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Pollution and ecological risk assessments for heavy metals in coastal, river, and road-deposited sediments from Apia City in Upolu Island, Samoa

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Abstract :

This study was the first to investigate the pollution and ecological risks of heavy metals in coastal, river/stream and road-deposited sediments (RDS) from Apia in Samoa. Cr and Ni concentrations in sediment samples were higher than those of other metals. River sediments and RDS had relatively high EF values around the intensive commercial areas, with a moderate to significant enrichment of Cu, Zn, Cd, and Pb. The results indicate that Cr and Ni have a natural origin from volcanic parent materials, while Cu, Zn, Cd, and Pb originated from anthropogenic activities, such as traffic emissions and the discharge of municipal wastewater. The assessments of pollution and ecological risk revealed that coastal sediments adjacent to the river are anthropogenically contaminated and present a moderate ecological risk. This study demonstrates that metals that have accumulated in the urban impermeable layer and river/stream bed have flowed into the coastal environment through runoff.

Highlights

► Metal concentrations of sediment were investigated for the first time in Samoa. ► Cr and Ni in sediments were strongly influenced by the origin of volcanic materials. ► River and road-deposited sediments were contaminated with Cu, Zn, and Cd. ► Metal contaminants were attributed to vehicle transport and municipal wastewater.

Keywords : Metal pollution, Coastal environment, Runoff, Enrichment factor, Pollution load index, Potential ecological risk index

Rapid urbanization is significantly increasing the impervious area and stormwater runoff in urban areas, causing environmental problems such as water quality deterioration and sediment pollution in the surrounding environment (Liang et al., 2020; Zhang et al., 2021). Because stormwater runoff does not flow into the sewer drainage system, it is very difficult to prevent it from entering the surrounding environment without undergoing any treatment process. Stormwater runoff in urban and industrial regions transports significant amounts of suspended particles and chemicals to riverine and coastal environments (Shen et al., 2015; Gong et al., 2016; Rhee et al., 2012). The United States has designated urban stormwater runoff as the one of largest contaminant sources (USEPA, 1990). Suspended particles, which account for a large portion of the stormwater runoff, can accumulate high concentrations of organic matter and heavy metals. Therefore, it is important to manage non-point pollution sources derived from precipitation consistently (Liu and Sansalone, 2020; Jeong et al., 2020a; Zhang et al., 2021).

Road-deposited sediment (RDS) in the urban environment is severely polluted with polycyclic aromatic hydrocarbons (PAHs) and heavy metals worldwide due to traffic and industrial activities (Alghamdi et al., 2022; Al-Shidi et al., 2020; Bisht et al., 2022; Yusuf et al., 2022; Xu et al., 2022). Khpalwak et al. (2019) reported that the PAHs concentration in urban road dust was higher than that in aerial dust. RDS is an important source of metal pollution in the surrounding rivers and coastal areas (Skorbilowicz et al., 2022; Jeong et al., 2020b; 2020c). The roughness of the paved road surface, the relative abundance of RDS by particle size, and the intensity of precipitation influence the transport processes and pathways of RDS particles to the surrounding environment along with stormwater runoff (Mikelonis et al., 2021; Zhao et al., 2018; 2022). Many studies have found that the heavy metal concentration in RDS increases with decreasing particle size (Jeong and Ra, 2022a; Logiewa et al., 2020). Guo et al. (2020) performed a toxicity test of the heavy metals in road dust using two different living organisms. They reported that heavy metals such as Zn, Ni, and Cu attached to RDS had a toxic effect on algae, and proposed that mammalian cell-based and algal-based toxicities are related to human health and ecological risks, respectively. If RDS polluted with heavy metals continues to flow into the ocean through rivers, it will have a detrimental effect on ecosystems in the coastal environment.

Samoa is an island that originated from a volcanic eruption. It consists of the two main islands of Savai'i and Upolu and four small islands. Its climate is characterized by uniform temperatures, high precipitation, and humidity. The annual precipitation ranges from 3,000 to 6,000 mm, with about 75% occurring between November and February. Apia is the capital of Samoa with a population of 35,000, and is located on the northern coast of Upolu. Business, tourism, government, and shopping facilities are concentrated in Apia. There are several rivers and streams flowing through Apia City, and Apia port is located at the estuary of Vaisigano River. Specific environmental characteristics such as intensive rainfall, steep slopes, tectonic uplift, and removal of tropical forest tend to be facilitated fluvial processes of high volcanic islands in the tropical South Pacific (Terry et al., 2006). Over the past decade, Samoa has made enormous commercial progress and its coastal areas are used for mercantile and fishing activities (Imo et al., 2014). The Apia port is one of the most frenetic international shipping routes in the Pacific region and increased maritime traffic in Apia port can pose a threat to adversely affect the marine environment (Imo et al., 2014). Vaisigano River in Samoa showed a 'near-catastrophic' flood variability index, implying that the high floodplain deposition rate on Upolu Island may have been affected by large-scale flooding, and it suggested the world's highest fluvial sedimentation rates for tropical Pacific islands (Terry et al., 2006). Bottom sediment is a final reservoir of various pollution sources in coastal environments and the benthic zone can accumulate heavy metals precipitated from the aquatic environment (Dash et al., 2021; Redwan and Elhaddad, 2022). Hence, pollution and ecological risk assessments of sediments are momentous to protect the coastal environment and prepare for potential adverse effects on the surrounding ecosystems. Ecological risk assessment can be used to predict the likelihood of future negative impacts or to systematically assess the likelihood of impacts arising from past exposure to a stressor (Wei et al., 2022). Tracking metal contaminants is important to sustainably manage and protect the aquatic environment (Abadi et al., 2018; Zhang et al., 2019; Logiewa et al., 2020; Gao et al., 2021), but there are still few studies on tropical Pacific islands. Therefore, the purpose of this study is to determine the spatial distribution and the metal pollution level and to estimate the potential ecological risk in coastal, river/stream sediment, and RDS around Apia City in Samoa.

