Journal of the Korean Society of Oceanography
Vol. 33, No. 4, pp. 168—177, December 1998

Environment Analysis of Kwangyang Bay after the Keumdong Oil Spill

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Five and a half months after the Keumdong oil spill accident on the 21st of September 1993, 34 seawater samples and 94 sediment samples were collected from Kwangyang Bay and Namhaedo area to assess its environmental impacts. Hydrocarbon concentration in the seawater ranged from 0.8 to 9.2 μg/l with an average of 3.3 μg/l. This average value was nearly the same as the value (3.7 μg/l) before the oil spill accident. This suggests that by the early March of 1994 majority of the coastal water in the study area restored to its background hydrocarbon concentration before the oil spill accident. Nutrients, heavy metals and other general environmental parameters of the seawater did not show any aggravated seawater quality compared with the previous records. From the regression analysis of time-course observation of hydrocarbon in the seawater, except the sediment environment, the effect of oil spill on the water column was estimated to last at least 4 months in the study area after the oil spill accident. In the shoreline sediments, oil deposits were, however, still found at the high water marks at several stations, and very high values were found in the west of Namhaedo, ranging from 3.7 to 40.1 mg/g of wet sediment. Gas chromatography of these samples showed a very distinct Bunker C chromatogram identical to the Keumdong oil spill. Hydrocarbons in the subtidal bottom sediments in the study area and the reference stations (YB and CB) ranged from 0.45 to 18.08 μg/g of wet sediment with an average of 3.09 μg/g. West of Namhaedo (Stations B12-B33) generally showed much higher values than inner Kwangyang Bay and in Chinju Bay. Chinju Bay generally showed the lowest value among the study area. Subtidal bottom sediments in inner Kwangyang Bay and Chinju Bay seemed to be less affected than west of Namhaedo. Heavy metal concentrations in the sediment were relatively higher in the Kwangyang Bay than in the Chinju Bay. However, metal concentrations in the study area were in general comparable to the reference areas.

INTRODUCTION

In Korea, oil spill accidents are recently increasing in terms of volume, and most of coastal areas are experiencing oil pollution at least every several years. Because most of coastal waters are densely occupied by aquaculture farms and by economically important fisheries business, there always exist conflicts on the compensation for the devastated fisheries business by oil spill accidents. Especially in the southern coast of Korea, fisheries mariculture business has been historically one of the major business in this local economic community. Recent establishment of coastal industrial complex and reclamation activities near the Kwangyang Bay area in favor of local socioeconomic development have aggravated the situation because increased shipping activity and vessel traffic pose a potential threat to oil spill accidents. Unpreparedness of local administrative organizations and fisheries industries for dealing with such accidents often renders them to catastrophe. The Keumdong oil spill accident happened with this sociogeographical background, and it is recorded as one of the biggest claims (about 100 million US$) in Korean coastal waters despite the small volume of oil spill.

The oil spill accident occurred in coastal waters around Namhaedo and Yeosupando covering about 300 km^2. On the 27th of September 1993, a Chinese-registered cargo carrier collided with a Korean-registered bunker barge *Keumdong No. 5* about 3 km south of the Kwangyang steel complex. She lost about 1200 metric tons of Bunker C, and oil slick rapidly spread over 200 km^2 within 4 days. The study area polluted by the oil spill can be largely divided into three sub-regions: Kwangyang Bay, Yeosu Bay tidal channel running north to south between Namhaedo and Yeosupando, and Chinju Bay. In the study area, north easterly wind dominates during autumn, and average annual wind velocity is 4.0 m/s (POSCO, 1983). Vertical structure of density (σ_t) shows poor stratification and water column is vertically well mixed. The study area can be characterized as mesotidal area. Tidal amplitude at Yeosu Harbor ranges from 3.0 m at spring tide and 1.1 m at neap tide with its average value about 2.0 m. However tidal amplitude at spring tide increases from 3.0 m to 3.2 m toward Kwangyang Bay. Maximum tidal current at spring tide ranges from 52 cm/s in Kwangyang Bay to 59

