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Urban stormwater sediment risk assessment from drainage structures in Bogotá, Colombia

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Urban stormwater sediments are associated with non-point source pollution. In Bogotá, Colombia, two urban rivers (Molinos – Arzobispo) and a constructed wetland with contributions from stormwater runoff located in areas of different land uses (residential, commercial, and parking lot) were selected. Sediments collected from the structures were characterized to determine heavy metal (HM) concentrations and the associated risks to the environment and human health through indices to propose criteria for sediment management. The HM concentrations found by ICP decrease as follows: Cu > Zn > Pb > Ni > Cr > Cd. Due to the Ni content, there is a tolerable to elevated risk in adults and high risk in children of developing cancer through involuntary ingestion. Dermal contact risk from Cr is tolerable in sites where the land use is not residential. No threats to human health were found from non-carcinogenic metals. Cu and Zn for all the indices analyzed present a high and medium-high risk of environmental contamination, respectively. The enrichment factor shows that the origin of the metals is mainly from anthropogenic sources. No ecological risks are expected with the sediments from residential land use, while sediments from other land uses generate intermediate risks. The risk levels found are a source of information to establish threshold values in which sediments present a risk to the environment and human health.

Water impact

In most cities of developing countries, the sediment accumulation in drainage systems is seen exclusively from a hydraulic point of view. With this research, we obtained the first results for Bogotá, Colombia, concerning the sediment risk of heavy metals to the environment and human health. These results demonstrate the need to consider sediment quality as a critical characteristic.

1 Introduction

Most cities face pollution at different levels, especially since their ecosystems receive a relatively high load of pollutants due to urbanization and human activities.[1,2] Roads and their respective urban traffic, homes, buildings, and industrial activities tend to increase the content of heavy metals (HMs) and organic pollutants in watershed soils and sediments.[3]

The rapid development of industry and other urban activities has led to increasing particulate dust on different impervious urban surfaces. During rainfall events, these particles are washed off and transported through urban drainage systems, becoming one of the most critical sources of non-point source pollution, causing water quality impairment in receiving water bodies, and are dominant stressors in urban aquatic ecosystems.[4–6]

Urban runoff is a critical vector of pollutants: it has been shown that they are contaminated by different chemical compounds that are transported mainly in the particulate phase and can vary considerably from one area to another.[7–9] Sediments act as indicators of environmental quality for stormwater because they can adsorb harmful pollutants such as nutrients, heavy metals, pesticides, and polycyclic aromatic hydrocarbons (PAHs) from the extensive and intensive impacts of anthropogenic activities.[10–14]

Most HMs become toxic at higher concentrations, while others are often neither toxic nor essential.[14–16] Trace metals and metalloids are enriched in urban environments, leading to their concentration values exceeding background values.[17–19] HM pollution can become a much more serious problem as these pollutants are non-biodegradable and prevail in soils and sediments, from where they are gradually released into water bodies and accumulate in plants, animals, and humans.[20–22] Human contact with contaminated particles could increase certain health risks since the body can absorb HMs through inhalation, ingestion, or dermal absorption, generating diseases that can

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be fatal. For example, Pb and Cr are considered human mutagens and probable carcinogens, and Cd and Cr are known to be toxic even at low concentrations.[9,14,20]

Load contaminants require detailed knowledge of pollutant concentrations as a function of each storm event.[9] HMs are one of the most dangerous pollutants in aquatic environments and are among the primary pollutants in urban watersheds because they are divided into several environmental components: water, suspended solids, biota, and sediments.[1,23] Knowledge of the concentrations of pollutants adhered to sediments is essential to evaluate their toxicity and potential to affect water quality by runoff in a precipitation event; changes in aquatic environments can pose a serious ecological risk.[1,9] Long-term sediment monitoring provides critical information on temporal waterway pollution trends, thereby improving the risk assessment process.[24] Attention has been paid to HM sediment contamination worldwide in the recent decades, as it is an indicator of environmental impacts and a tool to determine policies and management alternatives.[21,25,26] Recently, a few researchers have published results on some pollution indices in urban runoff sediments.[5,14,27] However, pollution degrees in cities located in developing countries with tropical climates have not yet been sufficiently studied.

Sediment risk assessment allows local authorities to implement management practices in order to reduce environmental and aquatic pollution in urban environments. Nevertheless, questions remain about the optimal frequency of removal and best disposal options.[7] Sediment disposal is typically incineration or direct discharge to a landfill. However, the reuse option as an alternative is growing in civil engineering applications and is likely to have environmental and economic benefits.[28,29] Consequently, a good understanding of sediments' physical and chemical characteristics is required, as no legislation for stormwater sediment management has been developed to date.[10,15]

There is a lack of studies investigating the prediction of sediment quality in stormwater drainage systems as a source of non-point source pollutants. Sediment quality depends on particle size distribution, hydrological variables, basin characteristics, and land use activities. This research aims to propose criteria for the management of sediments retained in urban stormwater systems, according to the pollution risk assessment based on levels of contamination by common heavy metals closely related to anthropogenic activities:[4,27,30] Cd, Cr, Ni, Cu, Pb, and Zn.

2 Materials and methods

2.1 Study site

This research was developed in Bogotá, Colombia's capital city. Located in the center of the country, it is within the intertropical confluence zone, producing two rainy seasons: from March to May and from September to November, with an average temperature of 13.1 °C and an average annual rainfall of 797 mm.[31]

We selected three structures belonging to the Bogotá (Colombia) urban stormwater system. In the selected sampling points, the accumulation of particles is evident and has different land uses. The first sampling point is the Pontificia Universidad Javeriana (PUJ) constructed-wetland/storage-tank (CW/ST) system (Fig. 1). It belongs to commercial land use and receives runoff water, with its respective sediment load, from the PUJ parking building's top floor, and has a drainage area of 3776 m^2. The second sampling point is a bypass from Arzobispo River (AR), located in commercial land, with sediment accumulation caused by a decreased water speed, with a drainage area of 18 592 m^2 (Fig. 2-right). The third sampling point is the Molinos River channel (MR), located in a residential area with substantial sediment accumulation with an urban drainage area of 972 m^2 (Fig. 2-left).