Twenty coastal sediments were collected from Apia Bay using a grab sampler in July 2014 (Fig. 1). A total of twenty-four river/stream sediments were collected from Vaisigano River (A), Valima River (B), Vaimoso Stream (C), and Fuluasau River (D) in Apia City using a sampler, in which a plastic scoop was connected to a PVC pipe. When sampling coastal and river sediments, care was taken to not disturb the surface layer, and about 1 cm of the surface layer was sampled with a plastic spoon. The RDS samples were collected at eighteen sampling sites around Apia City using a cordless vacuum cleaner (DC-35, Dyson Co., UK). The detailed sampling procedure is described in Jeong et al. (2020a). Four surface soils (0–1 cm) were sampled around the uppermost part of the river. All sediment samples collected from the study area were immediately frozen. After being transferred to the laboratory, samples were freeze-dried (UnifFreeze FD-8, Daihan Scientific Co, Korea) and pulverized (Pulverisette 6, Fritsch co., Germany) for a subsequent heavy metal analysis.

The analysis of heavy metals in the sediment samples was performed using a mixture of HF-HNO_3-$HClO_4$ for a total digestion procedure (Jeong et al., 2020a). The Al, Cr, Ni, Cu, Zn, As, Cd, and Pb concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS; iCAP Q, Thermo Fisher Scientific, Germany) at the Korea Institute of Ocean Science and Technology (KIOST). Hg concentration was determined using a direct mercury analyzer (Hydra-C, Leeman Labs, USA). The method detection limits of heavy metal analysis in this study were 0.11 mg/kg for Cr, 0.14 mg/kg for Ni, 0.09 mg/kg for Cu, 0.18 mg/kg for Zn, 0.08 mg/kg for As, 0.0003 mg/kg for Cd, 0.04 mg/kg for Pb, and 0.0002 mg/kg for Hg (Table S1). All analytical procedures were performed in a clean room (Class 1000) of KIOST, with high purity acids (Suprapure grade) for metal analysis. For quality control, three certified reference materials (CRMs; MESS-4 and PACS-4 from NRCC), and BCR-723 from IRMM) were analyzed in the same procedure as the sediment samples. The CRM recoveries were ranged from 94.2% (Ni) to 104.2 (Pb) for MESS-4 (n = 8), from 96.7 (Cu) to 100.4 (As) for PACS-3 (n = 8), and 96.7 (Cr) to 103.1 (Zn) for BCR-723 (n = 8), which was consistent with the certified and indicative values (Table S1).

To evaluate the degree of metal pollution from individual elements in the sediment samples of this study, the enrichment factor (EF) was calculated using Al as a conservative element as follows (Sutherland, 2000):

$$\mathrm{EF} = \frac{(\mathrm{C_n/Al})_{\mathrm{sample}}}{(\mathrm{B_n/Al})_{\mathrm{background}}}$$

where C_n is the concentration of heavy metals in sediment samples. Because the regional background value was not reported. The concentrations in upper continental crust reported by Rudnick and Gao (2003) were used as the background concentration (B_n).

The comprehensive contamination level of eight metals in this study was calculated using the pollution load index (PLI) as follows (Tomlinson et al., 1980):

$$\mathrm{PLI} = \sqrt[8]{\mathrm{CF_{Cr} \times CF_{Ni} \times CF_{Cu} \times CF_{Zn} \times CF_{As} \times CF_{Cd} \times CF_{Pb} \times CF_{Hg}}}$$

where CF is the contamination factor between sediments (C_n) and background values (B_n). A PLI value greater than 1 indicates the presence of anthropogenic pollution.

The potential ecological risk index (RI) is the sum of the individual factor ecological risk degree (E_r^i) and is calculated by the following equation (Hakanson, 1980):

$$\mathrm{RI} = \sum E_r^i, \qquad E_r^i = T_r^i \times (C_n / B_n)$$

where T_r^i is the toxicity response factor for each metal (Hg = 40, Cd = 30, As = 10, Cu = Ni = Pb = 5, Cr = 2, Zn = 1). C_n and B_n are the metal concentrations in sediments and the background value in the EF calculation, respectively. The RI values were classified into four grades between low risk (RI < 150) and serious risk (RI > 600). The E_r^i values were classified into five grades between low risk (E_r^i < 40) and very high risk (E_r^i > 320).

Statistical analysis (Pearson correlation matrix, principal component analysis; PCA, and hierarchical cluster analysis; HCA) were performed using PASW Statistics 18. Pearson's correlation analysis was carried out to present the relationships among various metals in sediments. PCA results of elemental concentrations extracted reduced-dimensional data with varimax rotation. A dendrogram of HCA was produced by multivariate statistics with the average linkage method (between groups).

The mean concentration of individual heavy metals in the coastal sediments was highest for Cr at 368 mg/kg, and followed by Ni at 161 mg/kg (Table 1). Samoa consists of a series of volcanic islands, with some volcanoes still being active, including its largest island. Several studies have reported high Cr and Ni concentrations in soils in islands formed by volcanic activity (Ahn and Chon, 2010; Doelsch et al., 2006, Kelepertsis et al., 2001). Surface soil of this study had higher concentrations of Cr and Ni than Reunion island, but lower than Susaki area (Greece) (Table 1). The Susaki region of Greece was affected by ultramafic rocks which caused natural contamination of these metals in the soil (Kelepertsis et al., 2001). The Cr and Ni concentrations in the surface soil around the upstream of rivers from Samoa were 619 and 376 mg/kg, respectively. The concentrations of these metals were higher than those of the other metals.

