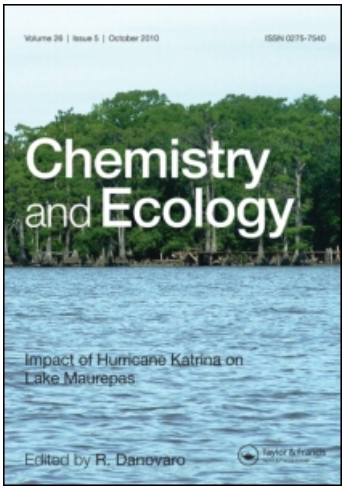

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Terrigenous Inputs and Accumulation of Trace Metals in the Southeastern Taiwan Strait

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TERRIGENOUS INPUTS AND ACCUMULATION OF TRACE METALS IN THE SOUTHEASTERN TAIWAN STRAIT

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Terrigenous inputs and sedimentary fluxes of trace metals were studied to understand the metal sources, transport and sinks in the southeastern Taiwan Strait. The major terrigenous metals come from seven major rivers in the southwestern Taiwan, even though significant fractions of most metals were retained in estuaries. The net fluxes of river borne metals contributed from 65% (Pb) to 92% (Fe, Zn) of total inputs. The remainder was attributed to marine sewage discharges (0.6–6.9%) and atmospheric inputs (5.3–31.5%). Sedimentary fluxes of trace metals were spatially variable as a result of derivation from site-specific sedimentation rates and metal distributions in sediments. In spite of imbalance between sources and sinks of trace metals, an accumulation of metals in the sediment of southeastern Taiwan Strait was found for sites close to Taiwan Island. Surface enrichment of metals in near-shore sediments beginning around 1976 was coincident with a time of industrial boom in Taiwan. The metal enrichment hierarchy was found as (Cd, Pb > Cu > Zn > Mn, Fe).

KEY WORDS: Terrigenous inputs, sedimentary fluxes, trace metals, surface enrichment

INTRODUCTION

Anthropogenic inputs of trace metals in the coastal sea of southeastern Taiwan Strait (off southwestern Taiwan) has attracted increasing attention during the last two decades arising mainly from the rapid economic growth in Taiwan. The increase of metals discharged into coastal waters may be largely responsible for a gradual decrease in biological resources in waters off southwestern Taiwan, although very few data are available in scientific documents. Nevertheless, the rivers of southwestern Taiwan, which discharge water into the southeastern Taiwan Strait, have been found to have unusually high levels of metal contamination (T.C. Hung, 1983; Hung, 1990; Hung and Huang, 1990; Hung and Wang, 1992; Kou and Hung, 1987). Since trace metals transported by rivers can be retained or added to a large extent in estuaries before emptying into the ocean (Sholkovitz, 1978; Eaton, 1979; Yeats and Bewers, 1982; Windom *et al.*, 1983; Byrd and Andreae, 1986; Church, 1986; Hung and Huang, 1990), the net fluxes of trace metals and their effects in coastal environments cannot be evaluated without considering metal behaviour in estuaries. Meanwhile, trace metals discharged in the coastal sea off southwestern Taiwan through marine disposals and sewage outfalls cannot be neglected, nor can contributions from atmospheric deposition. The fate of an influxed metal in the coastal environment is complex; however, the major terrestrial metals are generally believed to be trapped in coastal marine sediments (GESAMP, 1987; Windom *et al.*, 1989). Therefore, the aims of this study are focused on the terrestrial inputs and sedimentary depositions

of trace metals in order to understand the relationship between sources and sinks of trace metals in this coastal environment.

MATERIALS AND METHODS

Study Area

The study area includes seven rivers and estuaries in southwestern Taiwan and a coastal area of ca. 6500 km^2 between a range of (22° 20′ N–23° 30′ N) and a width of 45 km perpendicular to the land as shown in Figure 1. The rivers, from the north to the south, are Potzu river (A), Pachang river (B), Chishui river (C), Tsengwen river (D), Erhjen river (E), Kaoping river (F) and Tungkang river (G). The general characteristics and sampling time of the rivers are listed in Table I. Three submarine sewage outfalls, Tsoying (Ts), Chungjou (Ch) and Talinpu (Ta) along the coast of the Kaohsiung area, discharge primary treated sewage of 4.9×10^4, 4×10^5 and 4.6×10^5 m^3/day, respectively. Metals are also discharged through marine outfalls and a dumping site (D) is used for slag disposal by the Chinese Steel Corporation. Metal inputs through atmospheric deposition were evaluated from rain and aerosol samples collected from coastal stations locating on the National Sun Yat-Sen Univ. (S) and National Kenting Park (K) as well as from sites in the coastal sea of southeastern Taiwan Strait.

Sampling and Analytical Methods

The samples of riverine and estuarine waters were collected at various periods of time as shown in Table I to study the riverine and estuarine transport of trace metals. The samples were collected with a pre-cleaned horizontal sampler (Ekman Birge) from highway bridges over the rivers and aboard plastic vessels in the estuaries where the collection was made from the bow of the vessel to minimize the risk of contamination. Salinity, pH and dissolved oxygen (DO) were measured *in situ* with a portable salinometer (Hydro-Bios), a portable pH meter (Orion Research) and a portable DO meter (YSI model 58), respectively. Samples for analyses of dissolved organic carbon (DOC) and trace metals were filtered through pre-combusted GF/F filters (450°C, 4 hr) and acid-cleaned 0.4 μm filters (Nucleopore) immediately after the samples were brought back to the laboratory. DOC was measured with a TOC