Sediment sampling campaigns were conducted from February 2020 to November 2021 at all sampling points within different periods, considering the COVID-19 lockdowns, for a total of 25 wet-settled sediment samples in MR, 8 in AR, and 7 in CW/ST. Sample collection was made using handmade sediment traps and a Van Veen grab.

To measure the sediment HM concentration, a simultaneous atomic emission spectrometer Shimadzu ICP-E 9800 was used, which allows multiple elements to be analyzed simultaneously and rapidly regardless of their concentration levels. The sample preparation for determining the total HM concentration was done following the EPA method 3051A microwave-assisted acid digestion.[32] The soluble fraction was analyzed following the EPA method 1312.[33]

A particle size distribution (PSD) using laser diffraction was also made since it is linked to the pollutant's adsorption and washing.[34] For QC/QA, analyses were performed in triplicate using the median value for data analysis.

2.2 Human health assessment methods

The human health risk assessment is based on the mean lifetime average daily dose (ADD) of inadvertent human

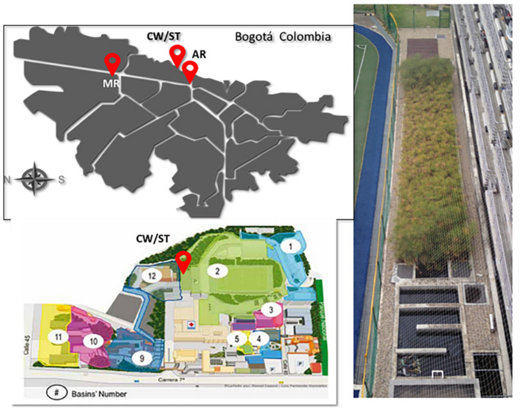

Fig. 1 Location of the three sampling points in the city (top-left). Sampling site 1: constructed-wetland/storage-tank (CW/ST).

Fig. 2 Sampling site 2 (left): Arzobispo River (AR). Sampling site 3 (right): Molinos River (MR).

exposure for children and adult populations to sediments through three different pathways: ingestion of contaminated food or water, dermal contact, and inhalation using the USEPA RAGS methodology of carcinogenic HMs (Cd, Cr, Ni) and non-carcinogenic HMs (Cu, Pb, Zn).[14,35,36] It is crucial to establish the degree of affectation by different pathways in humans by the contaminated sediments since many people have direct contact with the sediments in the drainage structures and disposal areas.

The hazard quotients (HQs) are the health risk associated with non-carcinogenic HMs for each pathway. The hazard index (HI) is the sum of HQs for all pathways, representing the potential threat from non-carcinogenic pollutants. HQ and HI values greater than 1 represent a threat to health due to the adverse effects of HMs.[30,35]

Carcinogenic risk (CR) is the probability of developing cancer in humans due to carcinogenic substances. It is calculated using the ADD and a constant (SF) for each hazardous substance. The total cancer risk (TCR) is the sum of the CR for all HMs on each pathway and the sum of all pathways. A tolerable risk of cancer is expected when the CR varies between 10^{-6} and 10^{-4}, and a high risk of developing cancer when the CR is greater than 10^{-4}.[14,36]

The equations to assess human health risk by HM exposure are shown in Table 1. The reference values to determine the risk for each pathway and population group were taken from Nawrot *et al.*[14]

Table 1 Human health risk assessment equations

Average daily dose (mg kg^{-1} per day)	
Ingestion	$\mathrm{ADD} = \frac{C_m \times I_{ing}R \times \mathrm{ER} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times \mathrm{CF}$
Dermal	$\mathrm{ADD} = \frac{C_m \times \mathrm{SA} \times \mathrm{SAF} \times \mathrm{ABF} \times \mathrm{ER} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times \mathrm{CF}$
Inhalation	$\mathrm{ADD} = \frac{C_m \times I_{inh}R \times \mathrm{ER} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \times \mathrm{CF}$
Hazard quotient	$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RfD}}$
Hazard index	$\mathrm{HI} = \sum \mathrm{HQ}$
Carcinogenic risk	$\mathrm{CR} = \mathrm{ADD} \times \mathrm{SF}$
Total carcinogenic risk	$\mathrm{CR_{path}} = \sum \mathrm{CR_{HM}}$ $\mathrm{TCR} = \sum \mathrm{CR_{path}}$

2.3 Geochemical assessment methods

Given the impact on aquatic ecosystems associated with urban runoff drains, it is necessary to evaluate the potential risks caused by pollutants such as heavy metals and human activities' influence on these pollutants' concentrations. Different sediment quality indices have been proposed to assess HM contamination and their toxicity evolution in river sediments, road-deposited sediments, and sediments in wetland areas.[5,25,37,38] Two or more methods should be applied to improve the precision of the risk assessment of HMs.[19]

The geographical accumulation index (I_{geo}) was proposed in ref. 39 for the evaluation of sediment pollution, according to the HM background concentration (B_n). Global mean concentrations B_n in soils reported in ref. 40 were used since there are no official reports on B_n values in the region.

The enrichment factor (EF) helps to establish the source of HMs: natural or anthropogenic, normalizing the HM concentration with a reference element such as aluminium (Al).[11,19,21,41] For the normalization, the Al concentration measured in each sample and Al B_n concentration in soils reported by Rauch and Pacyna[40] were used.

The pollution index (PI) for individual element pollution is the ratio of the HM concentration to their B_n.[14,20,21,37] The modified pollution index (MPI) is a variation of PI to establish heavy metal contamination at a site using EF instead of B_n, considering the non-conservative behavior of sediments.[42]

The potential ecological risk index (RI), proposed in ref. 43, expresses the ecological risk caused by sediments, which represents the sensitivity of biological communities to toxic substances,[5,27,44] using a toxic response factor for each metal, which is given by Zhao and Li.[44] The modified ecological risk index (MRI) is a variation of RI to assess the contamination degree at a specific site and uses EF instead of the PI for each metal.[42]

The pollution load index (PLI) is used to assess the cumulative pollution level of HMs in sediments using the PI.[4,11,21]

All the equations and the classification for each method used to assess the environmental risk for the collected sediments are shown in Table 2.