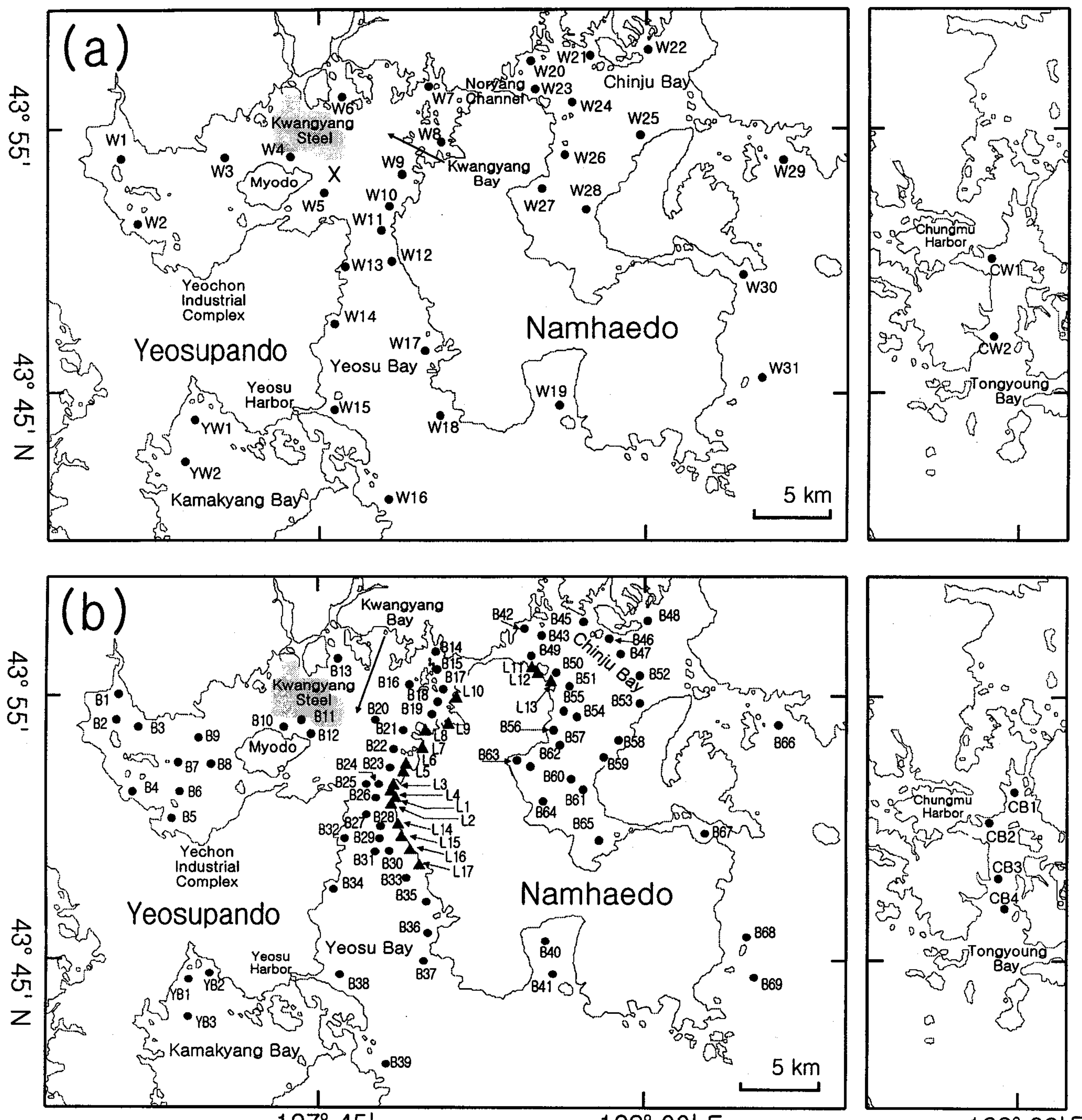

Fig. 1. Map showing sampling stations for seawater (**a**) and sediment (**b**) in the study area (March 1994). The mark 'X' denotes the location of the Keumdong oil spill accident.

cm/s in Yeosu Bay and it ranges from 17 to 21 cm/s at neap tide, respectively. Tidal wave propagates from Yeosu Bay tidal channel to Myodo and Noryang channel (Fig. 1a). Tidal wave propagation in inner Kwangyang Bay (west of Myodo) lags 20 minutes behind compared with tat in Noryang channel. Eddy diffusion coefficient in Kwangyang Bay is known to be 1.2×10^{6}—1.7×10^{6} cm^2/s. Tidal exchange volume in Kwangyang Bay ranges from 20% at spring tide to 8% at neap tide with its average value 14%. This value is known to be comparable to other bays of southern coastal areas of Korea. According to POSCO (1983) it takes about 7.5 days to renew all the seawater in Kwangyang Bay by tidal exchange. However, in case of inner Kwangyang Bay, average tidal exchange volume is, however, reported to be only 4%, implying poor exchange and circulation.

The main objectives of this study are (1) to assess the environmental impacts by the Keumdong oil spill accident with measuring hydrocarbon residues and environmental parameters in both the water column and sediments in affected areas, and (2) to estimate the period for which the water column is affected by the accident. Because the study area encompassed the Yeochon coastal industrial complex and the Kwangyang steel complex, it was necessary to discriminate the impact of the oil spill from the potential impact from the coastal industrial complex measuring general environmental parameters (COD, nutrients and heavy metals). There are some limitations in this study; first, there were few available data scientifically monitored before and after the accident in this area, and secondly, when the field survey was performed, it had already passed five months since the accident and natural decomposition of hydrocarbon must have been proceeded.

MATERIALS AND METHODS

Field survey

Sampling stations for seawater and sediment are shown in Figs. 1a and 1b, respectively. Seawater samples were collected from 31 stations in the study area (denoted by W), and 2 stations in Kamakyang Bay (denoted by YW) and 2 stations in Tongyoung Bay nearby Chungmu Harbor (denoted by CW) as reference stations (Fig. 1a). Subtidal sediment samples were collected from 69 stations in the study area (denoted by B), and 4 stations in Kamakyang Bay (denoted by YB) and 4 stations Tongyoung Bay nearby Chungmu Harbor (denoted by CB) as reference stations (Fig. 1b). Additionally, 17 shoreline sediments (denoted by L) were collected around the western and northern Namhaedo coastline where imprinting of oil slick was reported to be evident right after the oil spill accident: 14 stations were located on the shoreline and 3 stations in tidal prawn farms (Fig. 1b). To reduce sampling position error, a hand-held satellite-tracking global positioning system (Motorola GPS) was employed.

Sampling has been done from March 4 to 6, 1994. Water samples were collected by Niskin water sampler at 2 m depth below the surface at all water column stations. Inside of Niskin sampler was rinsed with distilled deionized water each time right before hydrocasting. Surface sediments of upper 10 cm were collected by gravity core sampler. In case of reference stations or sandy bottom stations, however, divers collected surface sediment samples which otherwise could not be done by gravity core sampler. During seawater sampling, CTD was used to measure salinity and seawater temperature. Collected samples were stored at 0—4°C in dry-ice-cooled containers until delivered to laboratory.

Analysis of seawater

Solvent extractable hydrocarbon. One liter of seawater was transferred into teflon separatory funnel and extracted 3 times with 40, 20 and 20 ml of tetrachloride after vigorous shaking. Extracted sample was dried in a rotary evaporator at *ca.* 30°C. After evaporation, 10 ml of *n*-hexane was added to dissolve the dried sample. Fluorescence of sample was measured by scanning spectrofluorometer (Shimadzu RF-540). To find optimum excitation and emission wavelengths, bunker C oil, obtained from the Keumdong oil spill, was scanned by spectrofluorometer. Optimum excitation and emission wavelengths were found to be 280 and 380 nm, respectively. These wavelengths are consistent to the previously known excitation and emission wavelengths for Bunker C oil (Park *et al.*, 1991). Slit width was set at 5 nm. Gas chromatography was also applied for the extracted hydrocarbons. However, hydrocarbon concentrations in seawater samples were too low (around a few μg/l) to be measured by gas chromatography. In general, fluorescence spectroscopy is used for quantitative analysis of petroleum hydrocarbons in seawater because of their low concentrations at the μg/l level in water columns (Parsons *et al.*, 1984). Quantification of hydrocarbon is based on Bunker C oil in this study.