Table I The general information for rivers in southwestern Taiwan

River	Length (km)	Drainage area (km^2)	Discharge[a] (m^3/yr)	Suspended[b] load (kg/yr)	Pollution[c] status	Sampling date (mo/yr)
(A) Potzu	75.67	426.6	$3{\cdot}69.10^8$	$1{\cdot}89.10^7$	Medium-heavy	10/1989; 02/1990
(B) Pachang	80.68	474.7	$5{\cdot}86.10^8$	$1{\cdot}51.10^8$	Medium-heavy	04/1992
(C) Chishui	65.05	378.8	$2{\cdot}84.10^8$	$9{\cdot}80.10^6$	Medium-heavy	12/1988; 09/1989
(D) Tsengwen	138.5	1177.0	$9{\cdot}26.10^8$	$1{\cdot}49.10^8$	Medium	09/1986; 01/1987
(E) Erhjen	65.18	350.0	$2{\cdot}47.10^8$	$1{\cdot}86.10^7$	Heavy	06/1990; 04/1992
(F) Kaoping	170.9	3257.0	$6{\cdot}68.10^9$	$7{\cdot}40.10^8$	Slight-medium	09/1989; 01/1987; 06/1990
(G) Tungkang	44.00	480.0	$5{\cdot}24.10^8$	$1{\cdot}64.10^8$	Medium	07/1989; 01/1990

a: Mean values over ten years, calculated from data in the Hydrological Year Books of Taiwan (1982–1991).
b: Mean values over ten years at zero salinity (river end-member), calculated from measured concentrations of suspended matter (this study) and river discharge over ten years (1982–1991).
c: Middle to lower sections of rivers, defined by EPA (ROC).

analyzer (O.I. Corporation) with improved procedures for sea water (Hung and Chang, 1992). Dissolved metals were preconcentrated with the chelation back extraction method (APDC/DDDC–freon-diluted HNO_3) modified from Danielsson *et al.*, (1982) and Statham (1985) with the exception that manganese was preconcentrated by oxine-C_{18} Sep-Pak cartridge (Waters, Milford, USA) as developed by Sturgeon *et al.*, (1982). Particulate metals were analyzed by digesting the residue of filtration with mixed superpure acids (HNO_3:$HClO_4$:HF = 2:1:2) in Teflon lined acid digestion bombs (Parr Instrument Co.) followed by dilution with distilled deionized water (DDW). The pre-treated dissolved and particulate metals were then determined with a Perkin-Elmer atomic absorption spectrophotometer (2380 or 5100 PC) equipped with a graphite furnace (HGA-400 or HGA-600). Precision of analyses were generally better than 10% (Hung, 1988; Hung and Huang, 1990).

Samples of treated wastewater prepared for marine discharge and disposal were collected monthly through a year (Sept., 1990–Aug., 1991) from wastewater treatment stations. Dissolved and particulate metals were measured with the same procedures as those described for river/estuarine samples. Dissolved trace metals in rain water samples at S and K stations collected since April 1990 were determined directly with a graphite furnace atomic absorption spectrophotometer (GFAAS). Aerosol metal deposition was estimated from the averages of dry depositions at S and K stations, at great Kaohsiung area of southwestern Taiwan (Chuang *et al.*, 1987), and at Penghu Island in the southern Taiwan Strait (Shih, 1992).

Sedimentary fluxes of trace metals in coastal environments of southeastern Taiwan Strait were determined from sedimentation rates and metal distributions in box-core sediments. Duplicate box-core samples (B3, B4, B10, B22, B30, B31, B41, shown in Figure 1) were taken from different coastal regimes in the study area during cruises aboard the R/V Ocean Research 1. Sediment subcores were taken on board ship in cleaned plastic tubes, which were then capped and sealed without air space and frozen before they were brought back to the land laboratory for further subsection into 2–5 cm intervals. The subsectioned sediments were centrifuged to exclude pore-water and then freeze-dried. The dried samples were ground to powder using a mortar and pestle for further analyses. Each sediment sample was measured for trace metal contents using the methods for particulate metals described above. Meanwhile, each sediment sample was measured for ^{210}Pb to establish the chronology of sediment layers using the facilities and procedures set up by Dr. Y. Chung (Chung and Craig, 1983; Tsai, 1989). The sedimentation rates of sediments were then derived from the ^{210}Pb dating results.

RESULTS AND DISCUSSION

pH, DO, DOC and Dissolved Trace Metals in River and Estuarine Waters

The distributions of pH, DO and DOC in seven rivers and estuaries were shown in Figure 2. They are plotted against river sampling stations sequentially from upper to lower streams, and against salinity in estuaries. For convenient comparison, the data presented are only for the dry season when river flow was usually constant and relatively low. However, the distribution and transport of trace metals discussed in the latter text were based upon both dry and wet seasons. In general, pH and DO in river water decreased from upper to lower streams indicating the greater influence of inputs from catchment runoff and human activity. These effects may also determine the distribution of DOC which generally showed a contrasting pattern to DO. In