The coastal sediments in Apia Bay, Samoa, consist of calcium carbonate derived from coral atolls and terrigenous sediments. The Al concentrations in the coastal sediments ranged from 0.1 to 8.1%, with large regional variability (Fig. 2). The coefficient of variation (CV) for heavy metals in different sampling sites had a high variability (81–111%). Heavy metal concentrations were relatively high at sampling sites close to the land (M1–M4, M17–M20). Particularly, Cu, Zn, Cd, Pb, and Hg concentrations were very high at sites M17 and M19, which were in the vicinity of a fish market and harbor. Heavy metal contents in this study were higher than those reported in Palau, Chuuk, Tahiti, and Tonga (Table 1). However, Zn levels were similar to that of Suva Bay, which has several harbors and is located in the capital city of Fiji. These results suggest that the origin of heavy metals in the study area was mainly terrigenous sediments, but there were also anthropogenic sources due to human activities.

The mean concentrations (mg/kg) of the individual heavy metals in the river sediments followed the decreasing order of Cr > Ni > Zn > Cu > Pb > As > Cd > Hg (Table 1). The upstream area had a relatively low concentration of heavy metals, and metal concentration tended to increase toward the downstream. In river sediments, the CV values for heavy metals (except Pb and Hg) had moderate variability (19–67%). The Cr and Ni concentrations were high in the Vaisigano River, where the mean concentrations of the other metals were lowest (Fig. 2). This indicates that the metal sources in this river mainly have natural origins. The mean concentrations of individual heavy metals were observed to be much higher in Valima River for Cu, Zn, Pb, ang Hg, and in Vaimoso Stream for As and Cd. Heavy metals such as Zn, Cd, and Pb had high concentrations at the C4 and B5 sites, where large-scale commercial facilities (markets, banks, electronic and hardware stores) were located. However, relatively low Cr and Ni concentrations were observed in the sediments at these sites. The Sogi wastewater treatment plant (WWTP) is located in the city of Apia, but sewerage networks are limited to commercial and governmental agencies located within the Apia central business district. Urban wastewater discharged through the sewer system from domestic households without sufficient treatment may be a source of heavy metal pollution in river sediments. Abadi et al. (2018) have reported that the high concentration of heavy metals in coastal areas is mainly caused by the increasing discharge of urban wastewater from surrounding cities. These results indicate that heavy metal pollution in the river sediments of Apia is influenced by human activities, such as traffic activity and the discharge of municipal wastewater, rather than having a natural from the volcanic parent material.

The Cu, Cd, and Pb concentrations of the river sediments in Samoa had lower mean values than those reported in Hawaii and Fiji (Table 1). However, the Zn concentration was about three times higher than that of the Nakuvadra-Rakiraki River in Fiji.

The mean Cr, Ni, Cu, Zn, As, Cd, Pb, and Hg concentrations in RDS were 449, 300, 81.6, 277, 4.5, 0.26, 28.2, and 0.015 mg/kg (Table 1). The CV values of heavy metals varied between 14% and 67%, with small differences between sampling sites compared to coastal and river sediments. Compared to other urban cities, Cr and Ni contents in RDS were higher than Busan (Korea), Isfahan (Iran), Dehradun (India), and Suva (Fiji), however, the other metals (Cu, Zn, As, Cd, Pb, and Hg) showed lower concentrations than those in these regions (Table 1). Cr and Ni concentrations in RDS were lower than those of surface soil and river sediments, which were highly affected by volcanic ash soils providing a natural source of the metals. However, the mean Cu, Zn, As, and Pb concentrations were 1.2 (Cu) to 2.2 (Pb) times higher in RDS than in surface soil. Tire and brake wear from traffic activities are the dominant pollution source of Cu, Zn, Cd, and Pb in RDS from urban areas (Aguilera et al., 2022; Huang et al., 2022; Jeong, 2022; Jeong et al., 2022c; Zglobicki and Telecka, 2021). The highest Cu, Zn, Cd, and Pb concentrations in RDS were found at site R5, which was located on a beach road with high tourism activities, and at sites R17 and R18, which had wide lanes and high volumes of traffic.

The mean Cu, Zn, Cd, and Pb concentrations related to traffic activity in Samoa were much lower than in other large cities of the world (Table 1). In particular, there was showed a lower concentration of heavy metals compared to Fiji, which is geographically close and has a similar climate. Heavy metal concentrations in RDS are related to the land-use type, population density, traffic volume, and frequency of road cleaning (Birch and Scollen, 2003; Jeong et al., 2020d; Loganathan et al., 2013; Miazgowicz et al., 2020; Trujillo-Gonzalez et al., 2016). According to the Land Transport Authority, there were about 18,000 registered vehicles in Samoa in 2014, accounting for only 18% of the number of registered vehicles in Fiji (LTA, 2015). Private cars accounted for about 60% of the total, and vans, taxis, pickups, and buses used in the tourism industry accounted for about 34%. The low level of metal contamination in the RDS of Samoa was attributed to the lower level of traffic activity compared to other cities.

The EF results for heavy metals in this study are presented in Table 2. The mean EF value in the coastal sediments followed the descending order of Cr > Ni > Cd > Zn > As > Cu > Hg > Pb. There was significant enrichment of Cr and Ni, whereas for Cu, Zn, As, Cd, and Hg there was moderate enrichment. The highest EF values for all sediment samples in this study were found for Cr and Ni, indicating that these metals were significantly enriched compared to the other elements (Table 2). This result indicates that the Cr and Ni derived from volcanic soil were primarily deposited on the road surface and then transported to the coastal zone through rivers and streams during rainfall. Of the four different rivers, the Vaisigano River, which had the lowest mean EF values of Cu, Zn, As, Cd, Pb, and Hg, and the highest mean EF results for Cr and Ni. In the Valima River and Vaimoso Stream, the mean EF values of Zn and Cu slightly exceeded 5, indicating significant enrichment. River sediments also had a relatively high EF value in sampling sites around commercial areas compared to residential areas.