Nutrients. Nitrite, nitrate and phosphate were measured by spectrophotometer (Shimadzu UV/VIS 260) according to Parsons *et al.* (1984). Ammonia was measured by spectrophotometer (Shimadzu UV/VIS 260) according to Solorzano (1969).

Chemical oxygen demand (COD), dissolved oxygen (DO) and pH. COD was determined by titrimetric method using excess $KMnO_4$ as an oxidant (MOE, 1991). DO was measured by field DO meter (YSI) with submersible probe. DO value was calibrated against titration method later in the laboratory. Saturation level of DO was also expressed in percent. pH was measured by field pH probe attached to CTD.

Heavy metals (Cd, Cr^{+6}, Cu, Pb and Zn). One liter of seawater was acidified by concentrated nitric acid, and ammonium pyrrolidine dithiocarbamate (APDC) and diethylammonium diethyldithiocarbamate (DDDC) were added. Metal complex was extracted with tetrachloride (Grasshoff *et al.*, 1983). After pretreatment, samples were determined by ICP-MS (VG Instrument).

Analysis of sediment

Solvent extractable hydrocarbon. Homogenized 10—20 g of sediment was treated with methanol/methylene chloride (50%/50%) and soxhlet extraction device was used (Clark, 1974). Fluorescence of extracted sample was routinely measured for quantitative analysis as described previously in *analysis of seawater*. GC (Shimadzu GC-14 APF) with FID detector was used for qualitative/quantitative analyses. Except for the shoreline sediment samples which contain measurable Bunker C oil residues, samples were further concentrated for GC analysis because most of samples were in the range of a few mg/l level.

Nutrients and COD. Porewater was extracted from sediment by centrifugation, and subsamples were determined for nutrients (nitrate, nitrite, ammonia and phosphate). Porewater COD was determined as described above in *analysis of seawater*.

Heavy metals (Co, Cd, Cu, Ni, Pb and Zn). Sediment and porewater samples were dried and digested by concentrated nitric acid in teflon bomb at 150°C for 5 hours. Samples diluted with 2*N* nitric acid were determined by ICP-MS (VG Instrument).

RESULTS AND DISCUSSION

Water column environment

Hydrocarbon concentration of the seawater ranged from 0.80 to 9.16 μg/l with an average of 3.33 μg/l in the study area (Table 1). Average hydrocarbon concentration which had been previously monitored by Korea National Maritime Police Agency in the study area were 4.6 μg/l on May 26, 1993 and 3.7 μg/l on September 21, 1993. Therefore, the present average concentration is nearly the same as before the Keumdong oil spill accident in the study area. High values above 6.00 μg/l were found at stations W9-W13 near the western shoreline of Namhaedo where the spilled oils were heavily stranded. Average hydrocarbon concentration inner Kwangyang Bay was 4.04 μg/l which was slightly greater than the average of the whole study area. Most stations in Chinju Bay showed lower values less than 3 μg/l. Presumably, majority of coastal water seems to have restored its background concentration before the accident.

Nutrients, COD and other general environmental parameters of the seawater are shown in Table 1. In general, these values were in the comparable range with previous records (KNMPA, 1986, 1988, 1990). Values of pH, SS, DO and COD were nearly similar to the previous records but nutrients were lower. There was no distinctive difference between the study area and reference areas. Judging from the Korean standard of seawater quality (MOE, 1991), the study area belonged to 1st or 2nd class coastal environment.

Heavy metal (Co, Cd, Cu, Ni, Pb and Zn) concentrations of seawater are shown in Table 1. Based on the Korean standard of seawater quality (MOE, 1991), corresponding metals (Cd, Cu, Pb and Zn) are below the criteria. Comparison of the present results with other coastal waters in Korea is shown in Table 2. Concentrations of heavy metals in this study area were higher than other areas in southern coast of Korea but much lower than Incheon coastal area. Zn and Cd concentrations in the Yeosu Bay channel (Stations W10-W16) were lower than other local areas in the study area. It might be due to active dispersion by strong tidal current in the channel. Zn and Cd concentrations were higher at the reference stations in Kamakyang

Table 1. General environmental parameters and concentration of hydrocarbon, nutrients and heavy metals of the seawater in the study area (denoted by W) and reference areas (denoted by CW or YW)

