psu, 33.9 psu, 34.2 psu, and 34.4 psu in January, April, July and December, respectively. While, at 300 m depth the value of salinity was approximately in the range of 34.4 psu to 34.6 psu. It is shown that July has high salinity compared to January and April, though December is the highest.

SSS increased toward offshore in January and April and westward during December and July. It suggests that the freshwater from river had diffused SSS in January. The value of SSS in December was very high. Regarding to this occurrence, Wyrтки (1961) mentioned that during the northwest monsoon the Subtropical Lower Water (SLW), which is Indian Ocean origins with characteristic of high salinity up to 34.6 psu, was traced nearby the study area as well as at the entrance of the Timor and Sawu Seas. Due to the existence of SLW, salinity in the upper layer was nearly the same as shown in the present research of Fig. 5h. Based on T–S diagram shown in Fig. 7, January, April and July had the similar patterns but December had an exception with no salinity maximum or minimum, that is, the salinity was practically almost constant from the surface to 400 m depth only varied between 34.45 and 34.60 psu. It suggests that during January, April and July, water mass from the Pacific Ocean passed through the study area, while in December water mass was from the Indian Ocean.

In addition, Hautala (2001) found that in December 1995 the South Java Current might penetrate to the Banda Sea farther eastward. It was observed that the eastward boundary current velocity reached 1 m/s at 25 m and 0.48 m/s at 145 m. These arguments are in accordance with the present result shown in Fig. 8d which exhibits that the geostrophic flow was eastward in December 2003.

Sigma-t

Since the density of sea water depends on temperature and salinity, all processes that alter the temperature or salinity influence the density. At the surface, the density decreases by heating and increases by evaporation. The value of sigma-t of the study area was in the range of 22.0–23.55 at the surface, and 26.9–27.5 at 300 m depth (Fig. 9).

The value of sigma-t in the surface layer was highest in April (23.55) followed by July (23.25), December (22.40) and January (22.08). April and July had heavier seawater than December and January due to lower SST properties. Temperature had given a significant effect to the density compared to salinity in the study area. Increasing seawater temperature would decrease seawater density and vice versa.

Horizontal sigma-t distributions (Fig. 9a to 9d) showed that sigma-t was higher towards the centre of the study area from the coast and offshore in January and July, towards offshore in April and December. It could be estimated that geostrophic currents would flow westward near the coast in January, north eastward in April and July, south eastward in