In RDS, heavy metals excluding As and Hg had the highest mean EF value compared to river and coastal sediments. The mean EF values for heavy metals in RDS followed the decreasing order of Ni > Cr > Zn > Cu ≈ Cd > Pb > As > Hg. The EF values of Cu, Zn, Cd, and Pb in RDS were higher than those in river sediments. The mean EF values for Cu, Zn, and Cd were 6.2, 9.0, and 6.2, which means that these metals were significantly enriched in RDS. The mean EF of Pb was 3.5, indicating moderate enrichment, with a range from 1.3 to 9.0. At sites R7 and R8 in downtown Apia City, where bank and shopping facilities are concentrated and vehicles are parked along the road, Pb was significantly enriched in RDS, with an EF value of 9.0. These results suggest that the enrichment of these metals might be related to non-exhaust emission sources from traffic activity.

The spatial distribution of PLI values in coastal and river sediments and RDS is shown in Fig. 3. At sampling sites close to rivers and streams in Apia Bay (M1–M4, M17–M20), the PLI value exceeded 1, indicating anthropogenic input of heavy metals derived from the terrestrial area. The surface soils, which originated from the volcanic parent material, had high Cr and Ni concentrations and had a large influence on the sediments in Samoa. As a result of calculating the PLI of six metals (Cu, Zn, As, Cd, Pb, and Hg), PLI values exceeding 1 were also found at these sampling sites. The mean PLI values of river sediments followed the order of Valima River (4.0) > Fuluasau River (2.5) > Vaimoso Stream (2.0) >Vaisigano River (1.5). The PLI value of river sediments had a tendency to increase from upstream to downstream, but increased significantly around commercial areas, indicating the presence of an anthropogenic pollution source for heavy metals. The mean PLI value decreased in the order of river sediment (2.5) > RDS (2.0) > coastal sediments (1.2). The reason for the high PLI value of river sediments was probably because they are simultaneously affected by inputs of small RDS particles with a relatively high metal concentration during rainfall and the discharge of municipal wastewater.

Table 3 shows the ecological risk degree (E_r^i) for individual elements. Cd presented a considerable risk in three river sediments (Valima, Vaimoso, and Fuluasau) and RDS, with the mean E_r^i value exceeding 80. Most metals including Cr and Ni with the highest concentration in all sediment samples indicated low potential ecological risks for these metals. The mean RI, which was the sum of all of the individual ecological risk values (E_r^i), was highest (271) in river sediment, followed by RDS (176) and coastal sediment (105). For river sediments, the RI values at the 6 sampling sits of B3, B5–B7, and C4–C5 exceeded 300, but were less than 600 and a considerable potential risk was identified (Fig. 3). Most river sediments had RI values in the range of 150 to 300, presenting a moderate potential risk. The RI values of coastal sediments and RDS were less than 300. Coastal sediments exceeded 150 in the 8 sampling sites close to the river and land. Most of the RDS sampling sites had RI values between 150 and 300, indicating a moderate ecological risk.

Zn and Cd had significantly positive correlation with all metals (Table S2). Particularly high correlations were observed in Cr and Ni ($r = 0.852$), Zn and Cd ($r = 0.854$) at the significant level of 0.01 ($p < 0.01$) (Table S2). In this study, Cr and Ni may have been originated from natural materials of volcanic parent. On the other hand, Pb and As were weakly correlated with Cr and Ni, suggesting that they could be derived from different sources.

Principal components (PCs) presented in Table S3 extracted eigenvalues greater than 1 and marine, river, and road-deposited sediments showed dissimilar characteristics of principal components. PC1 of river sediments accounted for 63.4% of the total variance with high loadings of Al, Zn, As, Cd, Pb, and Hg. The 13.3% of the total variance was explained by PC2 contained Cu component. Road-deposited sediments were extracted 4 components in PCA results explaining 78.6% of the total variance (Table S3). PC1 was dominated by Cr and Ni accounted for 28.9%, and Cu and As were contained in PC2 explained 22.8%. Meanwhile, all of the metals in marine sediment were explained by first principal component (87.4% of the total variance), revealing mixture of the multiple metal sources.

In Fig. 4, marine sediments contributed in PC1, whereas road-deposited sediments were dominated in PC2. River sediments were revealed mixing between marine and road-deposited sediments, exceptionally C4, C5, and B5 located in large-scale commercial facility appeared close to road-deposited sediments.

HCA results showed that Group 1 contained Cr and Ni, indicating these elements predominantly influenced by the geochemical processes of natural parent materials (Fig. S1). Group 2 was composed of As element and the other metals were included in Group 3, implying their sources other than natural origins.

Due to the rapid development of Samoa, a volcanic island in the South Pacific, metal contamination in the surrounding coastal environment is a concern, and appropriate management measures and approaches are desired. The present study evaluated the degree of metal pollution and potential ecological risks in coastal, river, and road-deposited sediments in Samoa. The Cr and Ni contents in all samples were higher than those of other metals, and these elements (Cr and Ni) were predominated by natural origins from the volcanic parent material. Active commercial areas had relatively higher Cu, Zn, Cd, and Pb contents in river sediments and RDS than residential areas. Nevertheless, the metal pollution level of river sediment and RDS in Samoa is currently lower than in other large cities around the world. However, the number of vehicles in the country increased from 17,705 in 2014 to 25,793 in 2019, and increased transport activities associated with tourism and urbanization have the potential to aggravate metal contamination in the RDS. Wind-resuspended fine RDS particles can be directly inhaled through the nose and mouth and can have detrimental health effects on humans. Moreover, they are transported and deposited in the coastal environment by stormwater runoff and bioaccumulated in living marine organisms, which can pose a risk to human health. Consequently, metal pollution was affected by both non-exhaust emission sources related to traffic activity and the outflow of urban wastewater. This work suggests the need for appropriate and economical road cleaning strategies to protect and conserve the coastal environment in Samoa. The results also emphasize efficient management of municipal wastewater from residential and commercial districts in order to preserve the surrounding ecosystems. It can be used as helpful information for improving management policies of maritime environments in Samoa.

