

Risk assessment of runoff sediments in an experimental catchment in Bogotá related to hydrological and granulometric characteristics¹

Jorge Alberto Sanabria Morales², Lorena Rivera-Soler³, Andrea Del Pilar Cabra Soto⁴, Carolina A. Jiménez-Rojas⁵, Juan Nicolas Torres Camacho⁶, María Alejandra Pimiento Avella⁷, Verónica Duque Pardo⁸, Andrés Torres⁹

ABSTRACT

Introduction. Urban runoff sediments contain heavy metals that generate risk to the environment. Several risk assessment indexes for heavy metals have been

developed, which show the level of contamination of particles in the environment and their origin. Besides, sediment risk is also associated with the particle size

1 Artículo original derivado del proyecto de investigación Gestión de sedimentos retenidos en sistemas urbanos de agua lluvia de acuerdo con la estimación del riesgo, acumulación y posibles usos (enero 2015-actual). Pontificia Universidad Javeriana. Financiado por los autores.

2 Candidato a Magíster en Hidrosistemas, Pontificia Universidad Javeriana Bogotá. Ingeniero Catastral y Geodesta, Universidad Distrital Francisco José de Caldas. ORCID 0000-0002-7203-5566

3 Estudiante de Ingeniería Civil, Facultad de Ingeniería Civil, Universidad Santo Tomás, Bogotá, Colombia. ORCID 0000-0002-8380-7162

4 Candidata a Magíster en Hidrosistemas, Pontificia Universidad Javeriana Bogotá. Ingeniera en Recursos Hídricos, Universidad Central de Colombia. ORCID 0000-0002-8712-7834

5 Candidata a Magíster en Hidrosistemas, Pontificia Universidad Javeriana, Bogotá. Ingeniera Química, Universidad EAN, ORCID 0000-0002-1846-0406

6 Candidato a Magíster en Hidrosistemas, Pontificia Universidad Javeriana, Bogotá. Ingeniero Civil, Pontificia Universidad Javeriana Bogotá. ORCID 0000-0002-9143-1599

7 Estudiante Doctorado Ingeniería, Pontificia Universidad Javeriana Bogotá. Magistra en Hidrosistemas, Pontificia Universidad Javeriana, Bogotá. Ingeniera Civil, Pontificia Universidad Javeriana, Bogotá. ORCID 0000-0002-7691-7291

8 Docente Temporal, Facultad de Ingeniería, Departamento Ingeniería Civil, Pontificia Universidad Javeriana, Bogotá. Magistra en Hidrosistemas, Pontificia Universidad Javeriana, Bogotá. Ingeniera Ambiental, Universidad Distrital Francisco José de Caldas. ORCID 0000-0003-1941-0256

9 Profesor titular, Facultad de Ingeniería, Departamento Ingeniería Civil, Pontificia Universidad Javeriana, Bogotá. Doctor en Ingeniería Civil, Institut National Des Sciences Appliquees De Lyon. Magister Génie Civil, Institut National Des Sciences Appliquees De Lyon. Especialista en Sistemas Gerenciales de Ingeniería, Pontificia Universidad Javeriana, Bogotá. Ingeniero Civil, Pontificia Universidad Javeriana, Bogotá. ORCID 0000-0001-8693-8611

Correspondence should be addressed to: María Alejandra Pimiento; mpimiento@javeriana.edu.co

Recibido: 26/08/2020 **Aceptado:** 23/11/2020

distribution and hydrometeorological characteristics. **Objective.** This work seeks to evaluate the risk of contamination from runoff sediments collected in an experimental catchment, related to their size distribution and hydrological characteristics of the area of influence. **Materials and methods.** The field and laboratory experiments were carried out on the constructed-wetland/storage-tank structure from Pontificia Universidad Javeriana, Bogotá. The hydrological data were obtained from a nearby El Paraíso rain gauge station. The geo-accumulation (Igeo), pollution index (PI), and enrichment factor (EF) rates were calculated. Furthermore, Principal Component Analysis was used in order to determine the relationships between the risk, hydrological and granulometric variables. **Results.** There is a low/medium

risk for Cu and Cr, in contrast to the high risk for Pb and Zn. According to multivariate statistical analysis, there is a relationship between risk indexes and average particle diameters (D50): these indexes increase for fine particles and periods of high rainfall intensity. **Conclusions.** The hydrological variables are important to determine the risks of urban runoff sediments. In this study, we found that the variable of dry weather is related to the values of geo-accumulation indexes and contamination. The findings of this work reinforce the possibility of developing early warning systems for sediment risks using key hydrological and sedimentological variables. **Keywords:** risks assessment, hydrology, sediments, particle size distribution, heavy metals, urban runoff.

Evaluación de riesgos de sedimentos de escorrentía en una cuenca experimental en Bogotá relacionado con características hidrológicas y granulométricas

RESUMEN

Introducción. Los sedimentos de escorrentía urbana contienen metales pesados que generan riesgos medioambientales. Se han desarrollado varios índices de evaluación de riesgos para metales pesados, que muestran el nivel de contaminación de partículas en el medio ambiente y su origen. Además, el riesgo de sedimentos también está asociado con la

distribución del tamaño de partícula y las características hidrometeorológicas. **Objetivo.** Este trabajo busca evaluar el riesgo de contaminación por sedimentos de escorrentía recolectados en una cuenca experimental, en relación con su distribución de tamaños y características hidrológicas del área de influencia. Materiales y métodos. Los experimentos de campo y laboratorio

se llevaron a cabo en el humedal-construido/tanque-regulador de la Pontificia Universidad Javeriana, Bogotá. Los datos hidrológicos se obtuvieron de la estación pluviométrica cercana El Paríso. Se calcularon los índices de geoacumulación (Igeo), índice de contaminación (PI) y factor de enriquecimiento (EF). Además, se utilizó el análisis de componentes principales para determinar las relaciones entre las variables de riesgo, hidrológicas y granulométricas. **Resultados.** Existe un riesgo bajo/medio de Cu y Cr, en contraste con el alto riesgo de Pb y Zn. Según el análisis estadístico multivariado, existe una relación entre los índices de riesgo y los diámetros promedio de partículas (D50): estos índices aumentan

para partículas finas y períodos de alta intensidad de lluvia. **Conclusiones.** Las variables hidrológicas son importantes para determinar los riesgos de los sedimentos de escorrentía urbana. En este estudio, encontramos que la variable del clima seco está relacionada con los valores de los índices de geoacumulación y la contaminación. Los resultados de este trabajo refuerzan la posibilidad de desarrollar sistemas de alerta temprana para los riesgos de sedimentos utilizando variables hidrológicas y sedimentológicas.