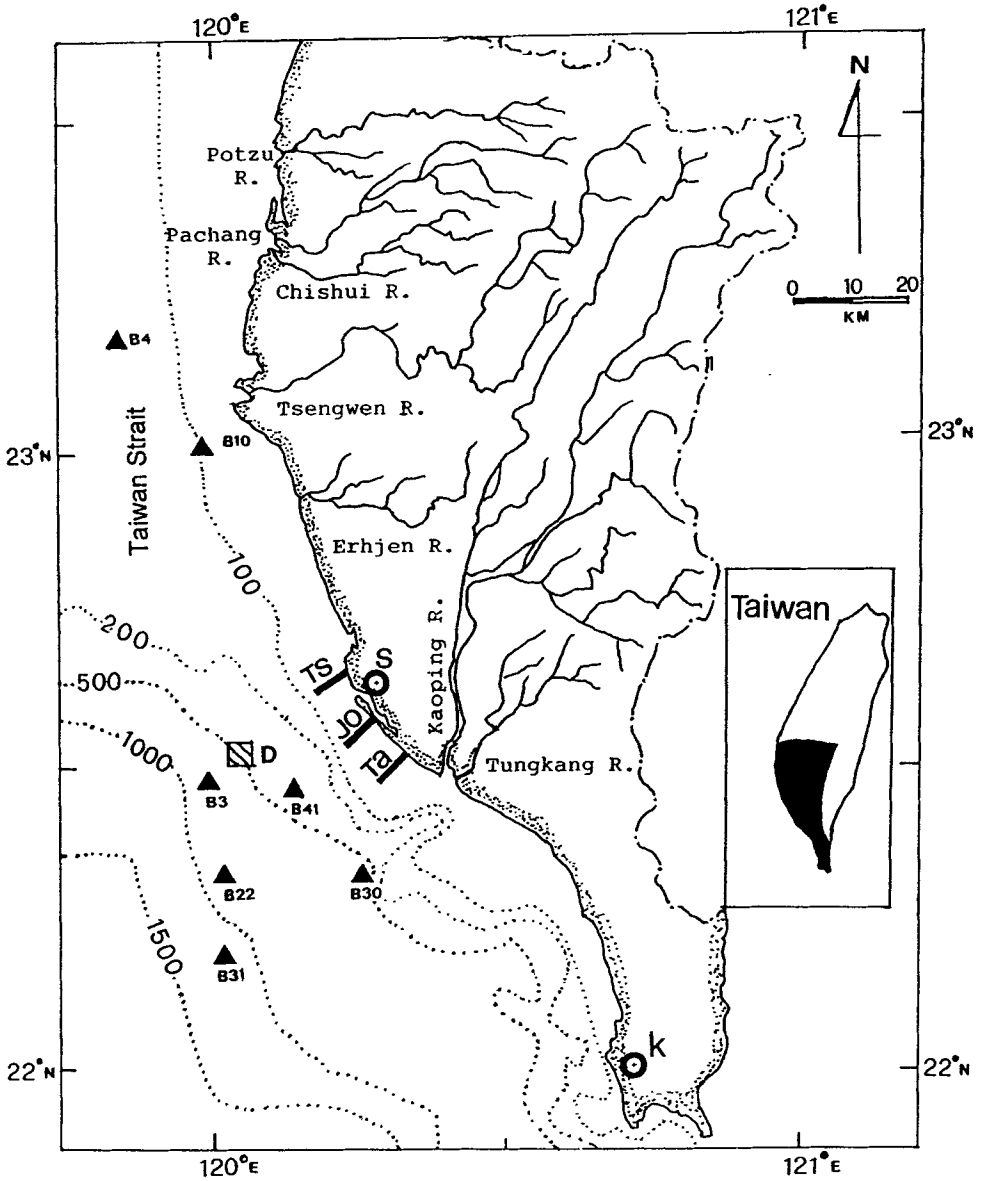

Figure 1 The map of study area; in addition to the labelled seven rivers, S and K are rain and aerosol sampling stations; Ts, Ch and Ta are sewage outfalls; D is a slag dumping site; ▲ are box core locations; contours (.....) are for depths (m).

estuaries, pH values generally increased as salinity increased as a result of gradual increase of sea water contribution, while DO usually decreased in the upper estuary due to the decomposition of enriched DOC (see DOC distribution) and unmeasured particulate organic carbon, and then increased toward the estuarine mouth due to the increase of mixing with oxygenated sea water.

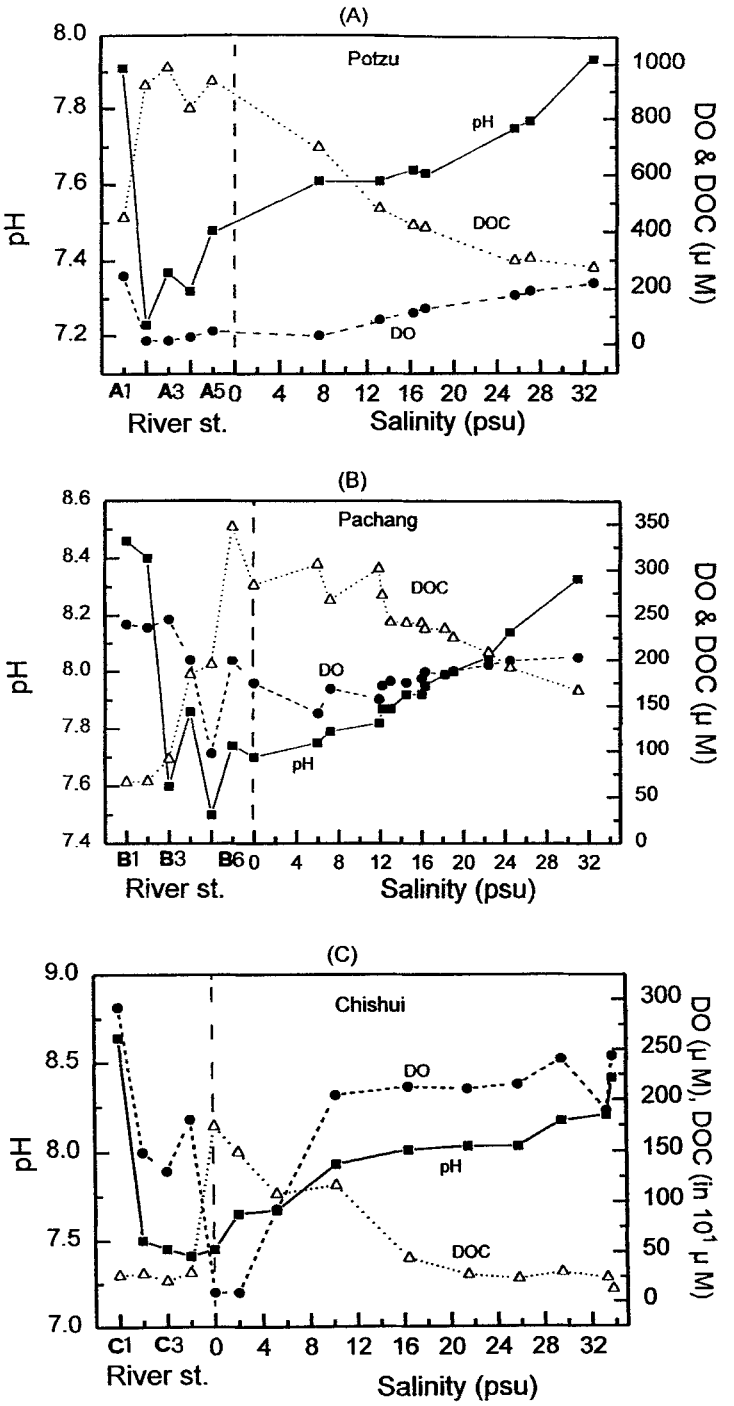

Figure 2(A–C) Distribution of pH, DO and DOC in riverine and estuarine waters of southwestern Taiwan; A, Potzu river; B, Pachang river; C, Chishui river.