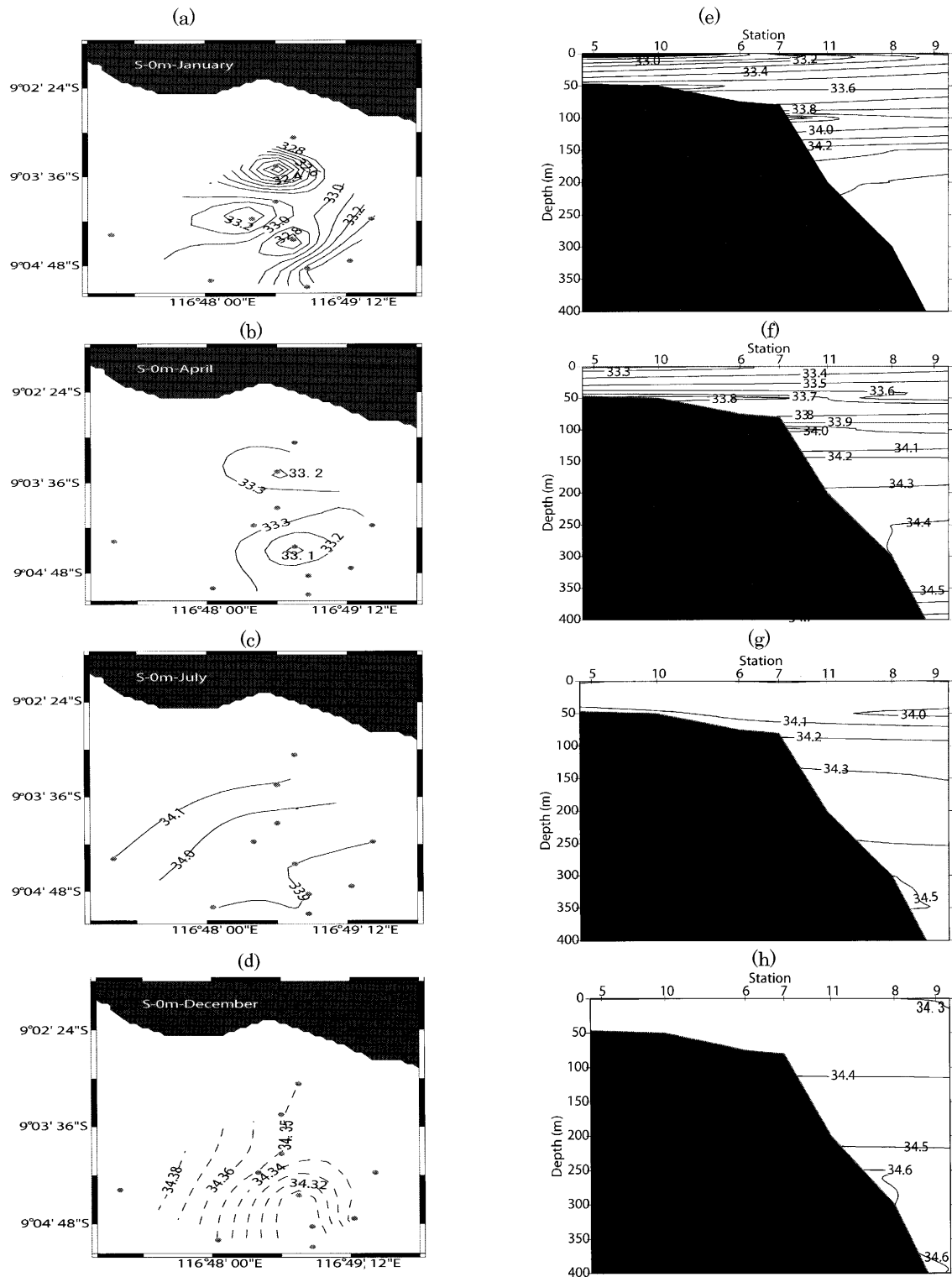


Fig. 5. Left column: horizontal distributions of salinity in (a) January, (b) April, (c) July and (d) December 2003. Right column: vertical distributions of salinity in (e) January, (f) April, (g) July and (h) December 2003.

December.

Mixed layer depth

The homogenous layer or mixed layer depth (MLD) has been defined in literatures by a number of criteria, depending on some particular, objectively prescribed degree of homo-

geneity of the mixed layer properties. The simplest and the most traditional method is the temperature difference (relative to the sea surface) which varies from 0.02°C to 1°C. Levitus (1982) used the vertical gradient of 0.006°C m⁻¹ to 0.1°C m⁻¹ or the maximum curvature in temperature profile. However, the most trustworthy way in defining the MLD is

by using the density difference (or its gradient) which should result from the combined temperature and salinity effects on vertical stratification. In this regard, Levitus (1982) suggested that the density difference criteria vary from 0.01 to 0.125 m^{-1} , while Price et al. (1978) proposed 0.02 m^{-1} . But, 0.03 m^{-1} will be applied in the present research which yields the most satisfactory results that suit to the sigma-t curves in the study area (Figs. 10 and 11).

Having made analysis based on the 0.03 m^{-1} criterion, the MLD in the study area was about 110 m in January, 105 m in April, 60 m in July, and 80 m depth in December (Figs. 10 and 11). We investigated the monthly variation of MLD at station 9, which shows that MLD in February, March, May, June, August, September, October and November

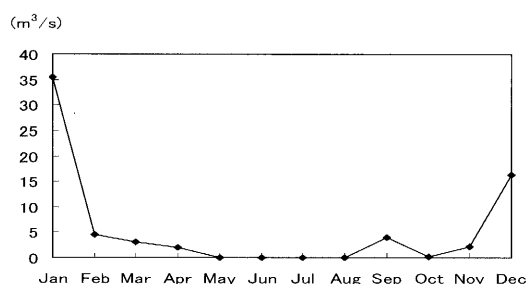


Fig. 6. River discharge of Sejorong River from meteorology station at Sumbawa Island in 2003.

was around 105 m, 105 m, 100 m, 80 m, 50 m, 50 m, 60 m and 65 m, respectively (Fig. 12).

Regarding to Fig. 12, the annual range of the mixed layer temperature variation was about 4°C , with the highest temperature (28.0°C) in January to March and the lowest one (24.0°C) in April. The mixed layer salinity varied with the highest salinity 34.3 psu in December and the lowest one (33.4) in April. Hence, the saltiest water in the mixed layer appeared in December, while the freshest one in April on av-

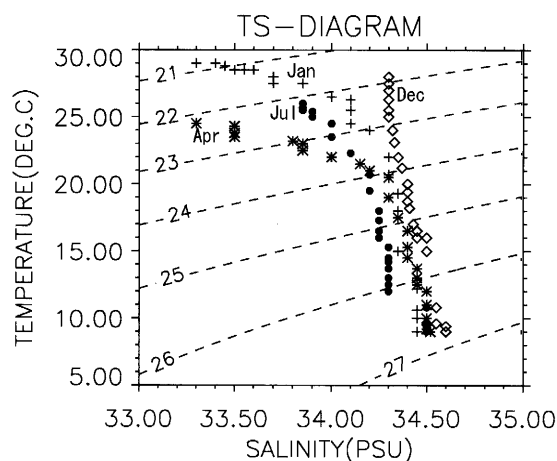


Fig. 7. Temperature-Salinity Diagram at Station 9 in January, April, July and December 2003.