CRediT authorship contribution statement

Hyeryeong Jeong: Conceptualization, Visualization, Writing – original draft. **Kongtae Ra:** Investigation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

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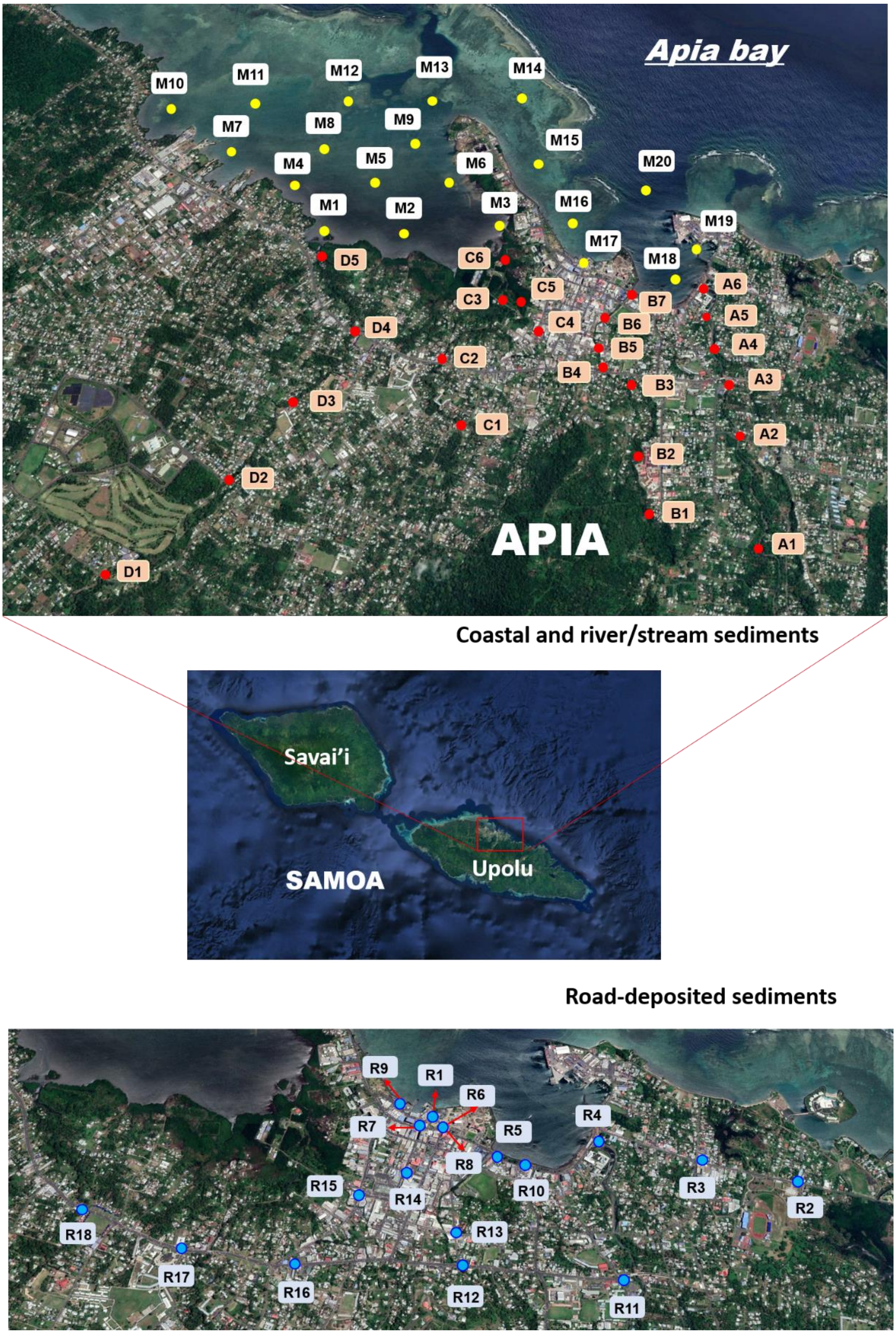

Fig. 1. Sampling locations of coastal, river/stream, and road-deposited sediments from Apia city of Samoa. Google earth image was used for the base map.