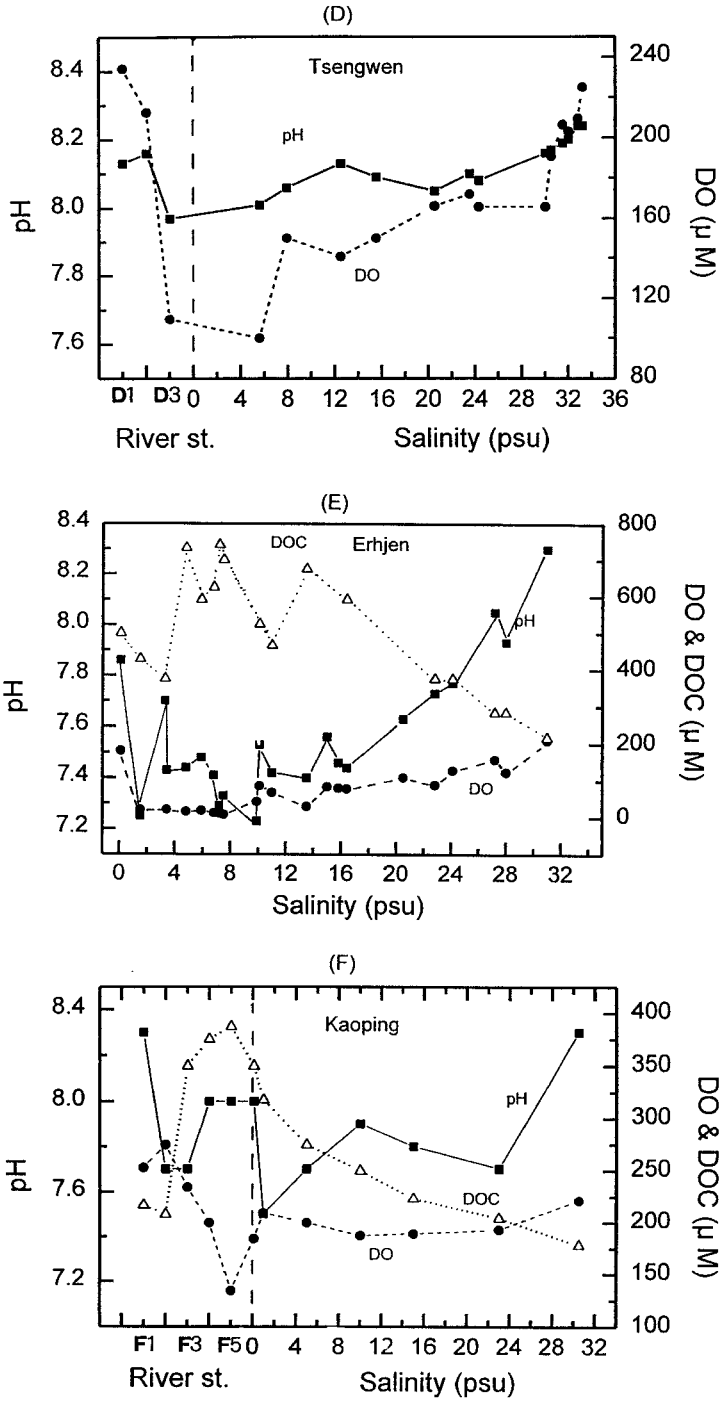

Figure 2(D–F) Distribution of pH, DO and DOC in riverine and estuarine waters of southwestern Taiwan; D, Tsengwen river; E, Erhjen river; F, Kaoping river.

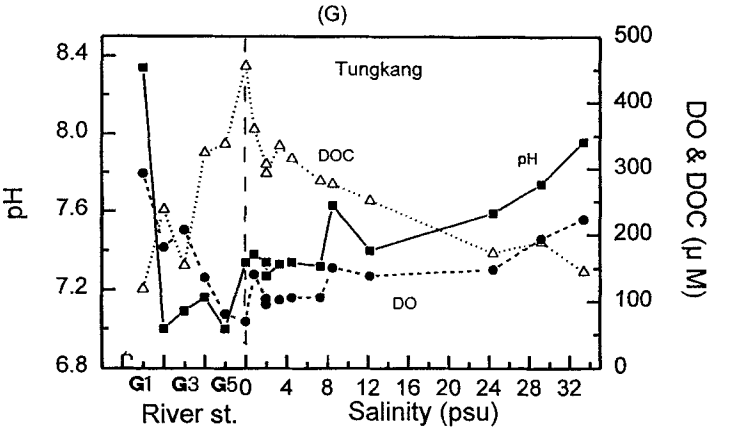

Figure 2(G) Distribution of pH, DO and DOC in riverine and estuarine waters of southwestern Taiwan; G, Tungkang river.

Distribution of DOC in estuaries is largely determined by the river inputs, and DOC apparently behaves non-conservatively as evidenced by its increase or slight reduction through the estuaries. The erratic distributions of pH, DO and DOC in the Erhjen estuary (E) were mostly due to direct discharge of pollutants into the estuarine region. Overall, the conditions of DO depletion and DOC enrichment in river and estuarine waters was closely correlated and both were induced mainly by pollution.

Concentrations of dissolved trace metals in river water (Table II) varied considerably within a river and among the rivers. However, the lowest concentration

Table II Distribution of dissolved metals ($\mu g l^{-1}$) in river and estuarine waters

River (R)/ Estuary (E)		Fe	Mn	Cd	Cu	Pb	Zn
Potzu	R	6.00–157	–	0.010–0.060	1.10–3.10	0.08–0.29	9.00–23.0
	E	4.00–190	–	0.010–0.030	1.10–2.80	0.20–0.35	4.80–9.0
Pachang	R	3.10–15.4	–	0.020–0.100	0.89–1.78	0.09–0.67	2.12–7.20
	E	1.40–11.0	–	0.020–0.137	0.69–1.40	0.10–0.32	1.90–6.90
Chishui	R	4.00–110	2.00–50.0	–	0.40–2.20	0.05–0.26	0.90–13.0
	E	5.00–1700	2.50–500	–	0.40–2.20	0.02–0.62	2.80–13.0
Tsengwen	R	8.20–23.3	7.10–16.0	0.040–0.110	1.09–3.30	0.82–1.14	4.40–24.4
	E	6.00–23.0	1.20–10.5	0.040–0.070	0.68–2.90	0.25–0.90	5.00–19.0
Erhjen	R	6.20–120	53.0–59.0	0.100–0.250	3.38–7.70	1.90–6.30	5.58–52.7
	E	5.00–760	–	0.003–0.900	0.61–27.0	0.07–1.56	5.00–55.0
Kaoping	R	7.00–24.0	1.30–4.80	0.030–0.060	1.02–2.30	0.32–0.50	6.40–16.2
	E	7.00–22.0	1.50–4.20	0.030–0.220	0.45–1.70	0.18–1.40	8.50–23.0
Tungkang	R	4.50–55.0	–	0.006–0.048	0.19–2.25	0.06–1.20	2.00–10.2
	E	3.50–36.0	–	0.010–0.070	0.25–1.60	0.04–1.10	1.00–10.0
Background[a]	R	55.0	6.00	0.020	1.00	0.20	10.0
Estuary[b] (U.S.A.)	E	0.03–283	0.28–549	0.002–0.096	0.32–3.81	0.004–0.19	0.79–11.8