Palabras claves: evaluación de riesgos, hidrología, sedimentos, granulometría, metales pesados, escorrentía urbana.

Avaliação de riscos de sedimentos de escoamento em uma bacia experimental em Bogotá relacionada com características hidrológicas e granulométricas

RESUMO

Introdução. Os sedimentos de escoamento urbano contêm metais pesados que criam riscos ambientais. Vários índices de avaliação de risco foram desenvolvidos para metais pesados, mostrando o nível de contaminação por partículas no ambiente e sua fonte. Além disso, o risco de sedimentos também está associado à distribuição do tamanho das partículas e às características hidrometeorológicas. **Objetivo.** Este trabalho tem

como objetivo, avaliar o risco de contaminação por sedimentos de escoamento coletado em uma bacia experimental, em relação à sua distribuição de tamanho e características hidrológicas da área de influência. **Material e métodos.** As experiências de campo e de laboratório foram realizadas no regulador de tanques / construção de zonas úmidas da Pontificia Universidad Javeriana, Bogotá. Dados hidrológicos foram obtidos

em uma estação pluviométrica próxima de El Paraíso. Foram calculados os índices de geoacumulação (Igeo), o índice de contaminação (PI) e o fator de enriquecimento (EF). Além disso, a análise de componentes principais foi utilizada para determinar as relações entre as variáveis de risco, hidrológicas e granulométricas. **Resultados.** Existe um risco baixo/médio de Cu e Cr, em contraste com o alto risco de Pb e Zn. De acordo com a análise estatística multivariada, existe uma relação entre os índices de risco e o diâmetro médio das partículas (D50): esses índices aumentam para partículas finas e períodos

de alta intensidade de chuva. **Conclusões.** Variáveis hidrológicas são importantes na determinação dos riscos de sedimentos urbanos. Neste estudo, identificamos que a variável clima seco está relacionada aos valores dos índices de geoacumulação e poluição. Os resultados deste trabalho reforçam a possibilidade de desenvolver sistemas de alerta precoce para riscos de sedimentos usando variáveis hidrológicas e sedimentológicas.

Palavras-chave: avaliação de risco, hidrologia, sedimentos, tamanho de grão, metais pesados, escoamento urbano.

INTRODUCTION

Urban stormwater runoff has a sediment load that is retained by different structures that allow their sedimentation and accumulation processes (Nawrot et al., 2020). Dredging and subsequent disposal of these sediments are taken into account in the management strategies of urban stormwater structures (Schwartz et al., 2017). However, urban stormwater sediments adsorb different pollutants, such as heavy metals (HM) that have received increasing attention in recent years because they are not biodegradable and generate risk for the environment and human health (Joshi et al., 2009; Zhang et al., 2017). Especially in water bodies, they have an impact due to their prevalence, persistence, bioaccumulation, and toxicity caused mainly by anthropogenic activities (Xiao et al., 2019)

Recently, different sediment quality indexes have been proposed to assess HM contamination and their toxicity evolution in bed sediments, road deposited sediments, and sediments in wetland areas. Some of

them are the geo-accumulation index (Igeo) to analyse natural fluctuations in the content of a given substance in the environment (Barbieri, 2016), the pollution load index (PI) which is the ratio of its concentration to their background concentration (Faiz et al., 2009), the potential ecological risk index (RI) which represents the sensitivity of the biological community to toxic substances (Zhao & Li, 2013), and the enrichment factor (EF) which helps to establish the principal sources of the metals (natural or anthropogenic) (Barbieri, 2016; Joshi et al., 2009; R. Kumar et al., 2019). Besides, human health risk assessment has become a widely applied methodology to evaluate the potential risks arising from exposure to environmental contaminants (Ferré-Huguet et al., 2009).

Physical and hydrological analyses have been carried out on the sediments collected in runoff waters, finding variations in the HM concentrations and the associated risk results according to their particle size distribution (PSD) and the antecedent dry weather period (ADP)

(Deletic & Orr, 2005; McKenzie et al., 2008; Pimiento et al., 2018).

Despite the progress reported above, there is a need for field studies that focus on understanding how human activities combined with hydrological conditions variables could generate diffuse HM pollution, especially for those that harmful to flora and fauna in low levels (Lynch et al., 2018). Also, the relationship between risks associated with sediment deposition and granulometric and hydrometeorological characteristics need to be studied (Jang et al., 2010). On the other hand, it is crucial to assess the influence of environmental factors such as the ADP, the rainfall characteristics (i.e. intensity and duration), anthropogenic factors such as land use, runoff contact surface, the PSD and the surface loads of HM in urban watersheds on the toxicity of the sediments (Guo et al., 2020; Zhan et al., 2020; Zhang et al., 2017) in

order to relate these variables with a possible risk alert.

Studies on the pollution process and efficient measures of its concentrations in urban stormwater runoff are lacking, especially in tropical regions such as Colombia (Liu et al., 2018; Ma et al., 2018). Additionally, Colombia does not have a regulation that allows establishing the permissible ranges of pollutants in urban stormwater runoff.

This study aims to evaluate the risk of contamination from runoff sediments, collected in a small experimental catchment at Pontificia Universidad Javeriana (PUJ), associated with hydrological, PSD, geo-accumulative and pollutive characteristics that will be able to contribute to the decision making for the adequate management of dredged sediments in the different urban stormwater bodies.