Station	Temp. (°C)	Salinity (psu)	pH	DO-S (%)	DO	COD	SS	Hydrocarbon	NH_4^+	$NO_2^- + NO_3^-$	HPO_4^{-2}	Cr^{+6}	Cu	Zn	Cd	Pb
					(mg/l)			(μg/l)								
W1	6.2	31.7	8.13	107.4	10.8	1.3	28.0	4.36	16.7	8.4	13.5	0.74	0.03	9.3	0.07	0.36
W2	5.2	31.5	8.11	108.6	11.2	1.2	20.0	1.78	9.9	7.1	11.4	0.81	0.65	9.7	0.07	0.65
W3	7.1	31.5	8.10	115.6	11.4	1.6	33.6	6.00	21.4	4.7	13.4	0.66	0.49	38.5	0.08	1.41
W4	–	–	–	–	–	–	–	–	–	–	–	0.45	0.91	38.3	0.11	1.41
W5	7.1	30.3	7.97	94.6	9.4	0.5	30.4	1.24	36.5	26.9	30.9	0.73	0.72	40.5	0.14	0.57
W6	6.7	30.0	7.87	105.5	10.6	0.8	23.4	2.80	30.8	5.1	7.0	0.59	0.85	13.8	0.08	1.06
W7	7.6	31.1	8.01	104.4	10.2	0.8	18.0	2.29	7.8	6.7	19.2	1.25	0.55	9.4	0.90	0.70
W8	7.0	30.6	8.02	101.6	10.1	0.8	22.2	2.33	2.1	6.1	18.9	0.35	0.56	42.8	0.45	0.62
W9	7.5	31.9	8.09	117.0	11.4	1.3	19.2	9.16	4.3	6.5	15.1	0.27	0.50	28.5	0.11	0.45
W10	7.5	32.0	8.14	99.6	9.7	1.9	22.8	4.14	2.7	5.4	20.2	0.26	0.51	8.7	0.05	1.23
W11	7.6	32.4	8.15	113.5	11.0	1.3	27.6	6.72	2.8	15.8	19.7	0.23	0.03	4.2	0.02	0.23
W12	7.6	32.5	8.15	110.5	10.7	1.4	19.8	2.40	3.2	–	23.8	0.69	0.47	8.4	0.05	1.28
W13	7.5	32.0	8.18	108.8	10.6	1.3	24.6	7.89	5.5	9.2	28.4	0.67	0.68	8.8	0.06	0.87
W14	7.4	32.2	8.18	110.8	10.8	1.3	22.2	3.67	10.9	5.8	20.6	1.21	0.70	8.1	0.06	0.61
W15	7.4	32.2	8.10	108.7	10.6	1.4	19.4	3.38	5.3	5.6	17.8	1.86	0.65	8.4	0.07	0.56
W16	7.7	32.2	8.15	111.6	10.8	1.3	24.6	1.42	12.3	4.8	20.2	1.49	0.60	8.6	0.05	0.66
W17	8.0	32.4	8.15	111.5	10.7	0.8	16.6	3.23	6.3	8.4	12.9	1.87	0.62	32.2	0.13	2.71
W18	8.3	32.5	8.16	100.7	9.6	–	23.2	2.69	11.0	4.3	12.4	0.40	0.38	19.7	0.03	0.23
W19	7.3	31.0	8.02	101.6	10.0	1.6	15.4	1.67	14.0	4.6	6.8	0.51	0.62	10.8	0.97	0.83
W20	7.5	31.8	7.91	105.6	9.9	0.8	26.4	3.13	4.5	5.5	17.3	0.59	1.32	82.9	0.15	0.59
W21	7.6	31.9	7.89	106.9	10.0	1.1	19.0	1.74	24.9	6.5	19.7	1.57	0.33	35.9	0.12	0.91
W22	7.5	31.7	7.94	106.6	10.0	1.1	23.6	2.54	7.0	0.3	14.1	0.43	0.81	11.6	0.07	0.75
W23	7.6	31.9	7.96	106.9	10.0	1.5	22.4	3.09	13.9	3.5	16.7	0.17	0.70	9.9	0.14	1.01
W24	7.1	32.2	7.97	104.0	9.8	1.3	22.6	2.69	20.3	7.2	18.8	0.69	0.68	11.5	0.10	2.09
W25	7.4	31.7	7.93	102.2	9.6	1.4	23.6	–	3.9	5.5	15.4	0.31	0.77	54.3	0.07	0.94
W26	7.3	32.1	8.05	106.3	10.0	1.1	20.2	2.33	12.5	5.3	16.9	2.30	0.77	36.7	0.06	3.22
W27	6.8	31.8	7.91	103.0	9.8	1.2	19.0	3.05	15.7	8.4	20.5	2.15	0.89	48.4	0.11	1.29
W28	7.4	31.9	7.95	104.2	9.8	1.4	18.8	4.54	19.6	6.9	18.4	0.19	0.85	37.2	0.08	0.85
W29	8.4	30.4	7.90	101.7	9.4	1.5	15.9	0.80	16.7	5.2	13.6	0.56	0.65	52.8	0.14	0.66
W30	7.2	31.4	7.94	101.6	9.6	1.5	18.8	2.98	9.9	4.4	16.2	3.28	0.67	42.1	0.05	0.88
W31	8.8	31.4	7.97	106.5	9.7	1.4	22.8	2.62	20.6	3.9	10.3	0.83	0.77	11.4	0.18	6.24
CW1	–	–	–	–	–	–	29.4	–	3.8	6.3	8.3	–	–	–	–	–
CW2	–	–	–	–	–	–	18.8	–	5.3	19.3	11.3	–	–	–	–	–
YW1	6.9	32.6	8.00	105.8	10.4	1.4	26.6	–	30.9	37.8	12.8	0.59	0.68	45.7	0.22	0.58
YW2	7.2	32.4	7.99	102.4	10.0	1.3	18.4	–	6.4	10.7	11.9	0.46	0.48	38.3	0.23	0.42

Table 2. Comparison of heavy metal concentrations (μg/l) of seawater among various marine environments (all values are average concentrations)

	Oceanic water	Incheon (Mar. 1992)	Pusan (May 1990)	Chungmu (May 1990)	Study area (Mar. 1994)
Cr	0.60	1.27	0.66	0.37	0.88
Cu	3.00	6.60	1.16	1.01	0.63
Zn	5.00	48.21	9.20	11.60	26.28
Cd	0.05	0.23	0.17	0.12	0.16
Pb	0.03	5.03	0.94	1.02	1.12
Source	Bryan, 1976	Kim, 1994	KNMPA, 1990	KNMPA, 1990	This study

Bay than the study area while Cr^{+6} and Pb concentrations were lower than the study area. In general, except Zn and Cd, no distinctive local difference of metal distribution could be found in the study area. Previous records of temporal variation of heavy metals showed wide fluctuation in the study area, but it was difficult to find any trend of aggravation by heavy metals since 1985 as shown in Table 3.