a. Salomons and Forstner (1984)
b. Cutter (1991)

was generally found in the upper streams and the highest was found either in the middle or in the lower streams. The anomalously high concentrations of iron and manganese were found in lower Potzu, Chishui and Erhjen rivers where DO was severely depleted. The concentrations of cadmium, copper, lead and zinc in most regions of the rivers were greater than background values for world rivers (Salomons and Forstner, 1984). The distributions of metals in estuaries (Table II) were largely determined by the river contribution, but effects of metal discharges direct to some estuaries were also significant. As a consequence, the concentrations of metals were also elevated in estuaries, and displayed higher concentrations than those reported in American estuaries (Cutter, 1991). The metals usually behaved non-conservatively with exceptions of iron and manganese in oxygen-depleted estuaries and cadmium in most estuaries, although their distribution patterns are not presented here. Exceptionally high concentrations of copper and zinc and enrichment of other metals were found in the Erhjen lower river and whole estuary, apparently the result of dumping of waste from acid cleaning of metal scraps. Distributions of particulate metals (not shown here), in general, also displayed similar patterns to those of dissolved metals.

Riverine Gross and Net Fluxes of Trace Metals

The gross river fluxes of metals were estimated from dissolved and particulate metals discharged through the interface of river and estuary at zero salinity, while the net fluxes of metals were defined as those dissolved and particulate metals leaving the estuary. The gross fluxes of riverine metals were shown in Table III. The dissolved transport index (DTI), derived from the fraction of a total metal transported in the dissolved phase at zero salinity, was rather small for particle-reactive metals (Fe, Mn and Pb) except for iron and manganese under anoxic conditions. The DTI of iron was therefore higher in the Potzu, Erhjen and Chishui rivers than in the Pachang, Tsengwen, Kaoping and Tungkang rivers. The unusually high DTI of iron and manganese in the Chishui river may stem from its extremely high concentration of DOC. However, DTI was relatively higher for those nutrient-type metals (Cd, Zn and Cu) as defined and discussed by Bruland (1983). Overall, river trace metals were mainly transported as particulates with the exceptions of iron and manganese in the Chishui river and cadmium in most estuaries. The annual gross fluxes of dissolved and particulate metals were primarily determined by river discharge (correlation coefficient, $r = 0.9940$ for dissolved, $r = 0.9743$ for particulates) rather than by metal concentration, although the concentrations of dissolved and particulate metals were higher in down-stream river reaches and upper estuary due to anthropogenic pollution and depletion of dissolved oxygen. The total fluxes of metals therefore depend mainly upon river discharge which varied over 10 times (Table I) between the highest and lowest flows.

The net fluxes of trace metals are listed in Table IV, which were estimated by using a simple box model. The net fluxes were calculated from the difference between metals fluxed to the estuary (both from the river and from the coastal sea driven by tidal currents) and the amounts of metals trapped or released in the estuary (Hung and Huang, 1990). Except for cadmium and certain cases of iron and manganese (in suboxic to anoxic conditions), river metals are retained by one-third to a half approximately in estuaries before they are exported to the coastal water.

Table III Gross fluxes of trace metals from rivers

River	Trace metal	DTI	Gross flux (kg/yr)		
		%	Dissolved	Particulate	Total
Potzu	Fe	1.18	4850	$4{\cdot}06.10^5$	$4{\cdot}11.10^5$
	Cd	25.0	7.40	22.0	29.4
	Cu	28.0	572	1480	2050
	Pb	7.40	108	1350	1460
	Zn	30.0	2760	6450	9210
Pachang	Fe	0.140	6200	$4{\cdot}44.10^6$	$4{\cdot}45.10^6$
	Cd	53.0	59.0	52.0	111
	Cu	26.0	1030	2850	3880
	Pb	6.30	230	3370	3600
	Zn	20.0	4220	$1{\cdot}70.10^4$	$2{\cdot}12.10^4$
Chishui	Fe	15.0	$2{\cdot}34.10^5$	$1{\cdot}34.10^6$	$1{\cdot}56.10^6$
	Mn	71.0	$1{\cdot}01.10^5$	$3{\cdot}02.10^4$	$1{\cdot}43.10^5$
	Cu	3.00	500	$1{\cdot}61.10^4$	$1{\cdot}66.10^4$
	Pb	0.170	5.00	2960	2970
	Zn	8.30	1850	$2{\cdot}04.10^4$	$2{\cdot}23.10^4$
Tsengwen	Fe	0.350	$2{\cdot}23.10^4$	$6{\cdot}33.10^6$	$6{\cdot}35.10^6$
	Mn	4.30	8770	$1{\cdot}95.10^5$	$2{\cdot}04.10^5$
	Cd	29.9	47.0	110	157
	Cu	24.0	2470	7820	$1{\cdot}03.10^4$
	Pb	7.00	800	$1{\cdot}06.10^4$	$1{\cdot}14.10^4$
	Zn	26.0	$1{\cdot}53.10^4$	$4{\cdot}17.10^4$	$5{\cdot}70.10^4$
Erhjen	Fe	2.80	$2{\cdot}67.10^4$	$9{\cdot}23.10^5$	$9{\cdot}50.10^5$
	Cd	8.20	9.00	101	110
	Cu	6.60	380	5330	5710
	Pb	1.30	25.0	1940	1965
	Zn	1.45	3460	$2{\cdot}36.10^5$	$2{\cdot}40.10^5$
Kaoping	Fe	0.480	$1{\cdot}47.10^5$	$3{\cdot}06.10^7$	$3{\cdot}07.10^7$
	Mn	2.30	$2{\cdot}13.10^4$	$8{\cdot}92.10^5$	$9{\cdot}13.10^5$
	Cd	34.0	322	620	942
	Cu	12.0	$1{\cdot}03.10^4$	$7{\cdot}36.10^4$	$8{\cdot}39.10^4$
	Pb	6.30	$3{\cdot}73.10^3$	$5{\cdot}50.10^4$	$5{\cdot}87.10^4$
	Zn	28.0	$1{\cdot}03.10^5$	$2{\cdot}55.10^5$	$3{\cdot}58.10^5$
Tungkang	Fe	0.79	$6{\cdot}29.10^3$	$7{\cdot}86.10^5$	$7{\cdot}92.10^5$
	Cd	31.0	6.90	15.0	22.0
	Cu	18.0	800	3480	4280
	Pb	5.40	110	1910	2020
	Zn	16.8	1440	7110	8550

