**ORIGINAL ARTICLE**

Annals of Agricultural and Environmental Medicine 2023, Vol 30, No 4, 677–684
www.aaem.pl

# Comparison of leaching behaviour of heavy metals from sediments sampled in sewer systems – environmental and public health aspect

**Justyna Kujawska**[1,B-F], **Sylwia Duda-Saternus**[2,3,A-C], **Joanna Szulżyk-Cieplak**[4,C-E], **Jacek Zaburko**[4,B-C], **Magdalena Piłat-Rożek**[4,C-D], **Konrad Jamka**[5,C-D], **Roman Babko**[6,C,E], **Grzegorz Łagód**[1,A,C-F]

[1] *Faculty of Environmental Engineering, Lublin University of Technology, Poland*
[2] *Institute of Rural Health, Lublin, Poland*
[3] *'TAYLOR' Sp. z o. o., Department Research and Development, Poland*
[4] *Faculty of Mathematics and Information Technology, Lublin University of Technology, Poland*
[5] *Department of Toxicology and Food Safety, Institute of Rural Health in Lublin, Poland*
[6] *Department of Invertebrate Fauna and Systematics, Schmalhausen Institute of Zoology, National Academy of Sciences, Kyiv, Ukraine*
*A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article*

Kujawska J, Duda-Saternus S, Szulżyk-Cieplak J, Zaburko J, Piłat-Rożek M, Jamka K, Babko R, Łagód G. Comparison of leaching behaviour of heavy metals from sediments sampled in sewer systems – environmental and public health aspect. Ann Agric Environ Med. 2023; 30(4): 677–684. doi: 10.26444/aaem/175553

## Abstract

**Introduction and Objective.** The article analyzes the content of heavy metals and standard physical as well as chemical pollution indicators in different types of sediments from stormwater, combined sewer and sanitary sewer systems.
**Materials and method.** Nickel, lead, chromium, copper, zinc and cadmium, as well as standard physical and chemical pollution indicators, were determined in sewage sediments. Aqueous extracts of sediments samples, taken from storm water sewer inlet sediments traps, storm sewers, sanitary sewers and combined sewers, were prepared in accordance with PN-EN 12457–2:2006. After mineralization, the concentrations of the metals: nickel, lead, chromium, copper, zinc and cadmium in the extracts were determined using the inductively coupled plasma emission spectroscopy technique.
**Results.** The results were analyzed with a non-metric multidimensional scaling algorithm. The heavy metal content was variable depending on the sediments collection site. The heavy metals nickel, lead, chromium, copper, zinc and cadmium were found in the sediments from stormwater inlets, storm sewer and sanitary sewer channels, with variability in the concentration of individual metals. The sediments from the flushing of sanitary sewers and combined sewers did not contain cadmium.
**Conclusions.** The content of heavy metals in sediments varied depending on the sampling location and type of sewer system, indicating the need for detailed monitoring to identify the sources of emissions. Sediments from stormwater sewers have higher concentrations of heavy metals, with those from sewer inlets showing zinc concentrations exceeding regulatory limits, highlighting the variability and potential environmental impact of different sewer systems.

## Key words

heavy metals, sediments, leaching behaviour, stormwater systems, combined sewer systems, sanitary sewer systems

## INTRODUCTION AND OBJECTIVE

In the context of today's urbanization processes, the management of stormwater and sewage sediments generated in urban catchments and sewer networks is becoming critical in the protection of public health and the ecosystem. A growing body of data indicates that heavy metals such as arsenic, nickel, lead, chromium, copper, zinc and cadmium present in sewer sediments have harmful effects on human health. These metals can react with biological systems, affecting cellular organelles and components such as the cell membrane, mitochondria, lysosomes, endoplasmic reticulum, nuclei, and some enzymes involved in metabolism, detoxification and damage repair [1]. Metal ions interact with cell components, such as DNA and nuclear proteins, causing DNA damage and conformational changes that can lead to cell cycle modulation, carcinogenesis or apoptosis [2].