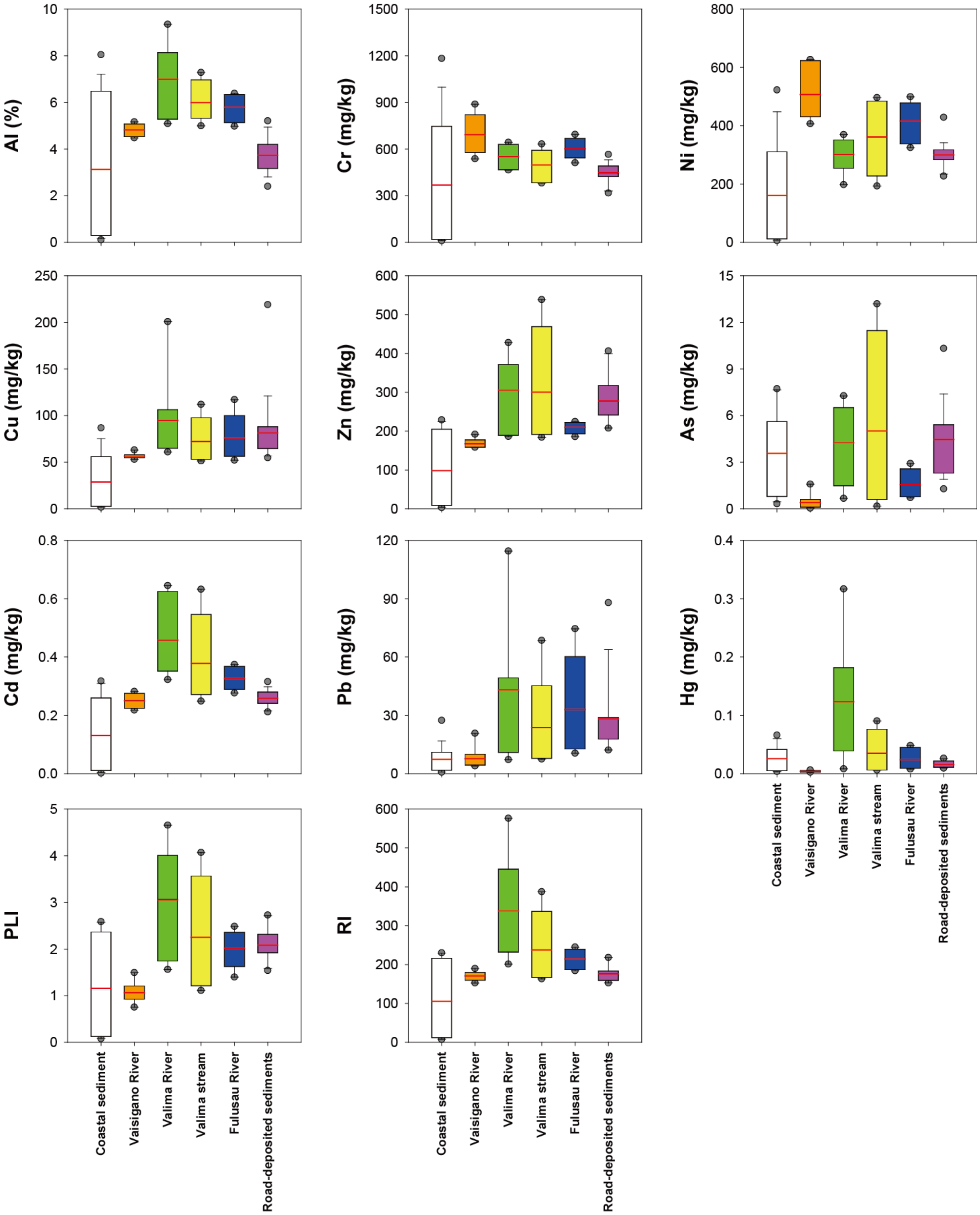

Fig. 2. Comparison of heavy metal concentrations, pollution load index (PLI), and potential ecological risk index (RI) in coastal, river/stream, and road-deposited sediments of this study. Red line indicates the mean value,

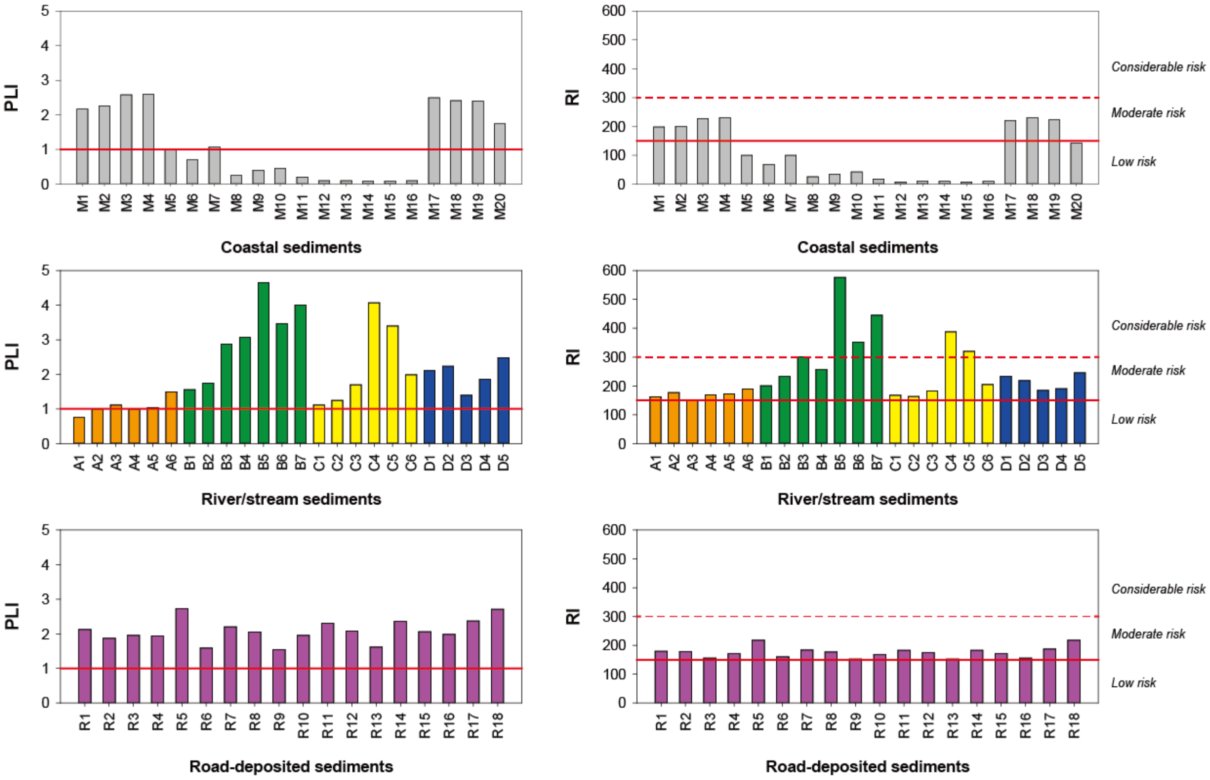

Fig. 3. Spatial distribution of pollution load index (PLI) and potential ecological risk index (RI) for heavy metals in this study.