MATERIALS AND METHODS

The field experiments were carried out on the constructed-wetland/storage-tank structure from Pontificia Universidad Javeriana (PUJ) which receives runoff from a soccer field and a parking lot building (Galarza-Molina et al., 2015). The sediments were collected from the sand traps for five months (May 2016 to September 2016). The heavy metals (HM) concentrations were measured using ICP for Cooper (Cu), Chromium (Cr), Lead (Pb), and Zinc (Zn). The rainfall data were obtained from El Paraíso rain gauge station, located approximately 500 meters from the

experimental site in latitude 4.62802611849305 and longitude -74.05863996311022 (Figure 1). This station is part of the early warning system of the district risk management institute of Bogotá (IDIGER, for its name in Spanish). The variables analysed were the following ones: total precipitation height (TPH), average intensity (AI), maximum intensity (MI), number of days with dry weather (DW), number of days with rainfall weather (RW), net average intensity (NAI) and antecedent dry weather period (ADP) (Table 1).



Figure 1. location of hydrometeorological station and sampling site

Source: "Lluvias en tiempo real" <http://app.sab.gov.co:8080/sab/lluvias.htm>

Table 1. Precipitation data

Sample	TPH (mm)	AI (mm/day)	MI (mm)	DW (day)	RW (day)	NAI (mm/day)	ADP (day)
1	19.00	1.00	6.00	4.00	5.00	6.00	1.00
2	19.45	1.30	6.40	4.00	5.00	5.80	1.00
3	29.30	1.95	9.00	3.00	7.00	11.28	2.00
4	29.30	1.95	9.00	3.00	7.00	11.28	2.00
5	32.70	2.18	10.60	4.00	10.00	0.66	2.00
6	32.70	2.18	10.60	4.00	10.00	0.66	2.00
7	34.70	2.31	17.50	2.00	10.00	7.61	2.00
8	34.70	2.31	17.50	2.00	10.00	7.61	2.00
10	15.90	1.06	5.10	7.00	6.00	12.24	2.00
11	18.20	1.21	10.20	6.00	7.00	2.54	2.00
12	52.91	3.53	20.00	2.00	10.00	8.33	1.00
14	43.20	2.88	16.90	6.00	7.00	6.79	2.00
15	13.30	0.89	5.80	6.00	4.00	6.08	1.00

Source: authors own creation.

RISK ASSESSMENT

Igeo was calculated using equation (1) initially proposed by Müller, (1979) to analyse the pollution in aquatic bottom sediments, where C_n is the measured HM concentration in sediments and B_n is the geochemical background value of the pollutant: Cu = 40 mg/kg, Cr = 74 mg/kg, Pb = 17 mg/kg and Zn = 65 mg/kg (Rauch & Pacyna, 2009). Igeo is classified as G0 unpolluted environment – $I_{geo} \leq 0$, G1 unpolluted to moderately polluted – $0 < I_{geo} \leq 1$, G2 moderately polluted – $1 < I_{geo} \leq 2$, G3 moderately to strongly polluted – $2 < I_{geo} \leq 3$, G4 strongly polluted – $3 < I_{geo} \leq 4$, G5 strongly to extremely polluted – $4 < I_{geo} \leq 5$, and G6 extremely polluted – $I_{geo} > 5$ (Faiz et al., 2009; Loganathan et al., 2013):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 * B_n} \right) \quad \text{Equation 1}$$

PI (see equation 2, where C_n and B_n are the same as for equation (1)) is classified in low level of pollution – $PI \leq 1$, medium level of pollution – $1 < PI \leq 3$, high level of pollution – $PI > 3$ (Faiz et al., 2009).

$$PI = \frac{C_n}{B_n} \quad \text{Equation 2}$$

RI expresses the ecological risk caused by sediments. We calculated it using equation (3) proposed by Hakanson, (1980), where C_n and B_n are the same as for equation (1), and Tr_n is the metal toxic response factor taken as 5 for Cu, 2 for Cr, 5 for Pb, and 1 for Zn (Zhao & Li,

2013). RI is categorized as low ecological risk – $RI \leq 150$ (G0), moderate ecological risk – $150 < RI \leq 300$ (G1), considerable ecological risk – $300 < RI \leq 600$ (G2), and very high ecological risk – $RI \geq 600$ (G3) (Hakanson, 1980).

$$RI = \sum_{i=1}^m Tr_n^i \times \frac{C_n^i}{B_n^i} \quad \text{Equation 3}$$

EF (equation 4) is the normalisation of an HM concentration respect to a reference element. In this study, we used Aluminium (Al) which is a stable element and without vertical mobility and degradation. In equation 4, C_n and B_n are the same as for equation (1), and C_{Al} (7000 mg/kg) (Feria et al., 2010), B_{Al} (15 mg/kg) are the measured and the background concentrations of Al respectively. EF is classified as deficiency to minimal enrichment – $EF < 2$, moderate enrichment – $2 < EF < 5$, significant enrichment $5 < EF < 20$, very high enrichment – $20 < EF < 40$, and extremely high enrichment – $EF > 40$ (Barbieri, 2016):

$$EF = \frac{C_n / C_{Al}}{B_n / B_{Al}} \quad \text{Equation 4}$$

The previously defined indexes were calculated to determine the risks of sediments in a small experimental catchment at PUJ, and the relationships between their size distributions and rainfall characteristics.

STATISTICAL ANALYSIS

The Data analysis was done using R software (R Core, 2020). The ade4 library was implemented (Dray et al., 2017) for Principal Component Analysis (PCA) (Lebart, L., Morineau, A., & Piron, 1995) to determinate which component explains the variance and which variables are the most influential on risks outcomes. Only numerical variables of precipitation and particle diameters were taken, as well as Cd, Cu, Zn and Pb concentrations, each one with their risk indexes. Additionally, corplot library (Wei et al., 2017) was used for Spearman correlation instead of Pearson Correlation, due to the non-normal distribution of the data (Minitab 18, 2019; Solutions, 2020; Statistics, 2018) searching the variables which are most related to geo-accumulation and pollution risks by HM on sediments. The Spearman correlation coefficient is classified into five statements according to their absolute magnitude: 1) 0.00-0.1 as a negligible correlation, 2) 0.1-0.39 as a weak correlation, 3) 0.40-

0.69 as a moderate correlation, 4) 0.70-0.89 as a strong correlation and 0.9-1 as the strongest correlation factor (Schober et al., 2018).