The acute and chronic effects of metal poisoning affect various organs of the body. Gastrointestinal and renal dysfunctions, nervous system disorders, skin lesions, vascular damage, immune system dysfunction, birth defects and cancer have all been reported as examples of toxic complications of the effects of heavy metals. In addition, exposure to several or more metals can have cumulative effects [3–5]. Human exposure to small doses of metals poses a risk that can cause a number of subtle neuropsychiatric disorders, including fatigue, detrimental effects on the intelligence quotient and general impairment of intellectual

---

Address for correspondence: Justyna Kujawska, Faculty of Environmental Engineering, Lublin University of Technology, Poland
E-mail: j.kujawska@pollub.pl

Received: 02.11.2023; accepted: 20.11.2023; first published: 01.12.2023

function (especially in children) [6]. In this aspect of hazards, five heavy metals – arsenic, cadmium, chromium, lead and mercury – have been found to be carcinogenic for human. Although the exact mechanism is unclear, it has been suggested that abnormal changes in the genome and gene expression lie as the underlying process [7]. Due to their high degree of toxicity, these five elements are among the priority metals that are of great importance for public health [8].

An integral component of the infrastructure of a city is an effectively functioning sewer system, the main purpose of which is the uninterrupted collection of wastewater and its transport to a treatment plant or other receiver [9]. The accumulation of sediments in sewer pipes can lead to complications in the operation of sanitary, storm and combined sewer systems, through deformation and reduction of the active cross-section of the channel. Sediments can also accelerate the process of sulfate corrosion of pipes, affect the transformation and biodegradation of wastewater, and be a source of odour emissions. Increased flows in channels can cause leaching of pollutants from sediments, leading to periodic increases in pollutant loads in wastewater flowing into the treatment plant, and affect receiving waters receiving direct discharges from storm overflows of the combined sewer system [10, 11].

Sewage sediments in the environment is an insoluble solid phase. They are mainly generated by organic and inorganic compounds in the form of solids from domestic as well as industrial wastewater and stormwater, manifesting themselves in the form of emulsions and suspensions. Under the right conditions, these sediments form deposits with specific physicochemical, mechanical and rheological properties [12, 13].

Heavy metals are present in sewage sediments [14]. Sources of metals in sediments have been linked to traffic, identified as a major emission factor [15], flushing processes, and corrosion of building and structure coatings [16], atmospheric deposition associated with air pollution [17, 18], industrial emissions [19, 20] and contamination associated with road salts and gravel used for winter road maintenance (de-icing) [21, 22].

According to Polish legislation, sewage sediments are included in the waste groups 20 03 03 and 20 03 06 [23]. There is an urgent need for proper management of these sediments due to technological challenges and legal requirements for their storage and management in accordance with the Waste Law of 14 December 2012 (*Journal of Laws,* 2013, item 21, as amended) [24]. According to the law, sewage sediments from sewer cleaning should be subjected to recovery processes or, if suitable methods are not available, to disposal processes.

As shown by Sikorska [25], the mere flushing (at a mass ratio of 1:10 waste:water) of pre-separated sewage sediments does not ensure that the values of all tested parameters are below the permissible limits specified in the Regulation of the Minister of Economy (*Journal of Laws,* 2015, item 1277) [26]. It is worth noting that the metal content of water extracts from sewage sediments must meet the requirements of the Regulation of the Minister of Economy of 15 July 2016 on admitting waste to landfills.

Although several studies have been conducted on the leaching of heavy metals from specific sources, such as stormwater or sanitary sewage, comparative analysis of the leaching potential from sediments of different origins – stormwater, sanitary sewage and combined sewage – remains under-researched [19, 27, 28]. Such research is necessary to develop strategies for the removal, recycling or reuse of raw materials contained in sediments and sludge, ensuring that environmental and occupant health risks are minimized.

The aim of the article is to bridge this gap by assessing the leaching potential of heavy metals from the sediments from stormwater, sanitary and combined systems, to provide valuable information on the risks associated with each type of pollutant, and to determine appropriate management strategies.

## MATERIALS AND METHOD

**Sediments sampling.** Samples of sediments were taken from stormwater sewer inlet sediments traps, stormwater sewer, sanitary sewer, and combined sewer channels, during the spring period, in order to take into account the contaminants in them accumulated during winter street maintenance. Sampling points were established on the basis of a site visit, taking into account the land use and development of the area within a radius of 100 m from the sampling point. The investigated parameters included the location of the object, accessibility (e.g., possibility to open the manhole) and the condition of the sewer (amount of accumulated sediments). In total, 13 manholes were selected for sanitary sewers, 3 manholes for combined sewers and 5 manholes for stormwater sewers, including street drains.