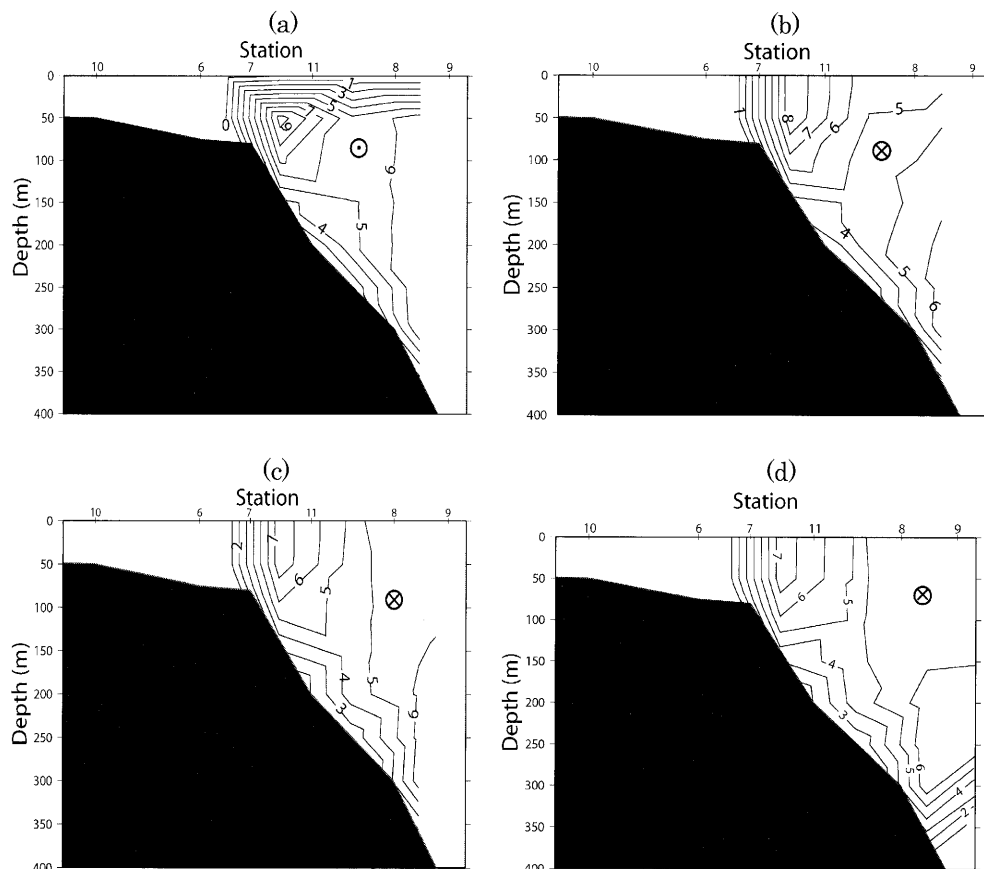


Fig. 8. Vertical distributions of geostrophic current in (a) January, (b) April, (c) July and (d) December 2003. Circle with dot means out of paper and circle with cross means into paper.