RESULTS

Risk Assessment

The results obtained for risk assessment demonstrate that according to the Igeo analysis, the sediments are unpolluted (G0) by Cr, moderately polluted (G3) by Cu, and heavily polluted (G4) by Pb and Zn. PI values obtained show that the sediments have a low level of pollution by Cr, a middle level of pollution by Cu, and a high level of pollution by Pb and Zn. From the weighted result RI, the sediments are classified as moderate ecological risk. Some specific samples were classified as low ecological risk with few samples categorized as moderate ecological risk, as shown in Figure 2.

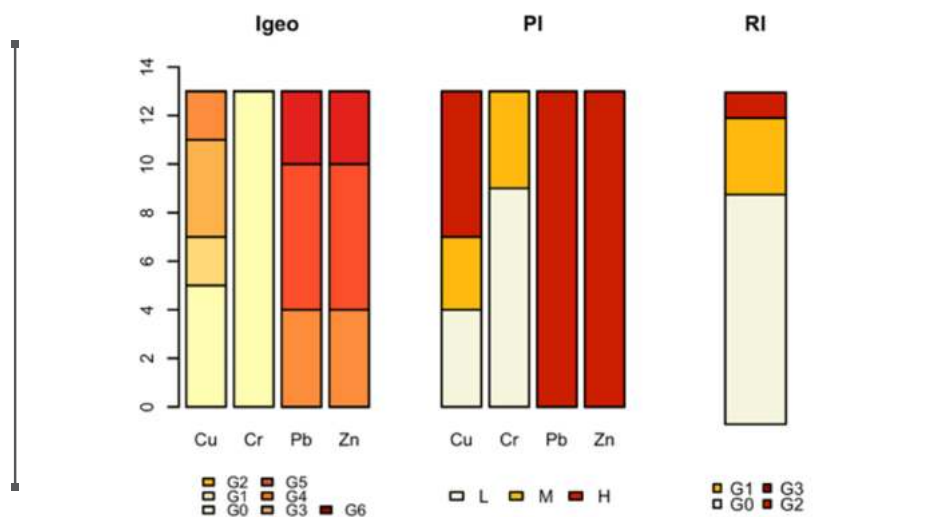


Figure 2. Risk assessment by geo-accumulation index - Igeo (left) (classified from G0: unpolluted environment to G6: extremely polluted), pollution load index - PI (center) (L: low level of pollution, M: medium level of pollution, H: high level of pollution), and potential ecological risk index - RI (right) (classified from G0: low ecological risk to G3: very high ecological risk)

Source: authors own creation.

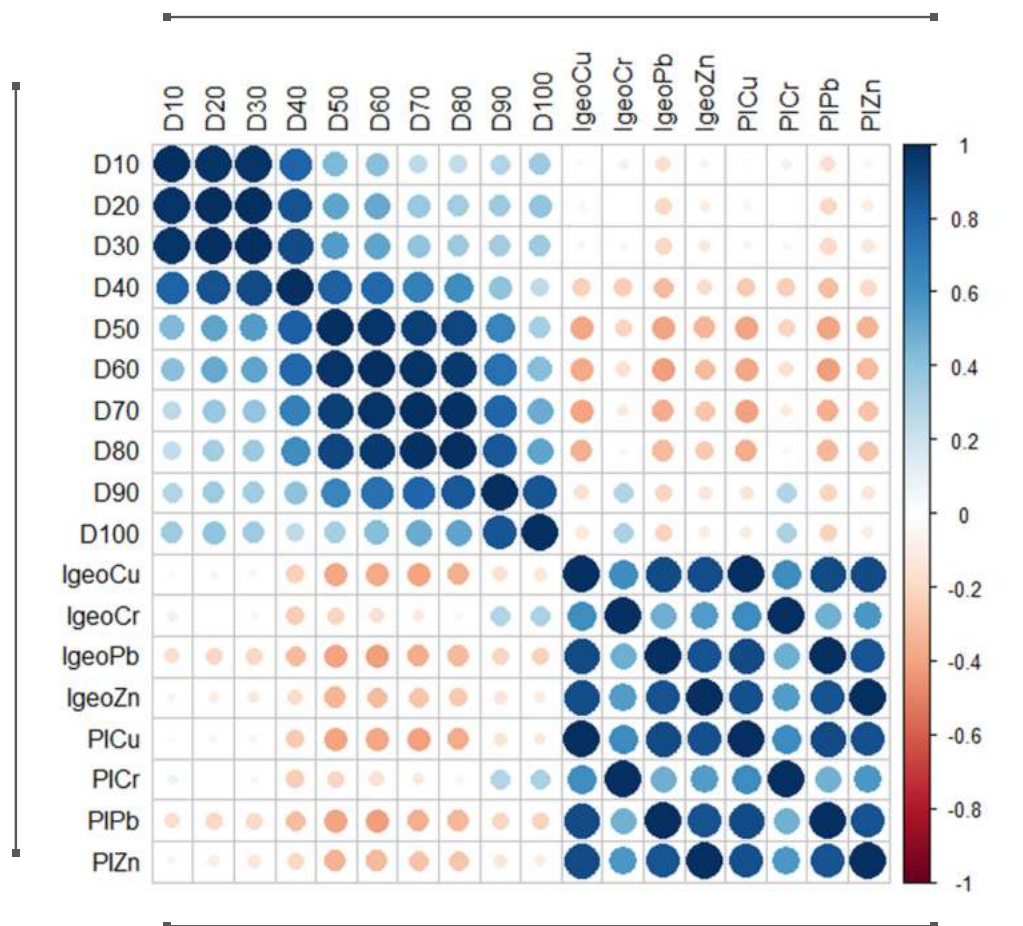
EF values show that the HM are generated as a result of anthropogenic activities because the values obtained for all the HM measured are higher than 40, which means that the sediments have an extremely high enrichment: pollutants come from different sources of non-cortical materials.