3 Results and discussion

3.1 Sediment characterization

The PSD of the three sampling points shows that the particles are less than 500 μm, and about 37% of the particles are in the fraction less than 63 μm, with a D50 of 117, 132, and 130 μm for MR, AR, and CW/ST respectively; therefore, they can be considered fine-grained particles.

For the total HMs analyzed, MR is the one with the lowest concentrations; even for Cd and Cr, no concentrations were detected, followed by Pb < Ni < Zn < Cu, with a median concentration of 9 < 17.1 < 100 < 570.5 mg kg^{-1} respectively. AR is the one with the highest concentrations except for Cu

Table 2 Geochemical indices: equations and classifications

Index	Equation		Classification
Geographical accumulation index	$I_{geo} = \log_2\left(\frac{C_n}{1.5*B_n}\right)$	$I_{geo} < 0$	G0: unpolluted environment
		$0 < I_{geo} \leq 1$	G1: unpolluted to moderately polluted
		$1 < I_{geo} \leq 2$	G2: moderately polluted
		$2 < I_{geo} \leq 3$	G3: moderately to heavily polluted
		$3 < I_{geo} \leq 4$	G4: heavily polluted
		$4 < I_{geo} \leq 5$	G5: heavily to extremely polluted
		$I_{geo} > 5$	G6: extremely polluted
Enrichment factor	$EF = \frac{C_n/C_{Al}}{B_n/B_{Al}}$	$EF < 1$	No: deficiency to minimal enrichment
		$1 < EF \leq 5$	M: moderate enrichment
		$5 < EF \leq 20$	S: significant enrichment
		$20 < EF \leq 40$	VH: very high enrichment
		$EF > 40$	E: extreme enrichment
Pollution index	$PI = \frac{C_n}{B_n}$	$PI < 1$	L: low level of pollution
		$1 < PI \leq 3$	M: medium level of pollution
		$PI > 3$	H: high level of pollution
Modified pollution index	$MPI = \sqrt{\frac{(EF_{ave})^2 + (EF_{max})^2}{2}}$	$MPI < 1$	No: unpolluted
		$1 < MPI \leq 2$	S: slightly polluted
		$2 < MPI \leq 3$	M: moderately polluted
		$3 < MPI \leq 5$	MH: moderately to heavy polluted
		$5 < MPI \leq 10$	H: heavily polluted
		$MPI > 10$	E: severely polluted
Ecological risk index	$RI = \sum_{i=1}^{m} Tr_i * \frac{C_n^i}{B_n^i}$	$RI \leq 150$	G0: low ecological risk
		$150 < RI \leq 300$	G1: moderate ecological risk
		$300 < RI \leq 600$	G2: considerable ecological risk
		$RI > 600$	G3: very high ecological risk
Modified ecological risk index	$MRI = \sum_{i=1}^{m} Tr_i * EF$	$MRI \leq 150$	L: low ecological risk
		$150 < MRI \leq 300$	M: moderate ecological risk
		$300 < MRI \leq 600$	C: considerable ecological risk
		$MRI > 600$	VH: very high ecological risk
Pollution load index	$PLI = \sqrt[n]{\frac{C_1}{B_1} * \frac{C_2}{B_2} * \ldots * C_n B_n}$	$PLI = 0$	Bn: background concentration
		$0 < PLI \leq 1$	No: unpolluted
		$1 < PLI \leq 2$	MN: unpolluted to moderately polluted
		$2 < PLI \leq 3$	MP: moderately polluted
		$3 < PLI \leq 4$	MH: moderately to highly polluted
		$4 < PLI \leq 5$	H: highly polluted
		$PLI > 5$	VH: very highly polluted

and Zn, and the total HM order was Cd < Cr < Ni < Pb < Zn < Cu with a median concentration of 4.8 < 5.3 < 22.3 < 43.1 < 114.2 < 613.7 mg kg^{-1} respectively. The CW/ST concentrations were in the order Cd < Cr < Ni < Pb < Zn < Cu with a median concentration of 1.7 < 5 < 20.8 < 33.6 < 476.1 < 818.2 mg kg^{-1} respectively. The HM concentrations obtained for all the sampling sites are shown in Fig. 3. Cu, Zn, and Pb concentrations in urban sediments are closely related to vehicle traffic due to tire and brake wear, easily transported from roads to drains by runoff.[4,5,12,19] Thus, the HM concentration variations can be attributed to land use. In this sense, the low HM concentrations of MR could be associated with residential use throughout the basin, and the high Cu and Zn concentrations in CW/ST associated with the high car traffic from the parking lot. However, the Cu concentrations at the three sampling points are much higher than those reported by other authors in sediments from different sources, so this could be attributed to factors other than vehicular ones. In addition to having a high traffic load, AR also has sediments of natural origin and other commercial activities, which have high concentrations of Cd. However, the median values of Cr, Ni, and Pb are similar to those of CW/ST and the median of Zn is similar to that of MR.

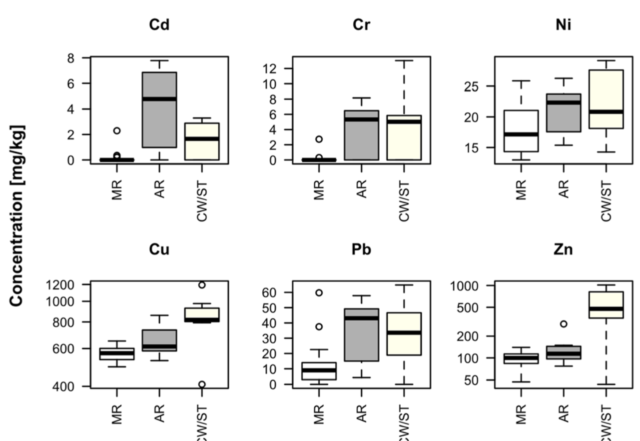

Fig. 3 Total heavy metal concentrations measured in sediments [mg kg^{-1}]. MR: Molinos River, AR: Arzobispo River, CW/ST: constructed-wetland/storage-tank.