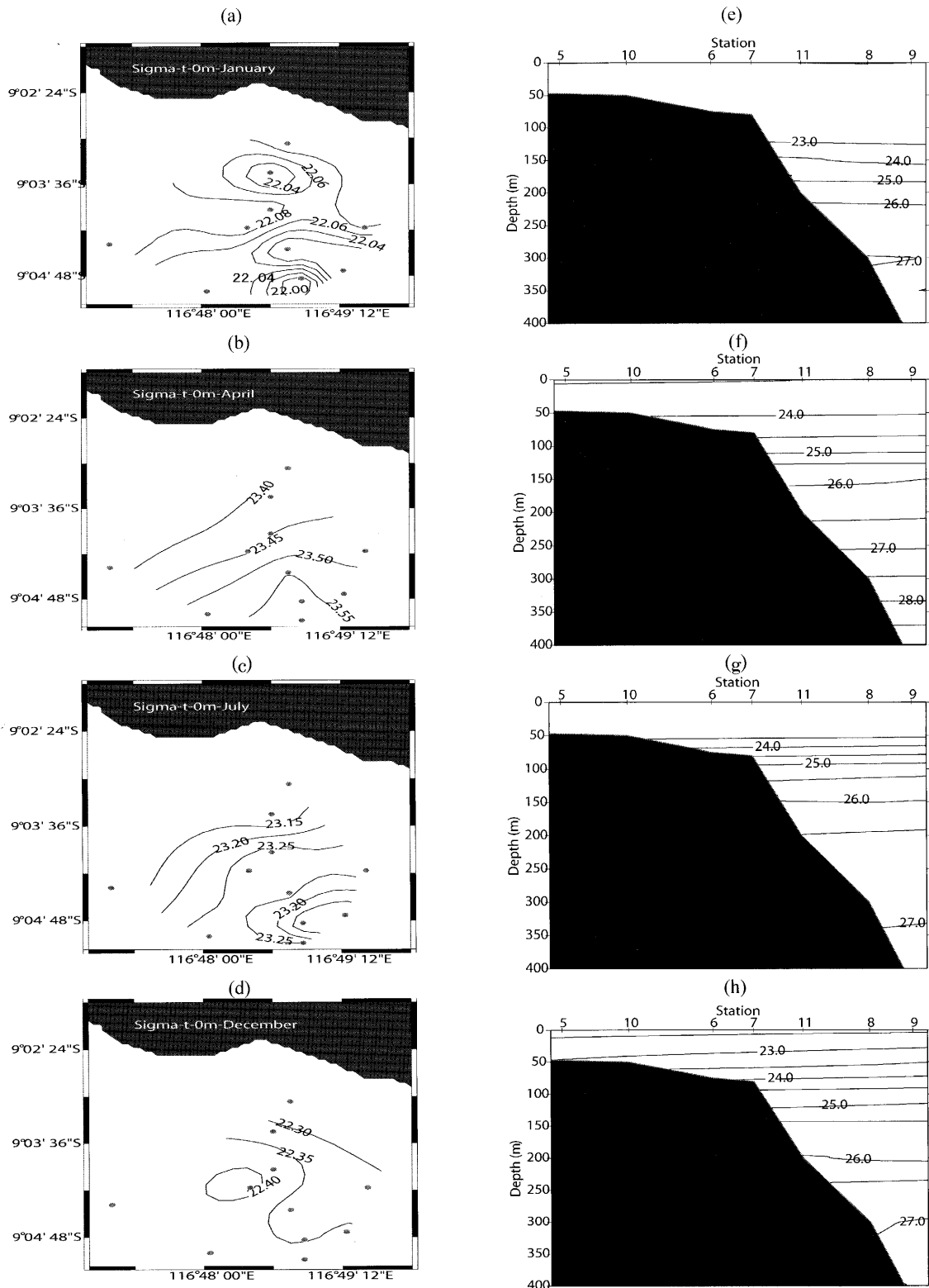


Fig. 9. Left column: horizontal distributions of sigma-t in (a) January, (b) April, (c) July and (d) December 2003. Right column: vertical distributions of sigma-t in (a) January, (b) April, (c) July and (d) December 2003.

erage. Meanwhile, sigma-t showed a little variation in the mixed layer during a year with the highest in April (24.0) and the lowest in October, November and December (23.0). Furthermore, it is noticed that the patterns of temperature and

density were similar. It indicates a big influence of temperature compared to salinity in defining sigma-t value.

Below MLD, pycnocline existed at 110–200 m in January, 105–150 m in April, 60–140 m in July and 80–140 m in

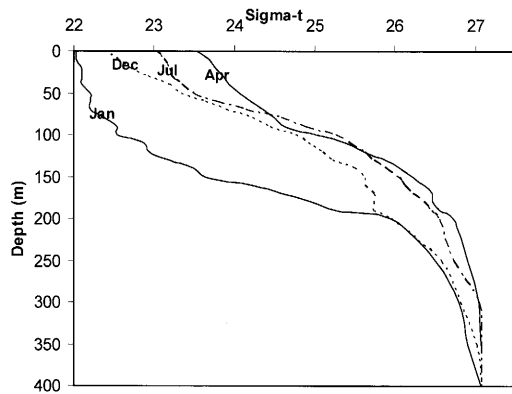


Fig. 10. Profile of sigma-t at Station 9 in January, April, July and December 2003.

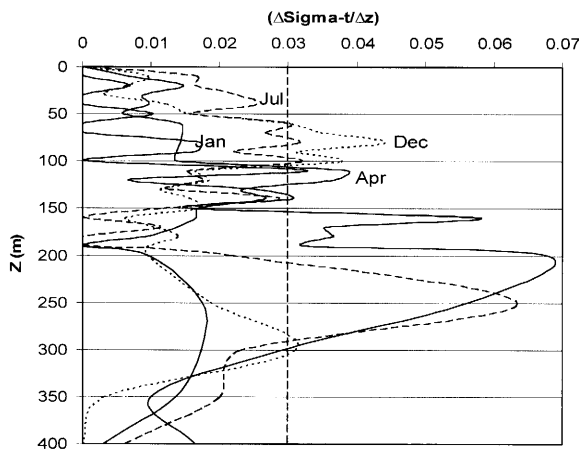


Fig. 11. Sigma-t gradients at Station 9 in January, April, July and December 2003.