Table 3. Temporal variation of heavy metal concentrations (μg/l) of seawater in the study area since 1985 (all values are average concentrations: data from KNMPA 1986, 1988, 1990)

Date	Cd	Cr^{+6}	Cu	Pb	Zn
July 1985	0.38	3.03	2.88	2.26	11.02
Sep. 1985	0.70	2.28	2.26	1.39	12.48
June 1986	0.40	–	7.10	6.70	33.00
Aug. 1986	0.90	–	14.20	13.50	90.00
Sep. 1988	0.28	0.28	3.29	2.18	19.81
Oct. 1988	0.19	0.20	2.13	1.78	12.73
May 1990	0.08	0.34	1.07	0.50	12.70
Mar. 1994 (This study)	0.16	0.88	0.63	1.12	26.28

Sediment environment

In the shoreline sediments, oil deposits were still found at the high-water marks at several stations (Stations L1-L7, L14 and L15). Oil residues were

Table 4. Hydrocarbon concentrations of the shoreline sediments

Station	Description of location	Hydrocarbon (μg/g of wet sediment)
L1	Yeumhae No.1 common fishing ground	35490
L2	Yeumhae (short necked clams)	40147
L3	Yopo gravel beach	17978
L4	Yopo beach	57004
L5	Nogu rocky shore	3669
L6	Nogu beach	28821
L7	Hwajurn (short necked clams)	21369
L8	Hwajurn No. 1 prawn farm	20
L9	Hwajurn No. 2 prawn farm	6
L10	Chamyeon beach	20
L11	Dongheung beach	5
L12	Dongheung prawn farm	20
L13	Bonguri beach	32
L14	Namsang ditch (small stream gulley)	24736
L15	Namsang rocky shore	6615
L16	Jagjang beach	757
L17	Yeagyea gravel sand beach	21

distributed in patches or sometimes entrapped in crevice of rock and gravel. Oil deposits were easily identified by visual observation after shoveling about 10 cm deep. Very high hydrocarbon concentrations were found in the sediments of Yeumhae (Stations L1 and L2), Yupo (Stations L3 and L4), Nogu (Stations L5 and L6), Hwajurn (Station L7) and Namsang (Stations L14 and L15), ranging from 3.7 to 40.1 mg/g of wet sediment (Table 4). Gas chromatograms of these samples showed a very distinct and typical Bunker C pattern (Fig. 2). Chromatograms of present study were identical to the Bunker C oil collected from the *Keumdong No. 5* which had been measured right after the oil spill accident. However, samples L5, L14 and L15 showed not only Bunker C but also considerable amount of dispersant (Gamasol) in their chromatograms (Fig. 2). Shorelines around these stations are known to have been applied with considerable amount of dispersant until January, 1994. Residue of mixture of Bunker C and dispersant in these intertidal sediments might be easily mobilized by tidal action into the water column and could elevate apparent hydrocarbon contents in the water column nearby these stations for some duration. It agrees with the result of high contents of hydrocarbon measured at water column stations (Stations W9-W13) adjacent to these shoreline sediment stations (Stations L1-L7, L14 and L15). On the other hand, other shoreline stations (Stations L8-L12 and L17) showed very low hydrocarbon concentrations less than 30 μg/g of wet sediment as shown in Table 4. These value were the same order of magnitude as those of the subtidal bottom sediments. Samples taken from tidal prawn farm (Stations L8, L9 and L12) showed 20, 6 and 20 μg/g of wet sediment, respectively.

Hydrocarbons of the subtidal bottom sediments in the study area ranged from 0.45 to 18.08 μg/g of wet sediment with an average of 3.62 μg/g of wet sediment (Table 5). Natural background hydrocarbon concentration is not known in this area. Overall hydrocarbon concentrations in the subtidal sediments were quite lower than those of the badly oiled

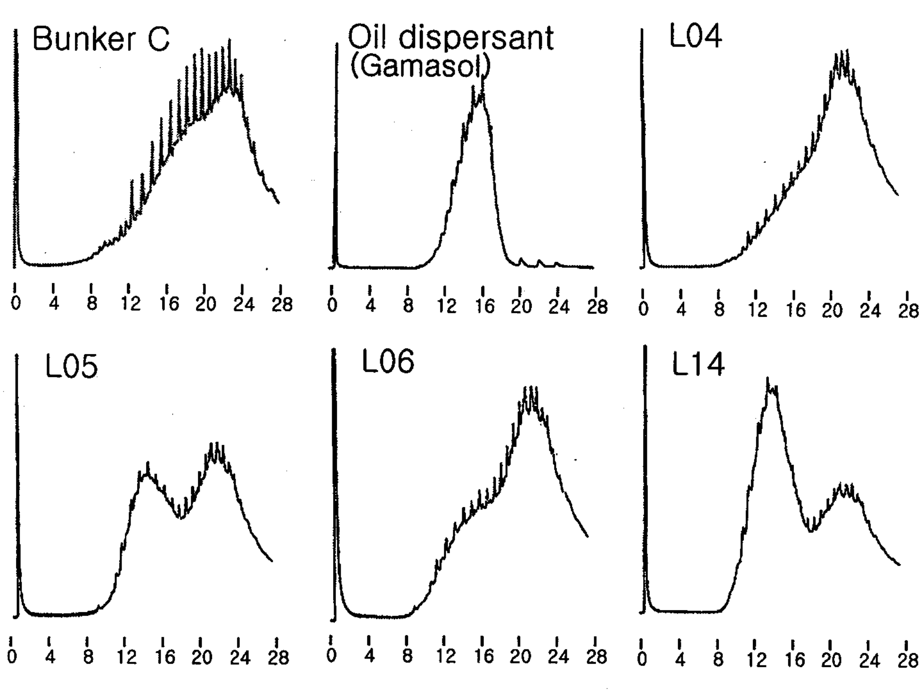

Fig. 2. Representative gas chromatograms of Bunker C, oil dispersant (Gamasol) and extracted hydrocarbon from the shoreline sediments. Gas chromatography condition: column = stainless steel (2 m×3 mm diameter) Silicon OV-1, Chromosorb-W, detector = FID, temperature program = 80—300°C (9.5°C/min), carrier gas = nitrogen (50 ml/min; injection temperature = 320°C).