The concentrations obtained for the soluble fraction with respect to the total concentration are 0% for Cd and Cr, around 1% for Pb and Zn, and about 5% for Ni and Cu. This means that the HMs remain attached to the sediments. Thus, it is inconvenient to consider the soluble fraction to the pollutant load of HMs in an urban stormwater drainage system.

3.2 Human health risk assessment

The evaluation of ADD in adults and children by each pathway for non-carcinogenic HMs is shown in Fig. 4. In terms of exposure route, the highest is through ingestion, followed by dermal contact, and finally, inhalation. Exposure to HMs decreases as follows: Cu > Zn > Pb, with CW/ST being the one with the highest exposure to Cu and Zn and AR to Pb. The greatest exposure by contact occurs in adults, while that by inhalation and ingestion occurs in children.

For all pathways, the non-carcinogenic ADD is less than the RfD. Therefore, the HQ is less than 1. The HQ results for all sediment samples decrease in the same way as the ADD, as shown in Table 3; therefore, no harmful effect is expected from exposure to stormwater sediment in urban areas. Even so, when summing the HQ by pathway and HMs to determine HI, it is still less than 1 for the three sampling points, as shown in Table 4, so there is no threat to human health from any non-carcinogenic HM.

Fig. 5 shows the carcinogenic HM ADD in adults and children for each pathway. The exposure from highest to lowest occurs as follows: ingestion, dermal contact, and inhalation. Children have the most significant exposure through ingestion and inhalation. For both population groups, Ni is the one that represents the most significant exposure, followed by Cr and, finally, Cd. Regarding the sampling sites, MR has the lowest degree of exposure, contrary to AR, which has the highest exposure.

Regarding the total cancer risk associated with HMs (Fig. 6), children have a high risk of developing cancer from contact with sediments. This is mainly due to accidental ingestion since 100% of the samples of the three places analyzed have a high risk due to Ni concentrations. Additionally, more than 60% for AR and more than 57% for CW/ST present a high risk from Cd and Cr. Despite this, there is a low risk for inhalation of sediments and a tolerable risk for associated dermal contact mainly by Cr. MR sediments have a tolerable and high risk for the adult population in approximately 60% of the AR and CW/ST samples. The most significant risk is related to ingestion associated with Cr. The tolerable risk is related to ingesting material contaminated with Ni and Cd for the three sampling points and dermal contact in about 50% of the samples from AR and CW/ST by Cr. No risk is expected from the inhalation of particles. Additionally, AR and CW/ST have a tolerable contact risk due to Cr concentrations.

The health risk results agree with those presented by other authors for urban sediments. They show that the most significant route of exposure is through ingestion, which is a risk to human health, especially in children, the most vulnerable population. Carcinogenic risk analyses carried out for urban sediments by other authors have shown that there is always a high risk, mainly due to the Cr content.[14,30,35]

Due to the above, it is necessary to review the protocols for the extraction and disposal of sediments from the urban drainage system in Bogotá. In cases where manual extraction

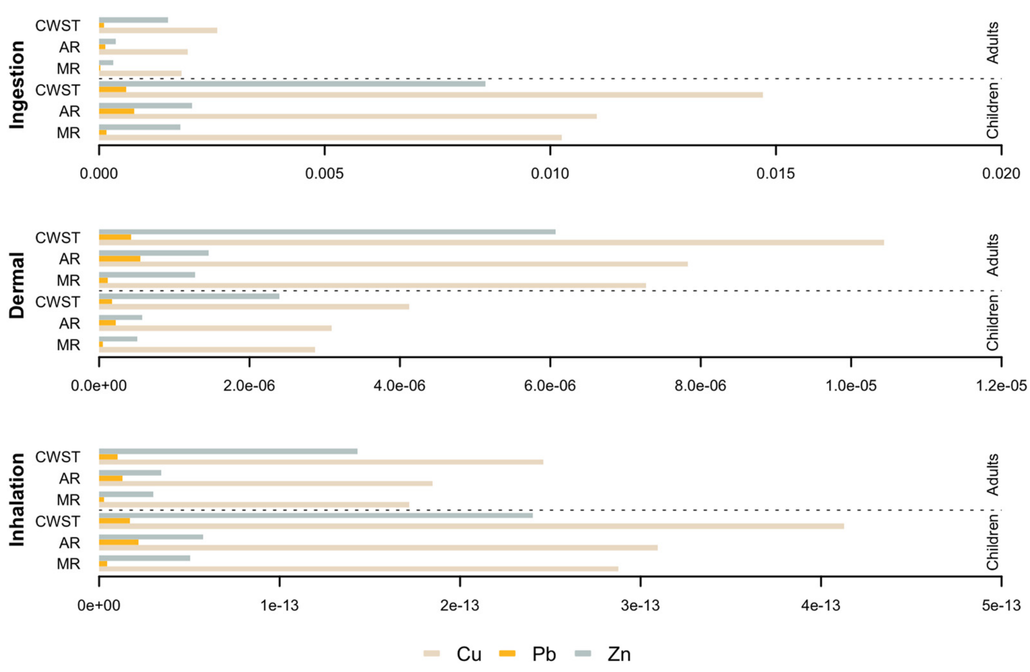

Fig. 4 Average daily dose (ADD) for each pathway for non-carcinogenic HMs in children and adults (mg kg^{-1} per day). MR: Molinos River, AR: Arzobispo River, CW/ST: constructed-wetland/storage-tank. Please note the different orders of magnitude.