December as shown in Fig. 10. Below the pycnocline, deep water, where the density is almost constant, was observed (Figs. 10 and 12). The existence of pycnocline has been utilized by the mining company to define the depth of tailing waste pipeline, which must be below the pycnocline, because the mining company has an assumption that the tailing waste sinks to deeper depths due to its density properties. As well, it is believed that tailing waste discharged below the pycnocline would not upwell to the upper layer or surface layer due to the stability of this layer. It would be very hard to displace a particle in water up or down across the pycnocline. We observed that the upper limit depth of pycnocline was at 110m in January 2003. While, the outlet of tailing wastes is at 108m. Hence, tailing waste would be mixed in the upper layer in January as it would be discussed in the next paragraphs. The tailing waste would expose heavy metals to food chain because fish ingest tailing particles or take up leached metals through their grill membranes. In addition, the tailing waste also increases turbidity and inhibits photosynthesis by reducing the amount of light that penetrates into the water column.

According to the wind data (Fig. 13), wind velocity

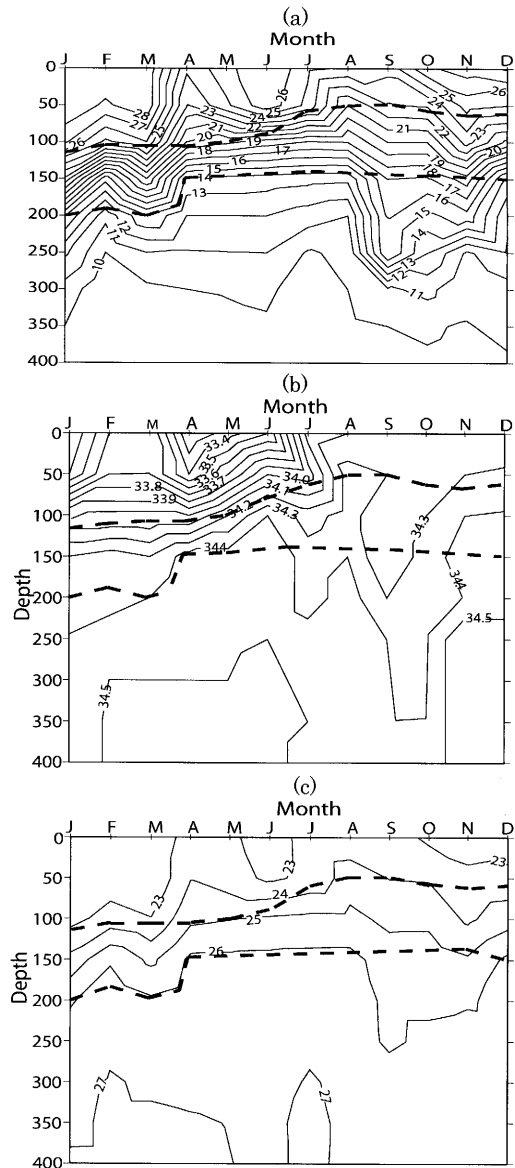


Fig. 12. Monthly vertical distributions of (a) temperature, (b) salinity, and (c) sigma-t at Station 9 in 2003. The broken lines indicate upper and lower limits of pycnocline layer.

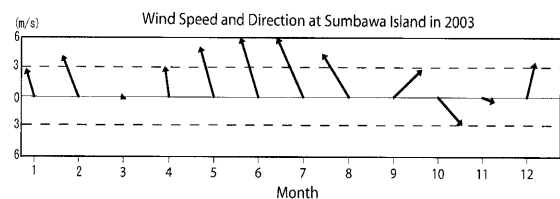


Fig. 13. Monthly wind speed and direction at (Sumbawa Island) 115–118°E and 9–11°S obtained from NOAA-CIRES climate diagnostics center in 2003.

reached 3 m/s in January and April, while 6 m/s during July and 3.2 m/s during December and between 0.5 to 6 m/s in the remaining month. There is no relationship between MLD and wind velocity in the study area because January had deepest mixed layer depth with weak wind velocity. The seasonal

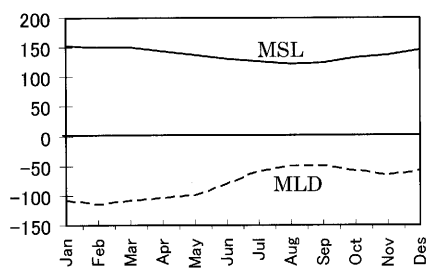


Fig. 14. Mean Sea Level (MSL) in centimeter at Benoa-Bali and Mixed Layer Depth (MLD) in meter at Station 9 during 2003.

variation of MLD has negatively correlated with the mean sea level (MSL). Mixed Layer Depth (MLD) is deeper when the mean sea level (MSL) is higher. The MLD deepening relates to the thermocline/pycnocline deepening as well, so that the MSL rising corresponding to the thermocline/pycnocline deepening (Fig. 14). Correlation coefficient of 91% in Fig. 14 indicates that the linear relationship between MSL and MLD is quite strong. January had a highest MSL and a thickest MLD followed by April and December, while July had the lowest and thinnest ones.