Statistical Analysis

The analysis showed that PICu, PIPb, IgeoCu, and IgeoPb are more associated with higher diameters (D50-D80),

and also with IgeoZn and PIZn. The sediments associated with diameters between D50-D80 have lower Igeo and PI values for Cu and Pb (Figure 2 – Upper).

As with the sediment sizes, NAI is inversely related to the IgeoZn ($r=-0.422$) and PIZn ($r=-0.416$). If the magnitude of this variable is higher, then Zn indexes would be lower. It could be confirmed with the reported results by Wicke et al., (2012). They establish that as the number of dry days in the background increases, there will be a decrease in the accumulation of pollutants, such as the accumulation rates of Zn as shown in Figure 3 – Lower



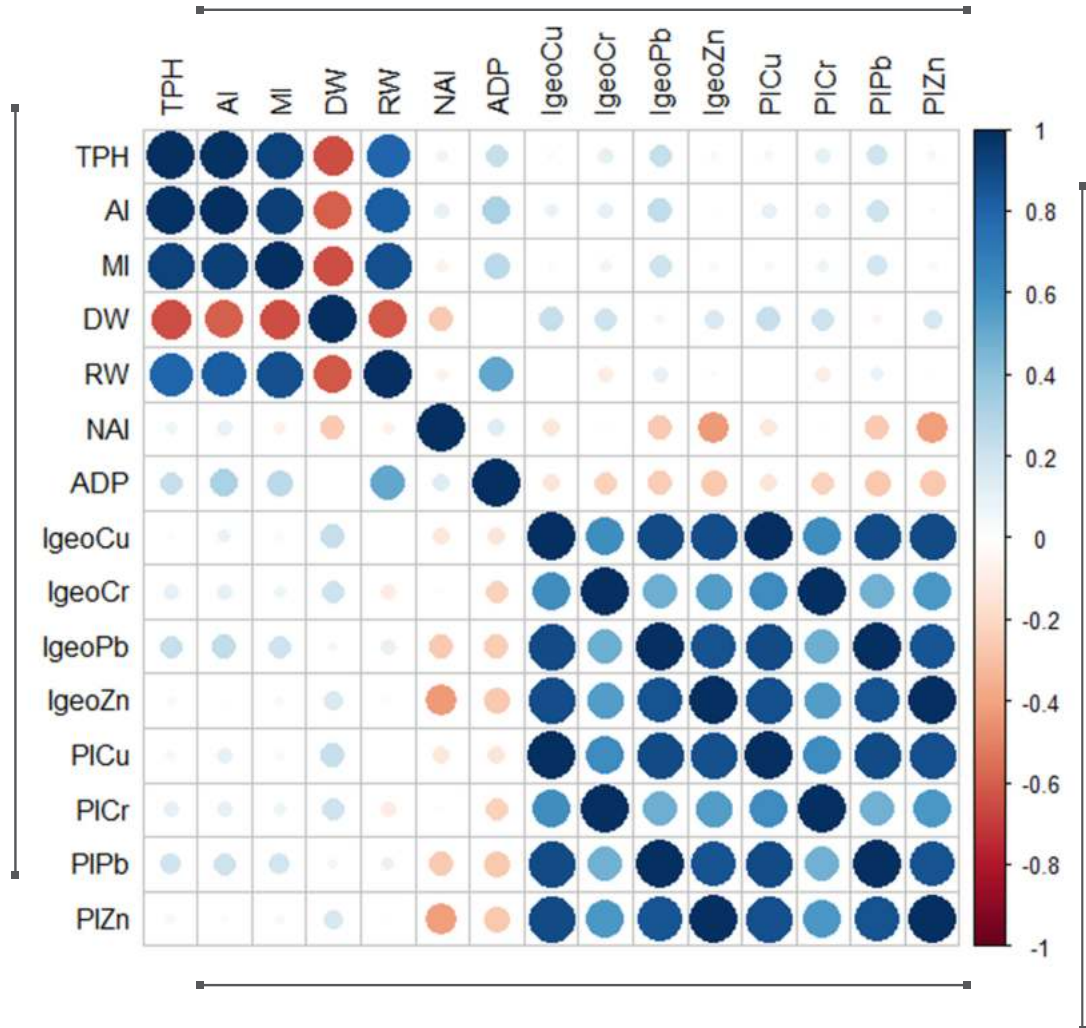


Figure 3. Upper: First segmentation of the Spearman matrix, correlation between granulometric diameters (D10 to D100) and risk indexes (geo-accumulation index - Igeo and potential ecological risk index - PI). Lower: Second segmentation of the Spearman matrix, correlation between hydrological variables (total precipitation height - TPH, average intensity -AI, maximum intensity -MI, number of days with dry weather - DW, number of days with rainfall weather - RW, net average intensity - NAI and antecedent dry weather period - ADP) and risk indexes (geo-accumulation index - Igeo and potential ecological risk index - PI).

Source: authors own creation.

On the other hand, it is confirmed that the PCA methodology is viable to determine the influence of the PSD and hydrological variables on the values of the indexes of each element, since the first two components represent 75% of the total variance of the data as shown in Figure 4. Also, it is possible to determine that the

second component shows the ADP as a variable inversely related to the IgeoCr and PI, while the DW, presents a small directly proportional relationship. Additionally, it is possible to affirm that the IgeoCu, IgeoPb, PICu, PIPb, and PIZn present high statistic variability regarding the particle diameters D50 and NAI.