Table 3 Hazard quotient (HQ) by pathway and non-carcinogenic heavy metals in children and adults. Ing: ingestion, Der: dermal contact, Inh: inhalation

Adults				Children		
HM	Ing	Der	Inh	Ing	Der	Inh
Cu	4.7×10^{-2}	6.2×10^{-4}	4.4×10^{-12}	2.6×10^{-1}	2.5×10^{-4}	7.4×10^{-12}
Pb	1.1×10^{-2}	3.1×10^{-4}	1.1×10^{-12}	6.6×10^{-2}	1.2×10^{-4}	1.8×10^{-12}
Zn	1.1×10^{-3}	2.2×10^{-5}	1.1×10^{-13}	6.3×10^{-3}	8.8×10^{-6}	1.8×10^{-13}

Table 4 Hazard index (HI) in children and adults. MR: Molinos River, AR: Arzobispo River, CW/ST: constructed wetland storage tank

Adults				Children		
HM	MR	AR	CW/ST	MR	AR	CW/ST
Cu	4.6×10^{-2}	5.0×10^{-2}	6.6×10^{-2}	2.6×10^{-1}	2.8×10^{-1}	3.7×10^{-1}
Pb	8.4×10^{-3}	4.0×10^{-2}	3.2×10^{-2}	4.6×10^{-2}	2.2×10^{-1}	1.7×10^{-1}
Zn	1.1×10^{-3}	1.2×10^{-3}	5.2×10^{-3}	6.0×10^{-3}	6.9×10^{-3}	2.9×10^{-2}
$\sum$	5.6×10^{-2}	9.1×10^{-2}	1.0×10^{-1}	3.1×10^{-1}	5.0×10^{-1}	5.7×10^{-1}

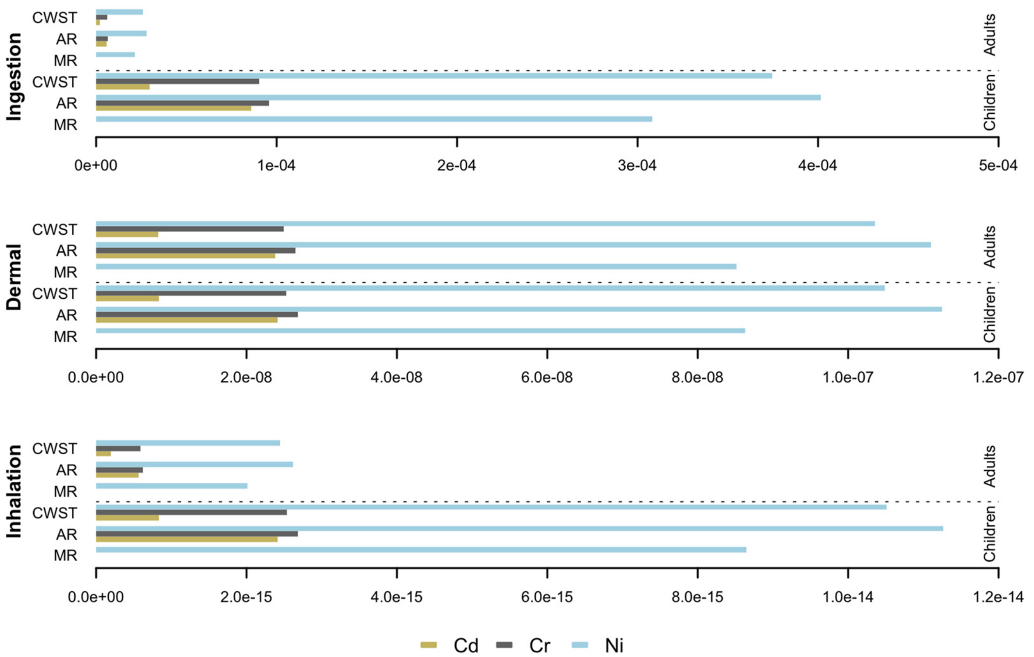

Fig. 5 Average daily dose (ADD) for each pathway for carcinogenic HMs in children and adults (mg kg^{-1} per day). MR: Molinos River, AR: Arzobispo River, CW/ST: constructed-wetland/storage-tank. Please note the different orders of magnitude.

is carried out, the risk increases for the workers in charge of these tasks, and inadequate disposal may increase the exposure of different population groups.

3.3 Environmental risk assessment

Following the I_{geo} classification shown in Fig. 7, the HM contamination degrees were established in the sediments of the three sampling points: an unpolluted environment (G0) by Cr, Ni, and Pb, then an environment uncontaminated to highly contaminated (G0–G4) by Cd, followed by a variation between unpolluted and heavily polluted environments (G0–G4) by Zn, and finally, the highest degree of environmental contamination due to Cu, which is highly contaminated (G4) and reaches heavily to extremely polluted (G5) in some samples. In MR, 84% of the sediment samples are classified as unpolluted to moderately polluted (G1) by Zn, 96% are not contaminated (G0) by Cd and Pb, and all of the samples are highly contaminated (G4) by Cu. 50% of AR sediment samples can be classified as uncontaminated to moderately polluted (G0–G1) by Pb, 75% unpolluted to moderately polluted (G1) by Zn, and highly contaminated (G2–G4) by Cd, and the greatest risk is due to Cu, with 100% of samples being highly contaminated (G4). 85.7% of the CW/ST sediment samples are classified as heavily to extremely polluted (G5) by Cu and between heavily polluted and heavily to extremely polluted (G4–G5) by Zn, while 67.1% are classified as moderately to heavily polluted (G2–G3) by Cd.

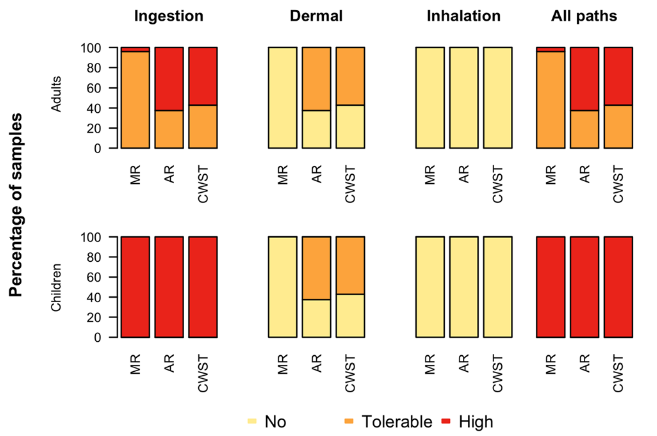

Fig. 6 Total cancer risk (TCR) by pathway and the sum of all pathways in children (bottom) and adults (top). MR: Molinos River – 25 samples, AR: Arzobispo River – 8 samples, CWST: constructed-wetland/storage-tank – 7 samples.