These phenomena are due to winds blowing westward during the southeast monsoon in Indonesian waters. During this monsoon, in Indonesian waters such as in the southern coast of the Java to Sumbawa, the waters were cooled by the Ekman induced upwelling. Thus, the shallower MLD during the southeast monsoon in the study area adjacent to Indian Ocean was due to the monsoonal winds that generate upwelling there. Reversely, during the northwest monsoon in Indonesian waters, winds blowing eastward which leads to an increase of mean sea level along the southern coastal sea of Sumbawa Island due to the downwelling and accumulation of warm surface water mass along the southern coast of Java to Sumbawa Islands.

Light transmittance

Low light transmittance (LT) corresponding to high particulate concentration in the seawater can be used to track the tailing waste plume. The lower light transmittance is the higher particulate concentration and vice versa.

According to Fig. 15e, low concentration of particles as shown at surface was observed. It is not clear yet whether the particles were from the mining activities that might leak to the Sejong River or from river-borne-natural particles. However, these particles did not sink to the pycnocline layer, but only dispersed at surface because LT was high between surface and pycnocline layer at about 100 m (Fig. 15e).

Horizontal distributions of LT near the bottom of the shelf from 40 m to 400 m were analyzed as shown in Figs. 15a to 15d, where gray zone indicates high concentration of tailing waste ($LT < 40\%$) and broken lines with dots are low concentration of tailing waste ($40\% < LT < 80\%$).

High concentration of tailing waste was spreading up to

225 m depth and the highest between 300 and 400 m depth ($LT = 10\%$) in January. However, the high concentration of tailing waste extended over a little further eastward and westward up to 250 m in April, reached 275 m depth in July, whereas the highest ($LT < 20\%$) was between 300 and 400 m depth. Furthermore, the high concentration of tailing was distributed between 300–400 m depth in December.

Vertical distributions of LT are shown in Figs. 15e to 15h. Low concentration of tailing waste extended up to 100 m depth over the study area in January. However, the low concentration of tailing waste spread to 175 m in April, reached approximately 200 m depth in July. In addition, the low concentration of tailing was distributed until up to 180 m depth in December. It is clear that the close relationship exists between MLD and spreading of tailing waste as shown in January, where the outlet of pipeline (108 m) above MLD (110 m) made very fine particles of tailing to extend vertically up to 100 m. Fortunately, the tailing waste was not coming up to the surface due to the density property of the tailing waste. This phenomenon was not occurred in other months because of the outlet of pipeline below MLD.

Vertical distributions of tailing waste were characterized by thicker and thicker with increasing depths as shown in Figs. 15e to 15h. It is shown that large river discharge (Fig. 6) contributed to enrich particulate concentration at the surface layer as indicated with low LT in January as shown in Fig. 15e. Because of the existence of pycnocline which prohibits the water movement vertically upward from the lower layer, no vertical mixing was generated in April, July and December. Moreover, high LT (90%) was observed in the upper layer up to 210 m in July, 160 m in April, 150 m in December and about 100 m in January.

Having analyzed further on the behavior of tailing waste related to oceanographic condition in the study area, it was observed that tailings extended over the area followed current direction in the lower layer (275–400 m) as shown in horizontal distributions of tailing waste near the bottom (Figs. 15c and 15d) during the southeast monsoon (July and December). High concentration of tailing waste spread eastward following the current direction and went further following the bottom contour downwards (Figs. 15g and 15h) as it is in line with the direction of geostrophic current in the study area (Figs. 8c and 8d).