$$\text{DTI (Dissolved Transport Index)} = \frac{\text{Dissolved}}{\text{Total}} \times 100$$

Total Inputs of Terrigenous Metals

The total terrigenous metals transported into coastal environments via river net fluxes, atmospheric deposition and marine sewage discharges are shown in Table IV. The results show that river net fluxes of metals contribute from 65% of total lead to 92% of total iron and zinc. Atmospheric deposition and marine sewage discharges supplied only 5.3–31.5% and 0.6–6.9% of total inputs, respectively. Obviously, river net fluxes are still the most important sources of terrestrial metals in coastal environments. However, it should be pointed out that the contributions of river net fluxes and marine sewage discharges may decrease from nearshore to

Table IV Annual inputs of terrigenous trace metals off southwestern Taiwan

Trace metal	Net river input (10^3 kg/yr)	Marine sewage discharge (10^3 kg/yr)	Atmospheric input (10^3 kg/yr)	Total input (10^3 kg/yr)
Fe	32,400(92.2)	446(1.30)	2300(6.50)	35,100
Mn	1100(85.3)	62.20(4.80)	127(9.90)	1290
Cd	3.86(88.5)	0.026(0.60)	0.470(10.9)	4.36
Cu	167(74.9)	15.40(6.90)	41.0(18.2)	223
Pb	65.0(65.0)	3.45(3.50)	31.8(31.5)	100
Zn	1240(92.1)	35.30(2.60)	72.0(5.30)	1350

Values in parentheses are fractions (%) of total inputs

offshore, because the boundary scavenging of trace metals is more significant in the nearshore than offshore. In contrast, the relative contribution from atmospheric deposition may increase from the nearshore to offshore areas.

Sedimentary Fluxes of Trace Metals

The overall sedimentary fluxes of trace metals for the study area were integrated with data from cores as shown in Figure 1. However, only two box-core data, core B30 and core B3 will be presented and discussed here. The profiles of metal concentrations, metal/aluminium ratios and sedimentary metal fluxes for the two cores are shown in Figure 3 and 4. The core B30 was closer to the Taiwan Island than was the core B3, and the area of B30 receives the largest source of sediment in southwestern Taiwan from the Kaoping river. Thus, the sedimentary flux of sediment was 7.7 times higher in the core B30 (0.64 g/cm^2.yr) than in the core B3 (0.083 g/cm^2.yr). This resulted in much higher fluxes of metals in the core B30, even though the bulk density of core B3 was greater than that of core B30. The high values of metal concentrations, metal/aluminium ratios and metal fluxes were very conspicuous for cadmium, copper and lead and also discernible for zinc in the surface layers of core B30, indicating the influence of anthropogenic inputs. Similar phenomena of surface enrichment were also found in the site of core B41. This surface enrichment should not totally result from post-depositional diagenesis, since significant enrichment was discovered only for sites near Taiwan and was not found for surface iron and manganese. If background levels of metals in sediments are assumed from the uniform concentrations of metals in deep layers of cores, then the natural background concentration of each metal was found to be spatially variable (not shown for each core), the likely result of variation in size distribution and chemical composition of sediments in various cores. Nevertheless, the surface enrichment factor, as defined by Bloom and Crecelius (1987), was found in a sequence of Cd, Pb > Cu > Zn > Mn, Fe in the core B30. The enrichment of anthropogenic metals apparently started to rise from about 1976 which corresponds to the time of industrial boom in Taiwan. In contrast, core B3 did not show surface enrichment of trace metals although the background levels of metals were little different from those of core B30. Apparently, anthropogenic trace metals transported by rivers do not reach the site B3 significantly.

When the terrestrial inputs of metals are compared to the sedimentary fluxes of metals in coastal environments (Table V), terrestrial inputs are approximately balanced by sedimentary fluxes for nutrient-type metals (Cd, Cu and Zn). However,