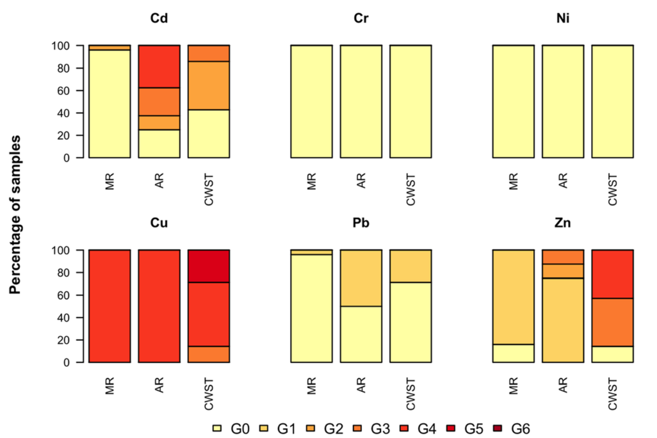

Fig. 7 Geoaccumulation index (I_{geo}) concerning the percentage of samples in each place. MR: Molinos River – 25 samples, AR: Arzobispo River – 8 samples, CWST: constructed-wetland/storage-tank – 7 samples. G0: unpolluted environment, G1: unpolluted to moderately polluted, G2: moderately polluted, G3: moderately to heavily polluted, G4: heavily polluted, G5: heavily to extremely polluted, G6: extremely polluted.

Thus, MR has the lowest degree of contamination, followed by AR and finally CW/ST.

According to the evaluation of the I_{geo} carried out by different authors (Table 5), the sediments with the most significant risk came from places with more human intervention. The highest degrees of contamination by Zn (G3 to G5) agree with those obtained for CW/ST. However, they are a higher classification degree than those obtained for MR and AR. They found a moderate to heavy Pb and Cu contamination degree (G3), which is lower for Cu and higher for Pb with respect to those found in the sediments in this research. Cd classification for most places agrees with that found for MR, and the variation found by Arisekar *et al.*[26] in a river agrees with the classification of CW/ST. Regarding the I_{geo} evaluation for Cr and Ni, a range between

Table 5 Geoaccumulation index (I_{geo}) in urban sediments. Road deposited sediments (RDS). Stormwater sedimentation tank (ST). G0: unpolluted environment, G1: unpolluted to moderately polluted, G2: moderately polluted, G3: moderately to heavily polluted, G4: heavily polluted, G5: heavily to extremely polluted, G6: extremely polluted

Cu	Cd	Cr	Pb	Zn	Ni	Sample location
G0	G0	G1	G1	G2	—	Trop. freshwater lakes[22]
G0	G1	G0	G0	G0	—	RDS[45]
G2	—	G1	G3	G3	G2	RDS[5]
G3	—	G1	G3	G5	G1	Stormwater[5]
G0	G0	—	G0	G0	G0	Abiete watershed[11]
G0	G0	—	G0	G0	G0	Toko watershed[11]
G2	G3	G3	G3	G4	G3	Lif coast[37]
G3	G0	G2	G3	G4	G2	ST[41]
G0	G0	G0	G0	G0	—	Haizhou Bay[46]
G0	G0–G3	—	G0	G0	G0	River[26]
—	G0	G0	G0	—	—	Urban river in summer[25]
—	G1	G0	G0	—	—	Urban river in winter[25]

uncontaminated and moderately contaminated (G0–G3) was reported. These results represent a greater risk than those found for sediments from the three sampling points. Due to the significant variability of the I_{geo} results, it is impossible to associate the sediments analyzed in this research with those reported by others.

For each studied metal, the EF classifications are shown in Fig. 8. The three sampling points' highest enrichment level is for Cu and Zn, while the lowest is for Cr. CW/ST has extreme enrichment by Cu and Zn in 100% of the sediment samples and by Cd in 57.1%, significant to extreme enrichment in 100% and 85.7% of sediment samples by Ni and Pb, respectively, and moderate enrichment by Cr in 14.3% of sediment samples. On the other hand, AR has an enrichment from significant to extreme by Cu, Zn, Ni, and Cd in 50%, 37.5%, 37.5%, and 25% of the samples, respectively, moderate to significant enrichment by Pb in

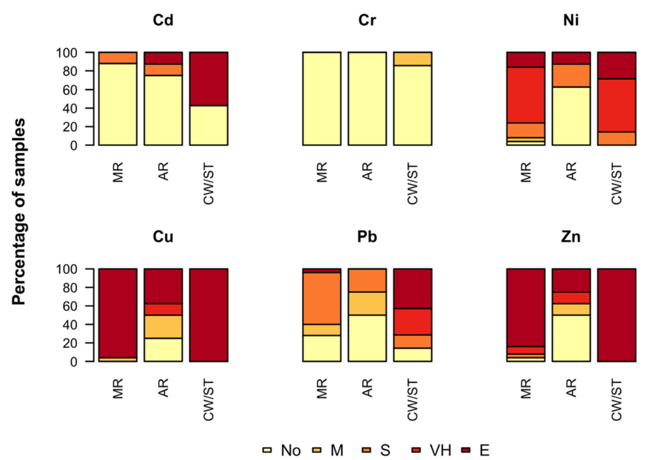

Fig. 8 Enrichment factor (EF) concerning the percentage of samples in each place. MR: Molinos River – 25 samples, AR: Arzobispo River – 8 samples, CW/ST: constructed-wetland/storage-tank – 7 samples. No: deficiency to minimal enrichment, M: moderate enrichment, S: significant enrichment, VH: very high enrichment, E: extreme enrichment.

50% of sediment samples, and no enrichment by Cr in 100% of samples. Finally, MR is classified in 84% and 96% of the samples with extreme enrichment by Zn and Cu, a very high enrichment by Ni in 60% of samples, significant enrichment by Pb in 56% of samples, and no enrichment by Cr in 100% of samples. Therefore, the sediments have high contamination by Cu, Zn, and Ni of anthropogenic origin.