Dissolved arsenic distribution

Dissolved arsenic is the only element that can be detected properly in depths among various elements that were sampled and analyzed in this research such as Cd, Cr, Mn, Pb, Cu, Hg, Se, Ag and Zn. The high dissolved arsenic concentration during January was in good agreement with the tailing waste concentration in the same month that was higher compared to July and October as shown in Fig. 16. Dissolved arsenic concentration at 50–250 m depth was be-

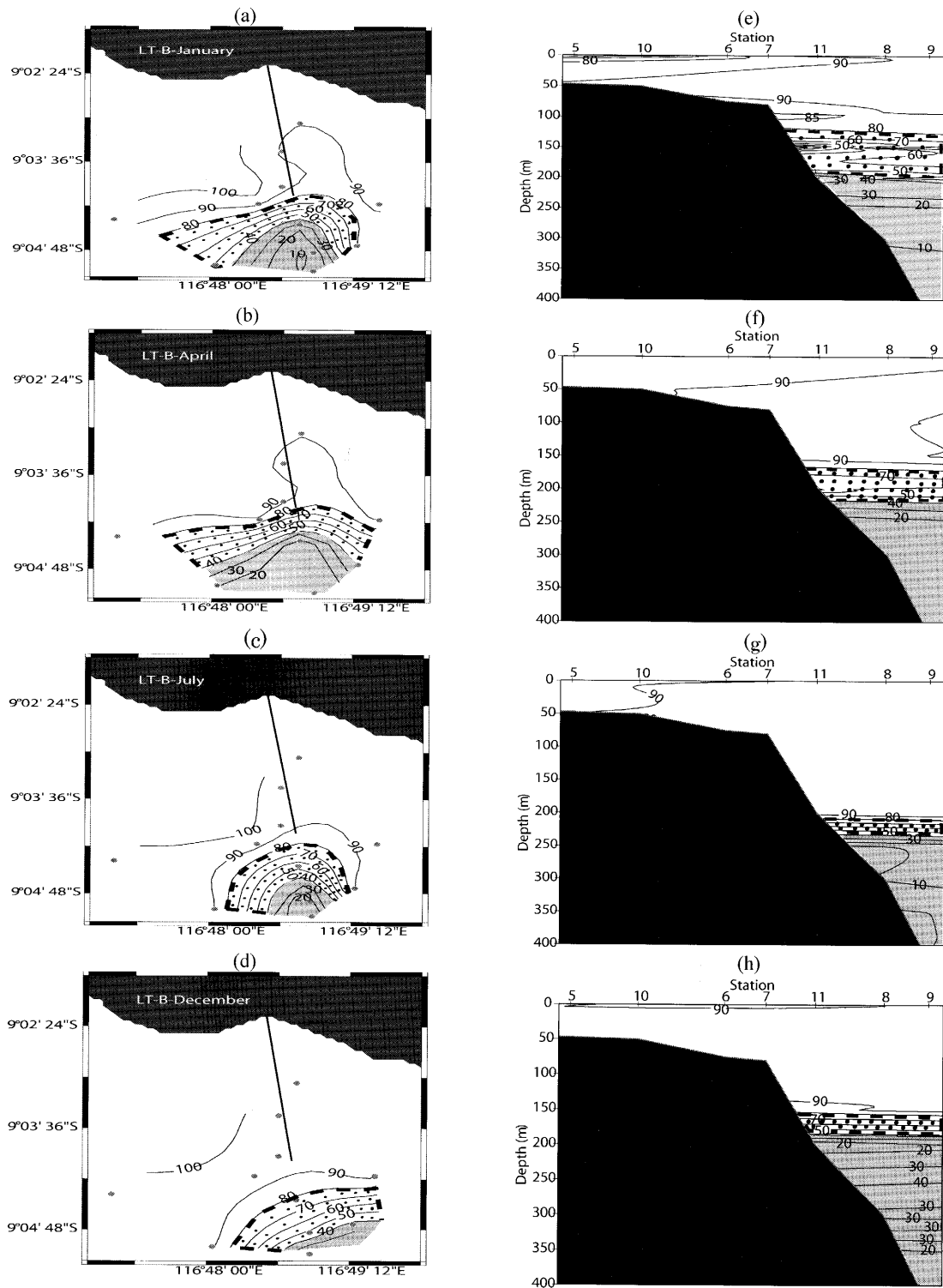


Fig. 15. Left column: horizontal distributions of light transmittance near the bottom in (a) January, (b) April, (c) July and (d) December 2003. The thick line across the stations shows the pipeline of the tailing wastes. Right column: vertical distributions of sigma-t in (e) January, (f) April, (g) July and (h) December 2003.

tween $20\text{--}22 \times 10^{-4}$ mg/l in January, $6\text{--}11 \times 10^{-4}$ mg/l in July and $12\text{--}14 \times 10^{-4}$ mg/l in October. Even though these concentrations are still below the maximum allowable value that is permitted by the Republic of Indonesia law (0.01 mg/l), this information is useful to support the event in January

2003.