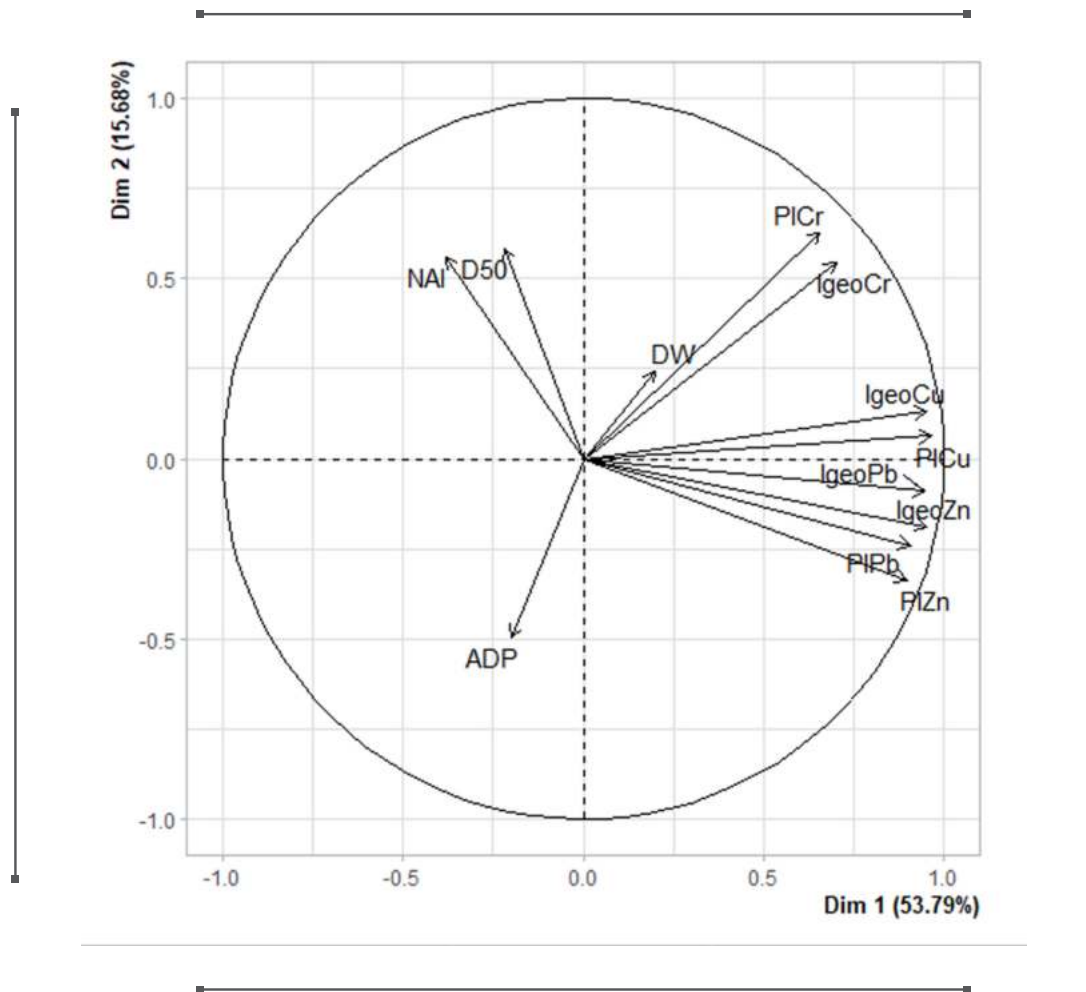


Figure 4. Principal Components Analysis (PCA). Medium diameter - D50, hydrological variables (number of days with dry weather - DW, net average intensity - NAI and antecedent dry weather period - ADP) and risk indexes (geo-accumulation index - Igeo and potential ecological risk index - PI).

Source: authors own creation.

DISCUSSION

The results obtained by EF show that the HM are supplied by various sources of pollution, such as human activities typical of urban areas, "the emissions of contained Cu, Pb and Zn particles are associated with nearby vehicular traffic, including both the combustion process and tire wear" (Machado et al., 2008).

The results related to ADP and DW were obtained and could be contrasted with literature findings. The Igeo and PI values for Cr have a little slightly directly related to DW, and this relation can be observed in Romero-Barreiro et al., (2015). Different authors have agreed with this behavior, stating that the more DW, the more pollutants charge will be found (Wicke et al., 2012). Romero-Barreiro et al., (2015) found a strong correlation of ADP with the Igeo and PI risk indices, this results agrees with those obtained in this research, suggesting that ADP is an important explanatory factor of the inverse variation of geo accumulation and pollution risks.

These relations observed between PSD and Cu and Pb risks agree with those reported in the literature concerning the importance of the PSD over the control of HM concentrations (Morelli et al., 2012; Yao et al., 2016): urban runoff sediments with a coarser grain size tend to have significantly lower HM concentrations and higher heterogeneity, which could explain their high variability in HM concentrations relative to their low HM concentration (Kang et al., 2017; Zhao & Li, 2013). Finer grain fractions could be reached in HM and be related to the large surface area of finer sediments with high adsorption capacity (Yao et al., 2016).

A possible accumulation derived from DW variables could affect different environment matrixes such as air,

soil and surrounding vegetation since this phenomenon can generate toxic effects on the health of users and residents of areas near to road corridors (Kang et al., 2017; Yao et al., 2016). In this case, higher risk indexes will be presented in the area, if the variables of NAI and ADP have lower values.

CONCLUSIONS

From the risk assessment, we can conclude that the elements that present the main geo-accumulation indexes are mainly given by Pb and Zn, and by Cu pollution index, presenting certain high risks in the samples.

Some RI values were classified as low and moderate on most of the campaigns; however, a few samples are evaluated as considerable risks which could be derived from high concentrations of Pb induced by vehicular traffic from the surrounding main roads.

Events can be classified, as representing a high or low risk according to hydrological and particle size variables. In a specific way, the D50 manages to represent the variability of the geo-accumulation and contamination indexes, opening the possibility of assessing the sediment quality indexes based on its median particle size.

Hydrological variables are important to determine the risks of urban runoff sediments. In this study, we found that the variable of dry weather is related to the values of geo-accumulation indexes and contamination of Cr and Cu. Based on this, it is possible to propose risk

management tools of these sediments based on the climatological characteristics of the sector.

The inverse relationship between diameters and geo-accumulation indexes and contamination for the rain event allows determining that, if the rain accumulates sediments that present more fine particles, the risk will be higher; in the same way, for the relationship between Zn indexes and the net average intensity, since at low net average rainfall intensities, higher values of Zn contamination and geo-accumulation in the sediment can be presented.