As shown in Table 6, there is no evidence of heavy metal enrichment in the sediments from natural water bodies. In environments with greater anthropogenic influence, the enrichment level reaches very high enrichment by Cu, Ni, Pb, and Zn, and extreme enrichment by Cd and Cr. These results agree with the Cr enrichment for the three sampling points, with those found in natural water bodies and with the Cd enrichment in MR and AR for most of the samples. Considering the enrichment levels found for the other HMs, all sediment samples analyzed exceed the reported levels when compared with the results of other researchers.

The pollution index of the sediments collected in all sampling points shows the following pollution levels: low level by Cr, a low to medium level by Ni and Pb, a low to a high level by Cd, medium to high by Zn, and a high pollution level by Cu (Fig. 9). Specifically, MR has a low level of contamination in more than 90% of the samples for all HMs except Zn and Cu, which have a medium level in 96% and a high level of contamination in 100% of the sediment samples, respectively. AR has a low level of contamination by Cd and Ni in 100% and 87.5%, a medium level by Pb and Zn in 62.5% and 75%, and a high level by Cd and Cu in 75% and 100% of the collected sediment samples, respectively. Meanwhile, CW/ST has a high pollution level of Cu, Zn, and Cd in 100%, 85.7%, and 57.1% of samples, respectively. 57.1% of samples have a medium pollution level of Pb, and a low pollution level of Ni. Cr has a low pollution level in 100% of sediments analyzed. In general terms, it is evident that the measured concentrations of Cd, Cu, Pb, and Zn greatly exceed the respective base concentrations, which implies medium to high levels of contamination for the urban drainage systems.

Table 6 Enrichment factor (EF) in urban sediments. Road deposited sediments (RDS). Stormwater sedimentation tank (ST). No: deficiency to minimal enrichment, M: moderate enrichment, S: significant enrichment, VH: very high enrichment, E: extreme enrichment

Cu	Cd	Cr	Pb	Zn	Ni	Sample location
No	No	No	No	No	—	Trop. freshwater lakes[22]
M	S	M	M	M	—	RDS[45]
VH	S	S	S	VH	M	Stormdrain[4]
M	S	M	M	M	—	RDS[5]
S	M	—	M	M	M	Abiete watershed[11]
S	M	—	M	M	VH	Toko watershed[11]
S	No	S	S	S	S	ST[41]
No	No	No	No	No	No	River[26]
—	E	E	VH	—	—	Urban river in summer[25]
—	E	E	VH	—	—	Urban river in winter[25]
M	M	S	M	M	S	Coastal[42]

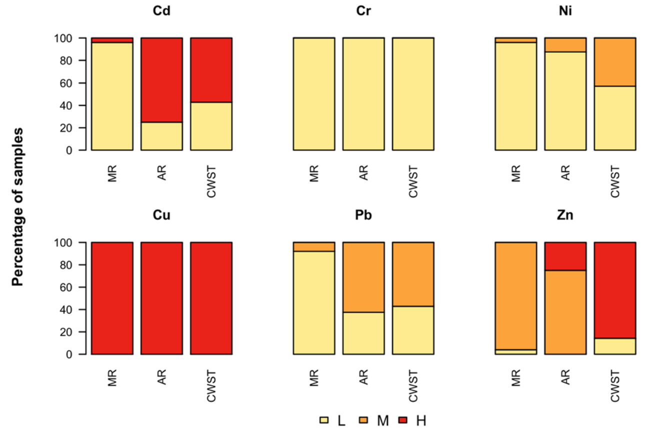

Fig. 9 Pollution index (PI) concerning the percentage of samples in each place. MR: Molinos River – 25 samples, AR: Arzobispo River – 8 samples, CW/ST: constructed-wetland/storage-tank – 7 samples. L: low level of pollution, M: medium level of pollution, H: high level of pollution.

The contamination levels have been analyzed in sediments from a few places, which mainly determined a low pollution level of Cr, Pb, Zn, and Ni, a low to medium level of Cu and a low to high level of Cd (Table 7). According to these classifications, the measured PI is higher in the sediments for Zn and Cu; Pb and Ni are higher in some samples, while the classifications of Cd and Cr agree with those found by other researchers. Despite the concordance in some classifications, it is not possible to thoroughly compare the sediments of a specific site with those analyzed here.

From the ecological risk results shown in Fig. 10-left, it is possible to identify that MR has a low ecological impact, followed by CW/ST and AR, in which both have a low to considerable ecological risk impact. This means that there is no sensitivity of the biological community to HMs for 96% of the MR sediments, 25% of the AR sediments, and 28.6% of the CW/ST sediments. For this reason, it is necessary to pay special attention to the sediments of AR and CW/ST. They must be removed from the basins to avoid the magnification of the concentrations.

As stated by different authors summarized in Table 8, a more significant ecological risk is associated with stormwater sediments. However, different classifications are found in each investigation, which makes it difficult to establish a contamination pattern. Even so, MR agrees with the classification reported for RDS and an urban river, and the

Table 7 Pollution index (PI) in urban sediments. L: low level of pollution, M: medium level of pollution, H: high level of pollution

Cu	Cd	Cr	Pb	Zn	Ni	Sample location
L–M	L–H	L	L	L	L	River[26]
—	M	L	L	—	—	Urban river in summer[25]
—	M	L	M	—	—	Urban river in winter[25]
L	L	L	L	L	M	Coastal[42]

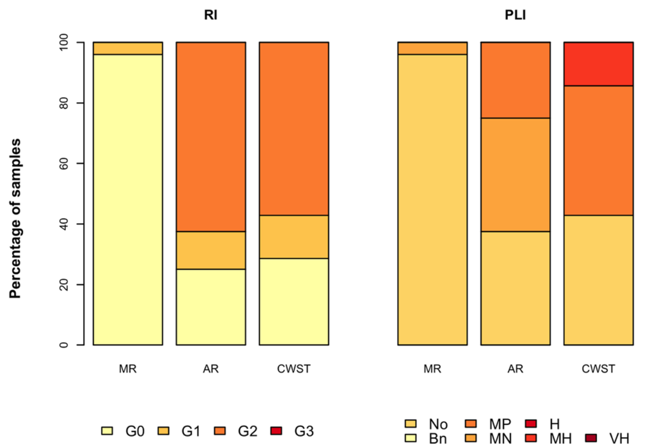

Fig. 10 Ecological risk index (RI) and pollution load index (PLI) concerning the percentage of samples in each place. G0: low ecological risk, G1: moderate ecological risk, G2: considerable ecological risk, G3: very high ecological risk. Bn: background concentration, No: unpolluted, MN: unpolluted to moderately polluted, MP: moderately polluted, MH: moderately to highly polluted, H: highly polluted, VH: very highly polluted.