According to Ng et al. (2001), concentrations of dissolved arsenic are typically low ($1\text{--}2 \times 10^{-3}$ mg/l) in the open ocean. While, in rivers and lakes, concentrations are somewhat higher but generally below 10×10^{-3} mg/l. Exceptions

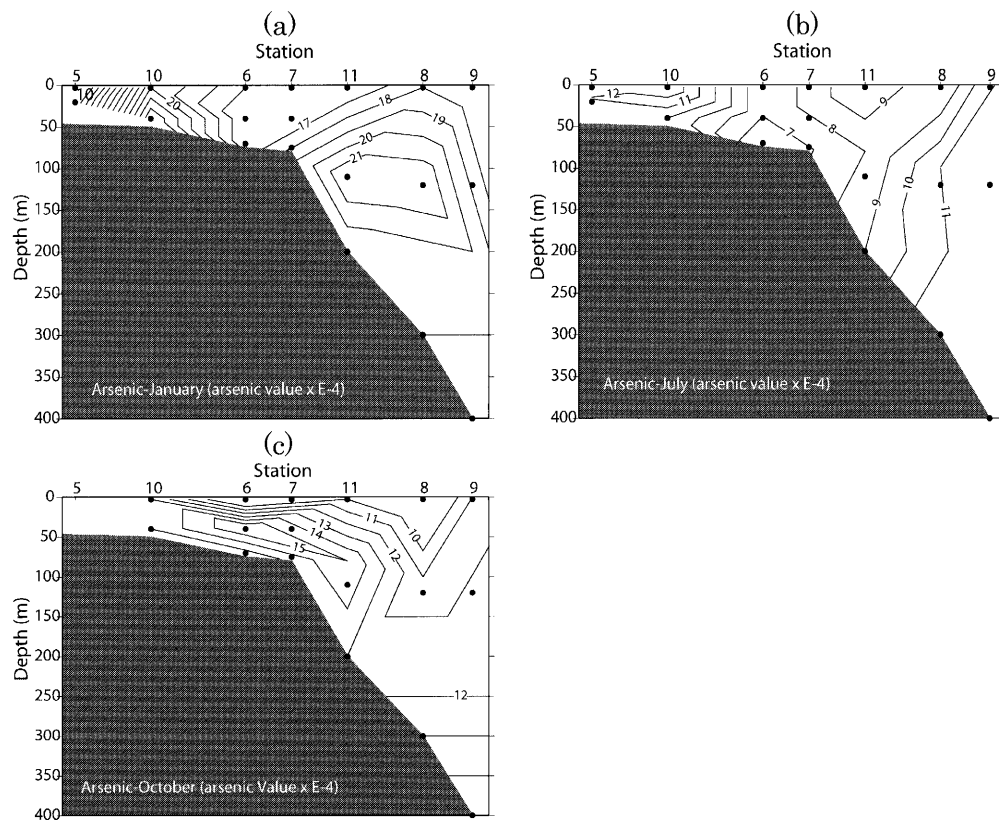


Fig. 16. Vertical distributions of dissolved arsenic in January, July and October 2003. Dots indicate water sampling depth.

are near man-made sources such as pesticide manufacturing or mining, where individual samples in surface waters may be 1000 times higher (up to 5 mg/l).

Conclusion

The seasonal variations of SST in the southern coastal sea of Sumbawa Island showed that January has the highest followed by December, July and April. On the other hand, SSS was the highest in December followed by July, April and January. Sigma-t distributions in the southern coastal sea of Sumbawa Island were largely influenced by temperature than salinity. The value of sigma-t was highest in April followed by July, December and January.

It is found that during the year 2003 low tailing concentration distributions reached up to 100 m (LT=70%) in January, whereas the highest tailing concentrations were on 300 m to 400 m in all months. The end of pipeline of discharging tailings is at about 108 m. It means that a part of very fine tailings, which are dispersed in seawater, mixed vertically up to 100 m as it was in the mixed layer during January 2003. However, the tailing waste did not show up at the surface due to its density property. Furthermore, the distributions of tailings below 200 m (the lower limit of pycnocline layer) followed the seasonal variation of geostrophic currents there.

The tailing waste extended over the area up to 100 m

depth and a part of them stayed at 150 m to 200 m and mostly sank to 3000 m and 4000 m depth. The fate of tailings below the lower limit of pycnocline can be estimated through seasonal variation of current directions. It is proposed that besides temperature, salinity, and light transmittance data, as well, the current data nearby the dumping site are necessary. Moreover, it is also strongly recommended that the outlet of discharging pipeline must be below the pycnocline (not 108 m but 200 m) to refrain from vertical mixing of very fine tailings which are dissolved in seawater.

In addition, considering the accumulation of dumped-waste-derived contaminants in the deep sea bottom is still in the area of continental shelf, where marine organisms live in, the research on the bottom sediments are strongly recommended. The contamination of bottom sediment possibly influences the benthic ecosystem so that a further observation must be conducted either by the government or by the mining company to search for the impact of the accumulation of tailing waste to the benthic ecosystem.

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