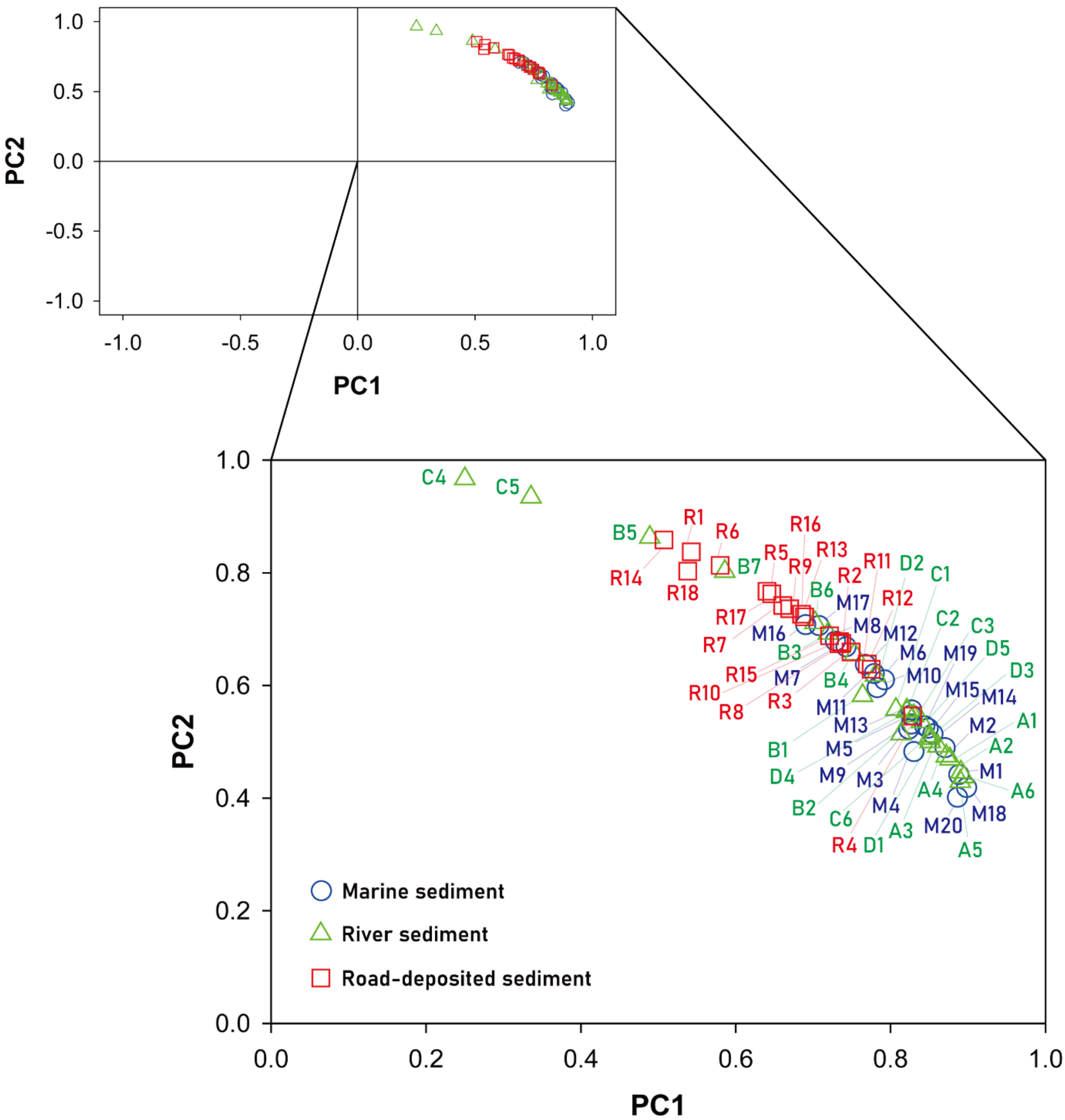

Fig. 4. Principal component analysis (PCA) of heavy metals in sediment samples.

Table 1. Comparison of average concentrations (minimum and maximum value in parenthesis) and coefficient of variation (CV; %) values for Al and heavy metals in coastal, river and road-deposited sediments from Apia of Samoa.