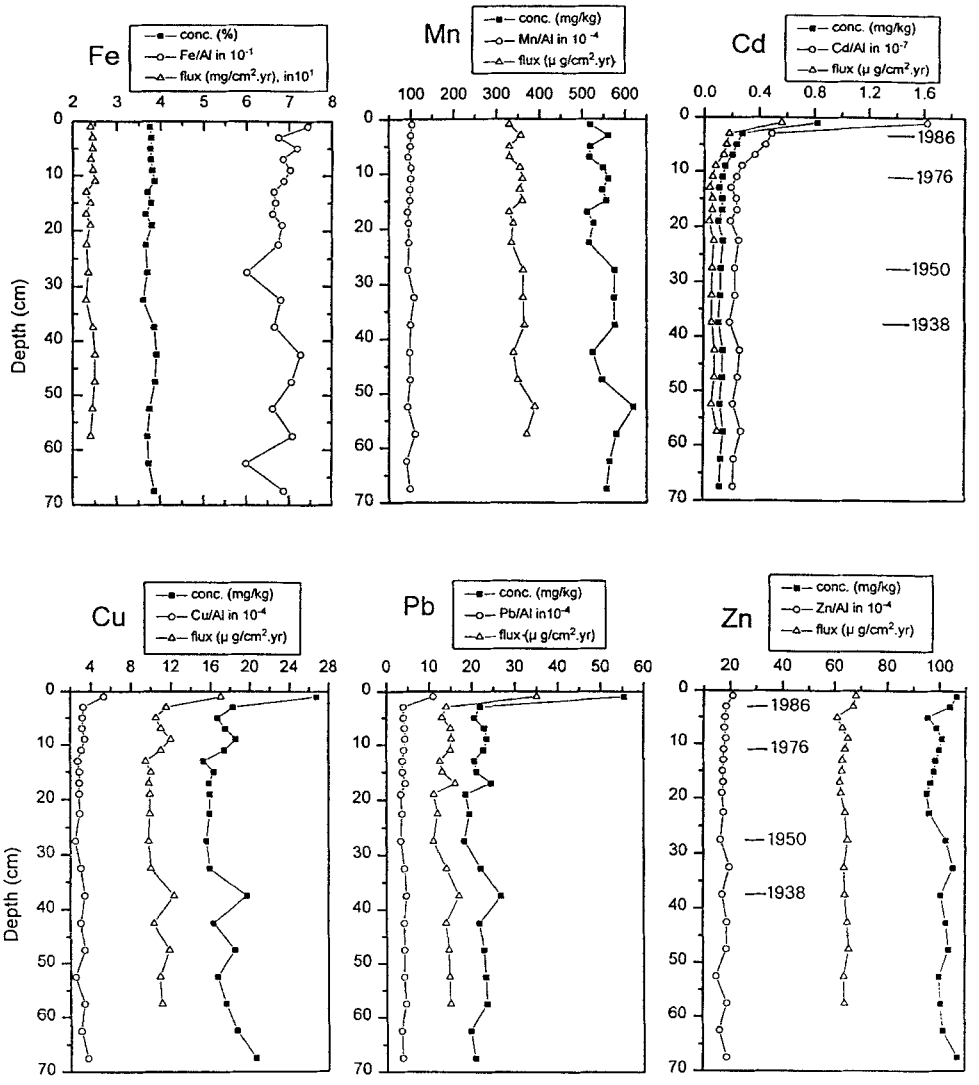

Figure 3 Profiles of metal concentrations, metal/Al ratios and sedimentary metal fluxes in the core B30.

terrestrial inputs were much less than sedimentary fluxes for particle-reactive metals (Fe, Mn and Pb). These results may arise from the overestimation of overall sedimentation rates of sediments in the study area due to insufficient sampling sites and the great variability of sedimentation rates, even though the overall metal fluxes have been estimated by using a weighted-average from box-core sites. However, this anomaly will not affect the truth of chronology, metal accumulation and metal fluxes for a single site. Meanwhile, the inputs of trace metals derived from the erosion of coastal land and from highly polluted small streams, which were not considered, may lead to the underestimation of total metal inputs.

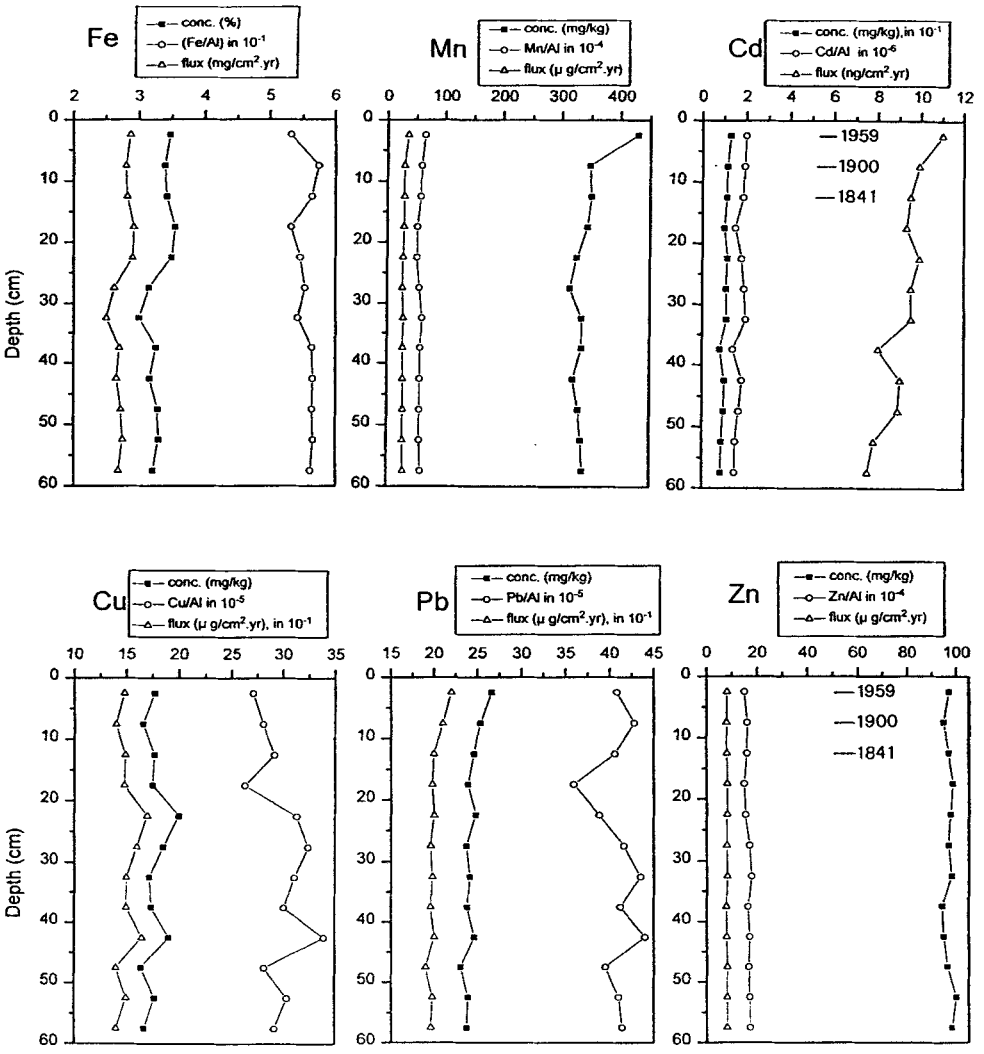

Figure 4 Profiles of metal concentrations, metal/Al ratios and sedimentary metal fluxes in the core B3.