Table 8 Ecological risk index (RI) and pollution load index (PLI) in urban sediments. RDS: road deposited sediments. G0: low ecological risk, G1: moderate ecological risk, G2: considerable ecological risk, G3: very high ecological risk. Bn: background concentration, No: unpolluted, MN: unpolluted to moderately polluted, MP: moderately polluted, MH: moderately to highly polluted, H: highly polluted, VH: very highly polluted

RI	PLI	Sample location
G0	—	Haizhou Bay[46]
G0–G1	—	RDS[45]
G1–G2	—	RDS[5]
G1–G3	—	Stormwater particles[5]
G2	—	Abiete watershed[11]
G3	—	Toko watershed[11]
G2	MN–MP	Lif coast[37]
G0–G1	No	River[26]
G0	No	Urban river in summer[25]
G0	No–MN	Urban river in winter[25]

risk variation in AR and CW/ST for some samples agrees with almost all the results reported by other authors.[26,45]

The PLI of the HMs analyzed by each site (Fig. 10-right) shows an unpolluted environment in MR for 96% of the samples. 37.5% of AR samples are classified from unpolluted to unpolluted to moderately polluted. Finally, 86% of the CW/ST samples vary equally between uncontaminated and moderately polluted. Only a few researchers have analyzed the sediment PLI, especially in natural water bodies, showing variations between unpolluted and moderately polluted (Table 8). The classification of the unpolluted environment is found in urban river sediments, especially in summer, which agrees with the contamination found in MR.[25,26] The AR and CW/ST classification agrees with the classification of river sediments in winter, and sediments from Lif coast, respectively.[25,37]

Considering that the MPI and MRI use the EF to classify the level of contamination, which mainly presents an enrichment above a very high level, severe pollution MPIs in 96%, 50%, and 100% of sediment samples are obtained from MR, AR, and CW/ST, respectively. Regarding MRI, 80%, 37.5%, and 57.1% of MR, AR, and CW/ST sediment samples, respectively, have considerable ecological risk. Thus, the risk assessment using the modified methods considers the anthropogenic source of HMs, and the three sampling points imply a higher level of contamination with respect to the original indices.

Concerning the results of the environmental indices, the MR sediments are those that present a lower risk. However, the Cu and Zn concentrations present a threat to this basin, in addition to the fact that they come from anthropogenic activities, and vastly exceed background concentrations. Secondly, AR has the most significant ecological threat, which can be attributed to the concentrations of Cd, Cu, and Zn, which present high levels of contamination for the sediments. On the other hand, CW/ST has high levels of Cu and Zn contamination; therefore, the sediments present an additional load of HMs compared to that expected from stormwater to be treated by wetland plants.

4 Conclusions

In Colombia, as in many developing countries, there are no quality standards for sediments or technical guidelines for their management. Criteria based on heavy metal (HM) risk assessment from urban stormwater drainage sediments are proposed. HM concentrations were evaluated in sediments collected in three stormwater drainage structures of Bogotá: Molinos River (MR), Arzobispo River (AR), and a constructed wetland (CW/ST). The HM concentrations found could be related to land use: higher for areas with significant anthropic activity and lower for residential land uses. MR has the lowest concentrations (none detected for Cd and Cr). Based on HM concentrations is possible to establish thresholds from which the sediments can be harmful to the environment and human health. Thus, it will be easier to make decisions regarding the periodicity and methodologies of dredging and disposal practices and even consider reuse options as a productive alternative.

An evaluation of the risk to human health due to carcinogenic and non-carcinogenic metals was conducted for two population groups: adults and children. Regarding human health, sediments present a high risk to children and a tolerable to high risk to adults associated with carcinogenic metals (Cd, Cr, and Ni), primarily due to inadvertent ingestion followed by dermal contact. This implies that sanitary protocols are needed for sediment management, due to carcinogenic HMs.

Different indices to evaluate environmental contamination were used: geo-accumulation index (I_{geo}), enrichment factor (EF), pollution index (PI), ecological risk index (RI), and pollution load index (PLI). Although the source of Cu, Ni, and Zn are mainly anthropic according to EF results, the RI and PLI represent a medium risk to the environment and the organisms that come into contact with them. Nevertheless, when analyzing the indices individually (I_{geo} and PI), Cu generates a high risk, followed by Zn, which presents an intermediate risk. In terms of environmental conservation, it is necessary to remove sediments from urban areas before they are discharged into natural water bodies since most of the pollutants are of anthropogenic origin and remain attached to the particles, causing environmental pollution and some risk to organisms that interact with them.

According to the results of this research, it is possible to provide the same management tools for the sediments from CW/ST and AR since they have similar levels of risk to health and the environment. Besides, the sediments from MR generate fewer effects than the previous two, implying that the range of alternatives for their disposal can be expanded, and even the reuse option can be considered.[29] For this reason, it is crucial as a first alternative to improve the quality of urban drainage to consider sediments in plans for their restoration and conservation. Specifically, in Bogotá, sediments are collected from different urban drainage structures mechanically or manually and transported to different dumps. The above means a risk to the workers' health because of the risk of developing cancer due to dermal contact.[47] The analyzed information serves as a tool for decision-making according to urban drainage sediment management, so special attention should be paid to workers in charge of dredging and disposal.

Conflicts of interest

There are no conflicts to declare.

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