Table 5. Concentrations of hydrocarbon, COD, nutrients and heavy metals of subtidal sediments in the study area (denoted by B) and reference areas (denoted by CB or YB)

Station	Hydrocarbon (μg/g of wet sediment)	COD	NH_4^+	NO_2^-	NO_3^-	HPO_4^{-2}	Cd	Co	Cu	Ni	Pb	Zn
		(mg/l of porewater)					(μg/g of dry sediment)					
B1	1.33	61.9	2.32	0.037	0.21	0.060	0.35	13.5	21.8	91.1	65.7	114.0
B2	2.93	30.2	3.35	0.037	0.21	0.242	0.07	13.3	20.5	101.0	65.8	121.1
B3	0.94	37.4	1.41	0.035	0.32	0.500	0.46	13.8	17.3	98.2	54.9	96.5
B4	3.49	86.8	6.37	0.037	0.20	0.751	0.29	17.1	25.2	128.0	58.0	124.5
B5	1.80	89.0	5.59	0.058	0.21	0.473	–	17.7	28.0	130.6	55.4	138.3
B6	2.14	89.9	2.65	0.030	0.81	0.350	0.83	17.1	27.2	130.6	49.2	142.0
B7	1.68	59.2	5.13	0.058	0.27	0.498	–	15.5	28.7	121.0	51.0	131.0
B8	2.06	50.4	2.11	0.036	0.19	0.370	0.71	16.1	28.8	123.7	55.3	128.7
B9	4.11	94.0	4.65	0.038	0.20	0.172	0.28	14.5	23.6	108.6	52.2	115.9
B10	0.47	86.1	1.60	0.063	0.18	0.372	–	19.2	23.0	120.2	57.0	133.3
B11	2.01	66.2	2.46	0.036	0.39	0.498	0.18	8.7	11.8	54.3	17.0	61.4
B12	5.53	51.8	2.94	0.039	0.15	0.005	0.61	15.3	20.8	102.4	46.2	118.5
B13	5.28	70.7	3.65	0.035	0.21	0.237	0.37	9.5	15.8	73.7	28.8	76.5
B14	1.91	93.3	4.45	0.034	0.31	0.336	–	15.2	20.5	114.4	50.3	112.3
B15	18.08	68.8	6.10	–	–	–	0.19	8.3	10.5	53.4	30.5	50.3
B16	1.43	88.4	1.44	0.030	0.19	0.083	0.67	13.5	17.9	97.3	57.8	109.3
B17	2.99	98.5	1.67	0.046	0.14	0.277	2.24	15.6	26.7	109.8	68.6	124.3
B18	5.70	104.8	–	0.054	0.07	0.008	0.95	15.1	20.3	103.0	62.9	101.0
B19	4.39	42.4	3.69	0.068	0.10	–	0.25	11.3	15.3	75.5	28.3	86.0
B20	0.52	49.0	2.39	0.056	0.33	0.117	0.11	11.4	14.9	74.2	28.8	85.7
B21	3.12	41.8	3.30	0.044	0.25	0.019	0.12	10.1	13.9	69.2	35.3	84.5
B22	1.49	37.4	1.73	0.034	0.22	0.199	0.46	15.4	18.7	94.0	40.5	106.4
B23	1.52	79.8	1.24	0.047	0.20	0.112	0.52	12.3	16.4	76.9	41.7	93.8
B24	4.39	107.7	1.84	0.052	0.11	0.001	0.03	11.7	15.8	76.2	46.0	91.5
B25	7.44	106.3	3.71	0.053	0.22	0.020	–	8.3	16.6	50.3	53.6	70.1
B26	2.45	76.9	1.60	0.045	0.11	0.443	0.17	11.0	15.5	79.5	45.1	89.7
B27	5.43	96.2	1.58	0.041	0.23	0.131	1.08	6.7	10.2	39.1	43.7	46.2
B28	8.38	96.0	–	0.055	0.22	–	0.35	10.4	11.4	67.9	40.8	67.7
B29	2.07	85.5	0.99	0.049	0.08	0.299	–	11.7	10.6	76.5	44.6	72.4
B30	5.70	53.3	2.36	0.037	0.28	0.021	0.02	4.9	5.7	30.8	35.9	36.1
B31	12.40	43.2	1.58	0.049	0.18	0.021	–	6.0	12.5	35.4	48.0	42.5
B32	3.21	114.3	2.36	0.027	0.27	0.101	0.36	13.5	19.6	104.3	44.7	115.8
B33	4.83	92.0	2.65	0.041	0.09	0.099	0.49	12.1	15.9	82.8	50.2	97.3
B34	3.17	94.9	2.02	0.030	–	0.169	0.18	15.2	16.7	102.8	44.1	114.4
B35	0.45	87.0	1.73	0.031	0.23	0.270	0.19	7.4	7.8	45.4	43.5	52.4
B36	2.63	116.4	1.43	0.035	0.21	0.135	–	6.1	7.0	38.8	43.3	46.7
B37	1.17	89.9	2.23	0.050	0.13	–	–	5.4	6.4	35.3	39.3	43.4
B38	7.38	97.8	2.50	0.036	0.13	0.293	1.44	31.3	40.1	200.5	90.5	221.9
B39	1.52	86.4	1.51	0.041	0.14	0.457	–	0.3	–	9.7	1.8	3.4
B40	0.69	67.7	1.78	0.040	0.19	0.505	0.23	11.6	18.6	87.9	41.7	90.4
B41	1.02	101.4	4.28	–	0.30	0.395	–	9.5	11.9	67.2	29.8	70.7
B42	0.54	87.6	2.13	0.047	0.17	0.094	0.52	7.1	8.5	45.4	49.6	51.3
B43	0.50	106.4	2.80	0.047	0.15	0.288	0.37	7.2	10.9	48.6	53.1	55.2
B44	1.36	92.0	–	–	–	–	1.51	10.0	17.5	66.5	37.8	68.6
B45	0.84	38.9	4.04	0.035	–	0.163	0.43	5.0	5.5	31.4	35.1	36.2
B46	1.98	86.4	5.01	–	–	–	0.53	9.3	10.8	57.4	31.9	56.0
B47	0.86	50.4	1.29	0.031	0.06	0.151	0.10	9.9	17.9	65.8	34.0	65.7
B48	3.48	70.6	1.28	0.057	0.08	0.032	0.63	6.0	6.5	34.4	19.2	33.9
B49	0.84	102.8	2.13	0.023	0.32	0.003	0.31	8.2	8.3	48.0	52.1	48.1
B50	1.50	61.9	1.27	0.027	0.09	0.144	0.30	12.7	10.2	63.1	48.7	60.8
B51	3.57	92.7	4.22	0.029	0.10	0.090	0.23	9.3	10.9	53.7	35.1	63.4
B52	0.87	25.9	–	0.056	–	0.092	0.34	9.9	10.4	57.7	32.4	64.9
B53	2.39	50.8	–	–	1.32	–	0.54	8.0	9.5	48.8	46.4	43.7
B54	1.47	47.6	1.51	0.050	0.07	0.069	0.37	10.1	13.3	62.8	43.8	71.8
B55	1.23	104.8	2.12	0.038	0.08	-	0.18	8.2	8.7	57.2	44.6	50.6
B56	0.68	96.9	2.79	0.032	0.10	0.315	0.38	8.7	10.6	50.6	38.3	59.2
B57	2.86	96.3	2.65	0.058	0.03	0.302	0.11	8.8	10.8	51.5	38.6	61.8
B58	4.17	50.8	–	–	0.27	–	0.79	8.8	11.8	51.3	37.2	55.3
B59	2.39	91.2	2.16	0.049	0.33	0.537	0.32	8.0	9.2	49.5	35.2	55.1
B60	0.48	88.3	2.10	0.070	0.24	0.448	0.21	7.1	8.3	41.6	39.8	48.6
B61	1.64	36.0	1.29	0.039	0.11	0.514	0.90	7.3	10.6	48.3	42.0	54.5
B62	1.81	88.4	3.21	0.081	0.05	0.689	0.77	8.0	10.7	52.4	43.3	57.7
B63	0.87	53.3	2.05	0.037	0.56	0.454	1.09	7.9	12.1	49.3	44.1	56.2
B64	1.15	91.3	3.24	0.076	0.17	0.694	0.24	7.5	7.4	43.3	13.9	47.5