Table V Comparisons of trace-metal budgets between total terrigenous inputs and sedimentary fluxes off southwestern Taiwan

Trace metal	Total input (10^3 kg/yr)	Sedimentary flux (10^3 kg/yr)
Fe	35,109	470,850
Mn	1289	5805
Cd	4.36	5.25
Cu	223	246
Pb	100	414
Zn	1348	1310

CONCLUSION

The sources and sinks of trace metals in the southeastern Taiwan Strait were studied comprehensively. With certain exceptions, river trace metals were transported non-conservatively through the estuaries. The net fluxes of river borne metals contributed from 65 to 92% of total metal inputs into coastal environments. Atmospheric deposition and marine sewage discharges supplied only 5.3–31.5% and 0.6–6.9% of total metal inputs. The sedimentary fluxes of metals were spatially variable but surface metal enrichment was found in the nearshore sediment and was general in a sequence of Cd, Pb > Cu > Zn > Mn, Fe. The imbalance between total terrigenous inputs and sedimentary fluxes indicates that sedimentary fluxes may have been overestimated, and/or certain unmeasured inputs have been ignored. Further evaluation of sources and sinks of trace metals are suggested and data could be revised.

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References

Bloom, N.S. and Crecelius, E.A. (1987) Distribution of silver, mercury, lead, copper and cadmium in central Puget Sound sediments. *Marine Chemistry*, **21**, 377–390.

Bruland, K.W. (1983) Trace elements in sea water. In *Chemical Oceanography*, J.P. Riley and R. Chester (eds). Vol. **8**, 157–220, Academic Press, London.

Byrd, J.T. and Andreae, M.O. (1986) Geochemistry of tin in rivers and estuaries. *Geochimica et Cosmochimica Acta*, **50**, 835–845.

Chuang, J.Y., Chiang, P.C., Wang, C.M., Yang, M.H., Lin, J.S., Shan, S.H. and Tsai, H.T. (1987) *Application of Source-Receptor Model to Study Air Pollutants in the Kaohsiung Area*. EPA(ROC) report, 207 pp.

Chung, Y. and Craig, H. (1983) Pb-210 in the Pacific: the GEOSECS measurements of particulate and dissolved concentrations. *Earth and Planetary Science Letters*, **65**, 406–432.

Church, T.M. (1986) Biogeochemical factors influencing the residence time of microconstituents in a large tidal estuary, Delaware Bay. *Marine Chemistry*, **18**, 393–406.

Cutter, G.A. (1991) Trace elements in estuarine and coastal waters-U.S. studies from 1986–1990. *Reviews of Geophysics*, Supplement, 639–644.

Danielsson, L., Magnusson, B., Westerlund, S. and Zhang, K. (1982) Trace metal determinations in estuarine waters by electrothermal atomic absorption spectrometry after extraction of dithiocarbamate complexes into freon. *Analytica Chimica Acta*, **144**, 183–188.

Eaton, A. (1979) Observations on the geochemistry of soluble copper, iron, nickel and zinc in the San Francisco Bay estuary. *Environment Science and Technology*, **13**, 425–432.

GESAMP (1987) *Land/Sea Boundary Flux of Contaminants. Contributions from Rivers*. Report and Studies No. 32. Unesco, Paris, 49 pp.

Hung J.J. (1988) Determination of trace metal species in the suspended matter of riverine and estuarine waters. *Journal of the Chinese Chemical Society*, **35**, 199–124.

Hung, J.J. (1990) Transport and behavior of trace metals in the Tsengwen river and estuary. *Terrestrial, Atmospheric and Oceanic Sciences*, **1**, 275–296.

Hung, J.J. and Chang, W.A. (1992) Measurement of dissolved organic carbon in seawater: A comparison between the high-temperature catalytic oxidation method and the persulfate oxidation method. *Terrestrial, Atmospheric and Oceanic Sciences*, **2**, 165–181.

Hung, J.J. and Huang, C.C. (1990) Geochemical distribution and transport of trace metals in the Kaoping riverine, estuarine and coastal waters. *Proceedings of the National Science Council, ROC(A)*, **14**, 410–421.

Hung, J.J. and Wang, C.K. (1992) Behavior of dissolved and particulate trace metals in an oxygen-deficient (Chishui) river and estuary. *Proceedings of the National Science Council, ROC(A)*, **16**, 212–222.

Hung, T.C. (1983) Study on heavy metals in rivers and estuaries of western Taiwan, Republic of China. *Journal of the Chinese Environment Protection Society*, **6**, 1–9.

Kou, J.L. and Hung, T.C. (1987) Investigation of water quality and ecological environment near the Erhjen estuary. *Taiwan Environment Protection*, **5**, 9–19.

Salomons, W. and Forstner, U. (1984) *Metals in the Hydrocycle*, Springer-Verlag, New York, 349 pp.

Shih, S.J. (1992) *Trace Elements in Marine Aerosols over the Penghu Islands*, M.S. thesis, National Taiwan University, ROC, 96 pp.

Sholkovitz, E.R. (1978) The flocculation of dissolved Fe, Mn, Al, Cu, Ni, Co and Cd during estuarine mixing. *Earth and Planetary Science Letters*, **41**, 77–86.

Statham, P.J. (1985) The determination of dissolved manganese and cadmium at low nmol l^{-1} concentrations by chelation followed by electrothermal atomic absorption spectrometry. *Analytica Chimica Acta*, **169**, 149–159.

Sturgeon, R.E., Berman, S.S. and Willie, S.N. (1982) Concentration of trace metals from seawater by complexation with 8-hydroxyquinoline and adsorption on C18-bonded silica gel. *Talanta*, **29**, 167–171.

Tsai, S.W. (1979) *Application of Pb-210 Chronology to Sediments in the Taiwan Strait*, M.S. thesis, National Sun Yat-Sen University, ROC, 81 pp.

Windom, H.L., Dulamge, R. and Storti, F. (1983) Behavior of copper in southeastern United States estuaries. *Marine Chemistry*, **12**, 183–193.

Windom, H.L., Schropp, S.J., Calder, F.D., Ryan, J.D., Smith, R.G., Burney, L.C., Lewis, F.G. and Rawlinson, C.H. (1989) Natural trace metal concentrations in estuarine and coastal marine sediments of the southeastern United States. *Environmental Science and Technology*, **23**, 314–320.

Yeats, P.A. and Bewers, J.M. (1982) Discharge of metals from the St. Lawrence River. *Canadian Journal of Earth Sciences*, **19**, 983–992.