	Al (%)	**Cr** mg/kg	**Ni** (mg/kg)	**Cu** (mg/kg)	**Zn** (mg/kg)	**As** (mg/kg)	**Cd** mg/kg	**Pb** (mg/kg)	**Hg** (mg/kg)	**References**
Coastal sediments										
Mean	3.1 (0.1–8.1)	368 (10–1191)	161 (6–526)	29.0 (1.7–87.4)	98.5 (3.1–229)	3.6 (0.3–7.7)	0.13 (0.002–0.32)	7.4 (0.8–28.0)	0.026 (0.004–0.066)	This study
Palau		61.6 (4.9–451)	14.1 (5.1–67.9)	8.0 (1.1–66.4)	11.0 (0.7–52.5)	12.8 (0.9–43.5)	0.02 (0.001–0.05)	1.0 (0.1–2.7)	0.015 (0.002–0.070)	Jeong et al., 2021
Weno island, Chuuk, FSM		16.0 (0.6–96.9)	10.8 (4.2–47.0)	7.5 (0.8–30.4)	19.8 (0.1–92.0)	5.5 (0.9–17.0)	0.04 (0.003–0.18)	7.7 (0.1–56.0)	0.027 (0.001–0.136)	Jeong and Ra, 2022b
Tahiti island, French Polynesia			89.2 (2.0–325)	8.9 (0.8–35.1)	37.5 (3.2–194)	10.0 (80–27.3).	0.03 (0.02–0.06)	5.3 (3.2–21.5)		Besson et al., 2020.
Suva, Fiji				54.0 (21.4–143)	110 (40–269)			45.4 (22.1–93.5)		Maata and Singh, 2008
Nuku'alofa, Tonga			11 (2–14)	9.8 (2–15)	23.9 (6–38)	5.3 (2–13)		4.6 (1–8)	0.03 (0.01–0.10)	Morrison and Brown, 2003
River/stream sediments										
Vaisigano river (A) (n=6)	4.8 (4.5–5.2)	692 (537–888)	507 (407–627)	56.7 (53.0–63.2)	168 (158–192)	0.4 (0.1–1.6)	0.25 (0.22–0.28)	7.8 (3.9–20.8)	0.004 (0.003–0.006)	This study
Valima river (B) (n=7)	7.0 (5.1–9.3)	552 (464–643)	301 (198–369)	94.9 (61.1–201)	306 (186–428)	4.3 (0.7–7.3)	0.46 (0.32–0.64)	43.1 (7.2–115)	0.123 (0.008–0.317)	This study
Vaimoso stream (C) (n=6)	6.0 (5.0–7.3)	498 (381–632)	362 (193–496)	72.3 (51.4–112)	300 (184–538)	5.0 (0.2–13.2)	0.38 (0.25–0.63)	23.7 (7.5–68.6)	0.035 (0.006–0.090)	This study
Fuluasau river (D) (n=5)	5.8 (5.0–6.4)	601 (511–694)	416 (325–499)	76.0 (52.2–117)	211 (186–225)	1.6 (0.7–2.9)	0.33 (0.28–0.37)	33.0 (10.5–74.6)	0.024 (0.008–0.048)	This study
Mean	6.0 (4.5–9.3)	583 (381–888)	392 (193-627)	75.8 (51.4–201)	250 (158–538)	2.9 (0.1–13.2)	0.36 (0.22–0.64)	27.3 (3.9–114.6)	0.051 (0.003–0.317)	This study
Stream, Hawaii	9.3		324	190	246		0.74	61.8	0.11	Sutherland, 2000
Nakuvadra-Rakiraki River, Fiji		108 (66.1–148)	71.5 (46.8–91)	42.1 (18.9–68.8)	53.7 (28.2–105)		0.99 (0.53–1.53)	32.0 (5.1–83.1)		Kumar et al., 2021
Road-deposited sediments										
Mean	3.7 (2.4–5.2)	449 (316–565)	300 (227–429)	81.6 (54.8–219)	277 (208–406)	4.5 (1.3–10.3)	0.26 (0.21–0.32)	28.2 (12.1–88.0)	0.015 (0.009–0.026)	This study
Busan, Korea		395	66.4	370	1,343	22.6	2.07	210	0.15	Jeong et al., 2020b
Isfahan, Iran		82.1	66.6	182	707	22.1	2.14	393		
Dehradun, India		138 (54.2–257)	46.0 (9.4–77.0)	198 (105–337)	305 (203–467)	28.9 (13.3–46.9)		61.5 (25.7–105)		Bisht et al., 2022
Suva, Fiji		40.0 (21.1–81.9)	54.3 (32.1–110)	172 (59.3–328)	685 (146–3,263)		3.7 (2.4–12.2)	71.0 (33.6–234)		Maeaba et al., 2019
Surface soils										
Mean	8.5 (5.0–11)	619 (467–774)	376 (315–443)	33.1 (29.3–38.0)	80 (61–103)	1.2 (0.8–1.9)	0.19 (0.05–0.30)	13.1 (6.2–19.0)	0.05 (0.01–0.07)	This study
Re´union island		301 (35–1,110)	206 (6.5–1,040)	58.2 (6.5–164)	162 (57.5–398)		0.19 (0.02–0.76)		0.19 (0.03–0.81)	Doelsch et al., 2006
Susaki area, Greece		920 (163–2,346)	994 (183–2,665)	23 (11–63)	95 (21–604)	22 (5–104)		33 (5–256)		Kelepertsis et al., 2001
Jeju island, Korea		662 (434–1,164)	170 (56–414)	49 (28–74)	125 (98–192)		0.4 (0.2–0.7)	44 (38–52)		Ahn and Chon, 2010

Table 2. Mean values of enrichment factor (EF) for heavy metals in coastal, river/stream, and road-deposited sediments (RDS) from Apia city in Samoa.

	Cr	**Ni**	**Cu**	**Zn**	**As**	**Cd**	**Pb**	**Hg**
Coastal sediments	7.8	7.7	2.7	3.6	2.9	3.9	1.8	2.1
Vaisigano river (A)	11.4	17.3	3.2	4.0	0.1	4.5	0.7	0.1
Valima river (B)	6.5	7.6	4.1	5.2	1.0	5.6	2.8	2.6
Vaimoso stream (C)	6.8	10.4	3.3	5.6	1.2	5.2	1.6	0.8
Fuluasau river (D)	8.3	12.0	3.6	4.2	0.4	4.8	2.6	0.6
RDS	10.0	13.8	6.2	9.0	2.1	6.2	3.5	0.7

EF < 2; depletion to minimum enrichment

2 < EF < 5; moderate enrichment

5 < EF < 20; significant enrichment

Table 3. Mean values of individual factor ecological risk degree (E_r^i) for heavy metals of this study.

	Cr	**Ni**	**Cu**	**Zn**	**As**	**Cd**	**Pb**	**Hg**
Coastal sediments	8	17	5	1	7	44	2	20
Vaisigano river (A)	14	54	10	3	1	83	2	3
Valima river (B)	11	32	17	5	9	153	13	99
Vaimoso stream (C)	10	38	13	4	10	126	7	28
Fuluasau river (D)	12	44	14	3	3	109	10	19
RDS	9	32	15	4	9	86	8	12

$E_r^i < 40$; low ecological risk

$40 < E_r^i < 80$; moderate ecological risk

$80 < E_r^i < 160$; considerable ecological risk