Table 5. Continued

Station	Hydrocarbon (μg/g of wet sediment)	COD	NH_4^+	NO_2^-	NO_3^-	HPO_4^{-2}	Cd	Co	Cu	Ni	Pb	Zn
		(mg/l of porewater)					(μg/g of dry sediment)					
B65	0.93	97.1	1.71	0.039	0.24	0.543	0.38	8.0	8.9	46.6	15.8	54.7
B66	5.87	90.4	5.25	0.042	0.11	0.468	0.20	7.3	8.1	41.0	12.5	45.5
B67	3.02	94.8	3.45	0.043	0.41	0.345	0.36	6.9	8.0	40.0	14.4	50.3
B68	1.43	87.7	1.36	0.037	0.11	0.404	0.38	6.8	7.4	40.2	12.3	47.4
B69	2.96	25.9	1.43	0.014	0.04	0.026	0.59	12.4	13.5	86.6	46.4	104.2
CB1	4.33	85.5	2.44	0.041	0.29	0.311	0.41	13.6	21.2	85.6	26.6	106.7
CB2	6.54	90.4	4.16	0.041	0.24	0.436	0.70	12.7	19.7	82.0	26.7	101.6
CB3	5.59	82.7	2.88	0.059	0.23	0.185	0.49	12.0	18.0	75.3	24.1	96.6
CB4	3.46	85.5	2.32	0.071	0.33	0.838	0.33	14.7	20.6	94.6	25.9	114.8
YB1	3.51	28.1	5.18	0.040	0.22	0.874	0.22	12.8	14.8	83.4	25.8	101.1
YB2	4.38	28.1	5.86	0.018	0.16	0.468	0.45	14.2	15.9	98.1	32.1	107.3
YB3	5.30	40.6	5.27	0.024	0.16	0.619	0.24	14.0	14.5	95.8	37.6	98.8

shorelines in the study area but were comparable to those obtained from the reference stations.

Stations along the northwest and west of Namhaedo (Stations B12-B33) generally showed much higher hydrocarbon concentrations than inner Kwangyang Bay and Chinju Bay. The highest values were found along the channel between Namhaedo and Kwangyang Bay. Inner Kwangyang Bay and Chinju Bay showed lower values than the reference stations in Kamakyang Bay and Tongyoung Bay (average value of 4.73 μg/g of wet sediment). Tongyoung Bay, one of the reference areas, showed higher values than inner Kwangyang Bay and Chinju Bay. It might result from maritime activities and transportation nearby Chungmu Harbor. Chinju Bay generally showed the lowest values among the study area. Bottom sediments in inner Kwangyang Bay and Chinju Bay seemed to be less affected than those in the west of Namhaedo. The overall results indicate that subtidal sediments in the channel between Yeosupando and Nambaedo were most heavily affected by the Keumdong oil spil accident.

Heavy metal concentrations of subtidal sediments in the study area are summarized in Table 5. Ni, Co, Cu, and Zn concentrations were relatively higher in Kwangyang Bay than Chinju Bay. This distributional pattern implies that possible sources of metals might be the Yeocheon and Kwangyang coastal industrial complexes. Chinju Bay sediments (Stations B42-B66) were relatively the lowest in these four metals. Sediment at Station B38 near Yeosu Harbor, however, showed exceptionally high values in all metals. Discharge of untreated metalliferous wastes is most suspected at this location. Pb concentration was generally higher in Kwangyang Bay but Cd did not showed any distinctive local distribution.