The findings of this work reinforce the possibility of developing early warning systems for sediment risks using key hydrological and sedimentological variables. To achieve this, we recommend, as future work, to analyze more extensive databases to reach more generalizable relationships, as well as it is possible to establish relationships regarding stormwater quality and sediment transport during runoff (Ji, 2017; V. Kumar et al., 2019). Additionally, this could only be achieved through hydrological measurements with better spatial-temporal resolutions, so that they can be processed as part of an online decision system.

REFERENCES

- Barbieri, M. (2016). The Importance of Enrichment Factor (EF) and Geoaccumulation Index (Igeo) to Evaluate the Soil Contamination. *Journal of Geology & Geophysics*, 5(1). <https://doi.org/10.4172/2381-8719.1000237>
- Deletic, A., & Orr, D. W. (2005). Pollution Buildup on Road Surfaces. *Journal of Environmental Engineering*, 131(1), 49–59. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2005\)131:1\(49\)](https://doi.org/10.1061/(ASCE)0733-9372(2005)131:1(49))
- Dray, S., Dufour, A.-B., & Thioulouse, J. (2017). Package 'ade4.' <https://cran.r-project.org/web/packages/ade4/ade4.pdf>
- Faiz, Y., Tufail, M., Javed, M. T., Chaudhry, M. M., & Naila-Siddique. (2009). Road dust pollution of Cd, Cu, Ni, Pb and Zn along Islamabad Expressway, Pakistan. *Microchemical Journal*, 92(2), 186–192. <https://doi.org/10.1016/j.microc.2009.03.009>

- Feria, J. j. (1), Marrugo, J. I. (2), & González, H. (3). (2010). Heavy metals in Sinú river, department of Córdoba, Colombia, South America. *Revista Facultad de Ingeniería*, 55, 35–44. <http://ezproxy.javeriana.edu.co:2048/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-77956832385&lang=es&site=eds-live&scope=cite>
- Ferré-Huguet, N., Nadal, M., Schuhmacher, M., & Domingo, J. L. (2009). Human Health Risk Assessment for Environmental Exposure to Metals in the Catalan Stretch of the Ebro River, Spain. *Human and Ecological Risk Assessment: An International Journal*, 15(3), 604–623. <https://doi.org/10.1080/10807030902892604>
- Galarza-Molina, S. L., Torres, A., Moura, P., & Lara-Borrero, J. (2015). CRIDE: A Case Study in Multi-Criteria Analysis for Decision-Making Support in Rainwater Harvesting. *International Journal of Information Technology & Decision Making*, 14(01), 43–67. <https://doi.org/10.1142/S0219622014500862>
- Guo, Q., Zhan, Y., Li, Y., Hong, N., Guan, Y., Zhang, Z., Yang, B., Meng, F., Yang, M., & Liu, A. (2020). Investigating toxicity of urban road deposited sediments using Chinese hamster ovary cells and *Chlorella Pyrenoidosa*. *Chemosphere*, 245, 125634. <https://doi.org/10.1016/j.chemosphere.2019.125634>
- Hakanson, L. (1980). An ecological risk index for aquatic pollution control. a sedimentological approach. *Water Research*, 14(8), 975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Jang, Y.-C., Jain, P., Tolaymat, T., Dubey, B., Singh, S., & Townsend, T. (2010). Characterization of roadway stormwater system residuals for reuse and disposal options. *SCIENCE OF THE TOTAL ENVIRONMENT*, 408(8), 1878–1887. <https://doi.org/10.1016/j.scitotenv.2010.01.036>
- Ji, Z. (2017). Sediment Transport. In *Hydrodynamics and Water Quality* (pp. 73–133). John Wiley & Sons, Inc. <https://doi.org/10.1002/9781119371946.ch3>
- Joshi, U. M., Vijayaraghavan, K., & Balasubramanian, R. (2009). Elemental composition of urban street dusts and their dissolution characteristics in various aqueous media. *Chemosphere*, 77(4), 526–533. <https://doi.org/10.1016/j.chemosphere.2009.07.043>
- Kang, X., Song, J., Yuan, H., Duan, L., Li, X., Li, N., Liang, X., & Qu, B. (2017). Speciation of heavy metals in different grain sizes of Jiaozhou Bay sediments: Bioavailability, ecological risk assessment and source analysis on a centennial timescale. *Ecotoxicology and Environmental Safety*, 143, 296–306. <https://doi.org/10.1016/j.ecoenv.2017.05.036>
- Kumar, R., Kumar, V., Sharma, A., Singh, N., Kumar, R., Katnoria, J. K., Bhardwaj, R., Thukral, A. K., & Rodrigo-Comino, J. (2019). Assessment of pollution in roadside soils by using multivariate statistical techniques and contamination indices. *SN Applied Sciences*, 1(8), 842. <https://doi.org/10.1007/s42452-019-0888-3>

- Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Singh Sidhu, G. P., Bali, A. S., Karaouzas, I., Bhardwaj, R., Thukral, A. K., Gyasi-Agyei, Y., & Rodrigo-Comino, J. (2019). Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere*, 236, 124364. <https://doi.org/10.1016/j.chemosphere.2019.124364>
- Lebart, L., Morineau, A., & Piron, M. (1995). *Statistique exploratoire multidimensionnelle*. In Paris: Dunod (Vol. 3).
- Liu, W.-R., Yang, Y.-Y., Liu, Y.-S., Zhao, J.-L., Zhang, Q.-Q., Yao, L., Zhang, M., Jiang, Y.-X., Wei, X.-D., & Ying, G.-G. (2018). Biocides in the river system of a highly urbanized region: A systematic investigation involving runoff input. *Science of The Total Environment*, 624, 1023–1030. <https://doi.org/10.1016/j.scitotenv.2017.12.225>
- Loganathan, P., Vigneswaran, S., & Kandasamy, J. (2013). Road-Deposited Sediment Pollutants: A Critical Review of their Characteristics, Source Apportionment, and Management. *Critical Reviews in Environmental Science and Technology*, 43(13), 1315–1348. <https://doi.org/10.1080/10643389.2011.644222>
- Lynch, S. F. L., Batty, L. C., & Byrne, P. (2018). Environmental risk of severely Pb-contaminated riverbank sediment as a consequence of hydrometeorological perturbation. *Science of The Total Environment*, 636, 1428–1441. <https://doi.org/10.1016/j.scitotenv.2018.04.368>
- Ma, Y., Hao, S., Zhao, H., Fang, J., Zhao, J., & Li, X. (2018). Pollutant transport analysis and source apportionment of the entire non-point source pollution process in separate sewer systems. *Chemosphere*, 211, 557–565. <https://doi.org/10.1016/j.chemosphere.2018.07.184>
- Machado, A., García, N., García, C., Acosta, L., Córdova, A., Linares, M., Giraldoth, D., & Velásquez, H. (2008). Metal contamination of air, street dust and soil in a high traffic area. *Revista Internacional de Contaminación Ambiental*, 24(4), 171–182.
- McKenzie, E. R., Wong, C. M., Green, P. G., Kayhanian, M., & Young, T. M. (2008). Size dependent elemental composition of road-associated particles. *Science of The Total Environment*, 398(1–3), 145–153. <https://doi.org/10.1016/j.scitotenv.2008.02.052>
- Minitab 18. (2019). Una comparación de los métodos de correlación de Pearson y Spearman. <https://support.minitab.com/es-mx/minitab/18/help-and-how-to/statistics/basic-statistics/supporting-topics/correlation-and-covariance/a-comparison-of-the-pearson-and-spearman-correlation-methods/>.
- Morelli, G., Gasparon, M., Fierro, D., Hu, W.-P., & Zawadzki, A. (2012). Historical trends in trace metal and sediment accumulation in intertidal sediments of Moreton Bay, southeast Queensland, Australia. *Chemical Geology*, 300–301, 152–164. <https://doi.org/10.1016/j.chemgeo.2012.01.023>

- Müller, G. (1979). Schwermetalle in den Sedimenten des Rheins—Veränderungen seit 1971. *UMSCH. WISSENSCH. TECHN.*, 79(24), 778–783. <https://www.scienceopen.com/document?vid=879b4fc9-0fe1-44a4-8e33-b23cb9b12c98>
- Nawrot, N., Wojciechowska, E., Reznia, S., Walkusz-Miotk, J., & Pazdro, K. (2020). The effects of urban vehicle traffic on heavy metal contamination in road sweeping waste and bottom sediments of retention tanks. *Science of The Total Environment*, 749, 141511. <https://doi.org/10.1016/j.scitotenv.2020.141511>
- Pimiento, M. A., Rivera, D. S., Lara Borrero, J. A., & Torres Abello, A. E. (2018). Relationship between hydrological, physical and chemical characteristics present in rainwater runoff sediments. *Ingeniería y Competitividad*, 20(2), 27. <https://doi.org/10.25100/iyv.v20i2.5846>
- R Core, T. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rauch, J. N., & Pacyna, J. M. (2009). Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. *Global Biogeochemical Cycles*, 23(2), 1–16. <https://doi.org/10.1029/2008GB003376>
- Romero-Barreiro, M. del P., Pinilla-Castañeda, R. D., & Zafra-Mejía, C. A. (2015). Evaluación temporal de la concentración de metales pesados (Pb y Cu) asociada con el sedimento vial: Fontibón-Barrios Unidos (Bogotá D. C., Colombia). *Ingeniería y Universidad*, 19(2), 315–333. <https://doi.org/10.1114/javeriana.iyu19-2.etcmm>
- Schober, P., Boer, C., & Schwarte, L. A. (2018). Correlation Coefficients: Appropriate Use and Interpretation. *Anesthesia & Analgesia*, 126(5), 1763-1768. <https://doi.org/10.1213/ANE.0000000000002864>
- Schwartz, D., Sample, D. J., & Grizzard, T. J. (2017). Evaluating the performance of a retrofitted stormwater wet pond for treatment of urban runoff. *Environmental Monitoring and Assessment*, 189(6), 256. <https://doi.org/10.1007/s10661-017-5930-6>
- Solutions, S. (2020). Correlation (Pearson, Kendall, Spearman). <https://www.statisticssolutions.com/correlation-pearson-kendall-spearman/>
- Statistics, L. (2018). Spearman's Rank-Order Correlation - A guide to how to calculate it and interpret the output.
- Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., & Zemla, J. (2017). *corrplot*.
- Wicke, D., Cochrane, T. A., & O'Sullivan, A. (2012). Build-up dynamics of heavy metals deposited on impermeable urban surfaces. *Journal of Environmental Management*, 113, 347–354. <https://doi.org/10.1016/j.jenvman.2012.09.005>

Xiao, H., Shahab, A., Li, J., Xi, B., Sun, X., He, H., & Yu, G. (2019). Distribution, ecological risk assessment and source identification of heavy metals in surface sediments of Huixian karst wetland, China. *Ecotoxicology and Environmental Safety*, 185, 109700. <https://doi.org/10.1016/j.ecoenv.2019.109700>

Yao, Q., Wang, X., Jian, H., Chen, H., & Yu, Z. (2016). Behavior of suspended particles in the Changjiang Estuary: Sizedistributionandtracemetalcontamination. *Marine Pollution Bulletin*, 103(1–2), 159–167. <https://doi.org/10.1016/j.marpolbul.2015.12.026>

Zhan, Y., Yang, B., Hong, N., Guan, Y., Liu, A., Du, Y., Wu, Q., & Guan, Y. (2020). Developing an equivalent toxicity area approach to comparing toxicity of urban road deposited sediments. *Environmental Pollution*, 257, 113588. <https://doi.org/10.1016/j.envpol.2019.113588>

Zhang, J., Hua, P., & Krebs, P. (2017). Influences of land use and antecedent dry-weather period on pollution level and ecological risk of heavy metals in road-deposited sediment. *Environmental Pollution*, 228, 158–168. <https://doi.org/10.1016/j.envpol.2017.05.029>

Zhao, H., & Li, X. (2013). Risk assessment of metals in road-deposited sediment along an urban–rural gradient. *Environmental Pollution*, 174, 297–304. <https://doi.org/10.1016/j.envpol.2012.12.009>