Nutrients and COD of porewaters are summarized in Table 5. In the shallow coastal waters, where biological productivity is high, particulated organic matters (POM) are usually accumulated in sediment and POM oxidation process further enriches porewater with remineralized nutrients. Naturally, nutrients and COD are much higher in the porewater than the overlying seawater. In the study area, COD values in the porewater ranged from 25.9 to 116.4 mg/l with an average of 76.9 mg/l. COD values in porewater were slightly higher in the west of Namhaedo than other areas. It might be due to higher hydrocarbon in this area. Nutrients, such as phosphate and ammonia, in porewater were generally lower in the area containing higher hydrocarbon. This might reflect consumption of N and P by oil decomposing bacteria required for the enhanced growth by added hydrocarbon. Ammonia in porewater ranged from 0.99 to 6.37 mg/l with an average of 2.65 mg/l. Ammonia in inner Kwangyang Bay and Kamakyang Bay were generally higher than in the west of Namhaedo and in Chinju Bay. This result suggests that inner Kwangyang Bay and Kamakyang Bay were in poorer circulation and in more reduced sediment environment than other areas.

Time-course observation of hydrocarbon concentration in seawater after the oil spill accident

It may take many years for all the oil residues to be cleaned up or degraded by nature in the contaminated shores and in the affected subtidal sediments, even though majority of shores was void of oils by clean-up operation after the oil spill accident. At this point, some questions arise on:

How long has the water column been affected and how much oil was released into the water column by the Keumdong oil spill accident? After the spill, 600 metric tons of oil slick had been recovered during the first 10 days of clean-up operation. It should be pointed out that major fraction of the spilled oil was driven ashore within a few days after the incident as confirmed by many earlier records. Afterward, approximately over 200 metric tons of oil in pounded spots and contaminated soil were mechanically removed. Then it implies that at least about 400 metric tons of unrecovered oils might have dispersed into the water column or precipitated in the subtidal sediments. During the first few weeks of the clean-up operations, 160 metric tons of dispersants were applied to the sea surface and contaminated shores. In the west of Namhaedo (shoreline length of 33 km), the most affected area by wind-driven stranded oil, more than 1/3 of total dispersants were applied from the 3rd of October to the end of December. Therefore, some portion of the oil in the contaminated shores was suspected to be remobilized and dispersed into the water column during this clean-up operation.

Time-course observation of hydrocarbon in the water column was carried out at 10 stations covering the affected areas at 10 times from October 11 to December 14, 1993. On the 11th of October, average hydrocarbon concentration was 25.7 μg/l and subsequently declined. Maximum hydrocarbon concentration was 76.4 μg/l found in the west of Namhaedo and minimum was 9.6 μg/l in Chinju Bay. Theoretically, dispersion behavior of dissolved oil in the water column depends on the advection (tidal currents) and eddy diffusion. A characteristic of dispersion is the exponential decrease with time. Therefore, after logarithmic transformation of observed hydrocarbon concentration, linear regression analysis was made (Fig. 3). The result showed a very high correlation coefficient ($r^2=0.9252$) between time and logarithmically transformed concentration. From this regression equation, recovery time could be extrapolated; average hydrocarbon concentration in the seawater should have been decreased to its background level of 3.7 μg/l by the end of January 1994. This suggests that the effect of oil spill on the water column would have lasted at least for 4 months in the study area. This conjecture is reasonably consistent with the fact that average hydrocarbon concentration of seawater (3.3 μg/l) in March 1994 was nearly the same as the value (3.7 μg/l) on the 21st of September 1993 before the Keumdong oil spill accident. This suggests that majority of coastal water, except the sediment environment, restored its background hydrocarbon concentration by March 1994.

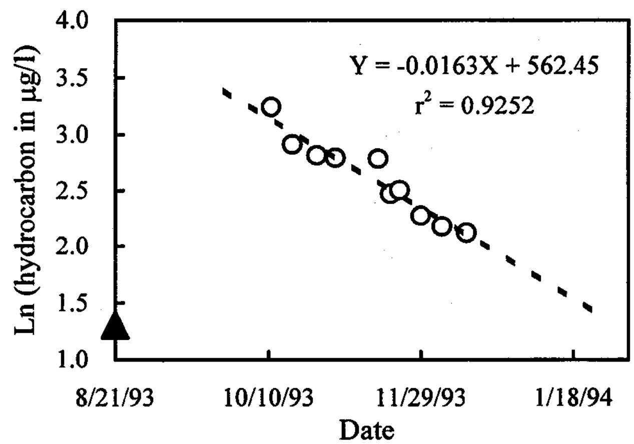

Fig. 3. Regression analysis of time course observation of hydrocarbon in the seawater monitored by Korea National Maritime Police Agency in Kwangyang Bay after the Keumdong oil spill accident. Hydrocarbon concentration measured in Kwangyang Bay on the 21st of August 1993 (marked as closed triangle) before the Keumdong oil spill accident was 3.7 μg/l (Ln 3.7=1.3).

CONCLUSION

Oil deposits were able to be found at the high water marks at several stations and very high values were found in the west of Namhaedo in March 1994. West of Namhaedo (Stations B12-B33) generally showed much higher values than inner Kwangyang Bay and Chinju Bay. Subtidal sediments in Chinju Bay generally showed the lowest values among the study area. Subtidal bottom sediments in the west of Namhaedo were more contaminated by oil than those in inner Kwangyang Bay and Chinju Bay. Regression analysis of time-course observation of hydrocarbon in the seawater suggests that the effect of oil spill on the water column, except the sediment environment, would have lasted at least more than 4 months in the study area after the Keumdong oil spill accident. Except high COD values of several subtidal sediment samples contaminated by oil deposits, there was no clear correlation among nutrients, heavy metals and hydrocarbon concentrations in the study area. Coastal industrial complex might be the most potential source of COD, nutrients and heavy metals. However, nutrients, heavy metals and other environmental parameters in the seawater did not show any aggravated signs for seawater quality compared with the previous records. Heavy metal concentrations at all sediment stations were in general comparable to those in the reference stations. It suggests that the coastal industrial complex was not the main cause for the heavy damages in fishery business in the study area after the Keumdong oil spill. Therefore, it was most likely that the Keumdong oil spill accident affected the marine ecosystem and might impose adverse impacts on the mariculture and fishery business in Kwangyang Bay.

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Manuscript received August 12, 1998
Revision accepted November 13, 1998