The area in which the sanitary sewer manhole of the first sampling point was selected was dominated by single-family housing. The houses were characterized by low-rise buildings with gable roofs, with a total area of 12576 m$^2$. There were green areas belonging to the river flowing in the neighbourhood.

The second sampling point was located on a cycling lane next to the pavement. The area contained low-rise multi-family buildings with mono-pitched roofs, a petrol filling station, and public buildings with a total roof area of 9,876 m$^2$.

The third sampling point was located on the roadway. The area was dominated by dense development with service buildings with mono-pitched roofs, with a total area of 7,600 m$^2$ and a parking space with an area of 12,376 m$^2$.

The fourth sampling point was located on an unpaved road. It was characterized by the location of low multi-family buildings with retrofitted mono-pitched roofs with a total area of 14275 m$^2$, parking areas belonging to multi-family buildings with a total area of 8,633 m$^2$, and a commercial establishment.

The fifth point was located along the roadway in the vicinity of a manufacturing plant, parking areas and high-rise buildings taken out of service (vacant buildings). The total area of the roofs was 19,863 m$^2$.

The sixth measurement point was located on a pavement next to a busy dual carriageway. The area was characterized by dense, mixed single-family and multi-family housing, as well as a low-rise commercial and retail building and an associated parking area; the total area of roofs was 16,587 m$^2$.

The seventh point was located on the roadway. The area was dominated by industrial plants, forges and factories, as well as associated low-rise multi-family housing with a total area of mono-pitched roofs of 28,065 m$^2$.

The eighth point was located on the pavement of a dual carriageway in an area dominated by multi-family housing and large-scale commercial establishments and a petrol filling station.

The ninth point was located on an unpaved road. The surrounding single-family housing with a total area of mono-pitched and gable roofs was 2,667 $m^2$.

The tenth and eleventh sampling points were located near green areas in an area of on-going construction of an access road.

The twelfth and thirteenth sampling points were located in green areas in the vicinity of low-rise single-family houses, commercial and retail establishments, and tall buildings with a total roof area of 13,554 $m^2$.

The sampling points for combined sewers were located in the areas with dense and low-rise multi-family housing (mainly multi-family housing with associated parking areas) and services (car wash station). The intake points for stormwater sewers intended for the discharge of stormwater or snowmelt captured in open or closed sewer systems were in the vicinity of parking areas and access roads next to low-rise public buildings with mono-pitched and gable roofs with a total roof area of 13,652 $m^2$ (Tab. 1).

**Table 1.** Characteristics of sampling points

| NO. | LOCATION | TYPE OF DEVELOPMENT | D / MAT. / YEAR OF CONSTRUCTION |
|---|---|---|---|
| | | Sanitary sewer system | |
| 1 | TZ by the river | SFH | 800 / reinforced concrete / 1996 |
| 2 | Cycling lane | MFH, S, G | 1000 / reinforced concrete / 1969 |
| 3 | Roadway | "Bulwar" continuation | 600 / reinforced concrete / 1969 |
| 4 | Unpaved road | SFH | 400 / concrete / 1964 |
| 5 | Roadway | MP | 400 / concrete / 1964 |
| 6 | TZ by the river | SFH | 800 / reinforced concrete / 1996 |
| 7 | Cycling lane | MFH, S, G | 1000 / reinforced concrete / 1969 |
| 8 | Roadway | MP | 600 / reinforced concrete / 1969 |
| 9 | TZ by the river | SFH | 800 / reinforced concrete / 1996 |
| 10 | Cycling lane | MFH, S, G | 1000 / reinforced concrete / 1969 |
| 11 | Roadway | "Bulwar" continuation | 600 / reinforced concrete / 1969 |
| 12 | Unpaved road | SFH | 400 / concrete / 1964 |
| 13 | Roadway | MP | 400 / concrete / 1964 |
| | | Combined system | |
| 14 | Roadway | SFH + car wash | 300 / PVC (currently) / 1971 |
| | | Stormwater system | |
| 15 | Channel 1 | S | 1000 / reinforced concrete / nd |
| 16 | Parking area in front of the canteen – gully | S, G | – / m / nd |
| 17 | Public building | S | 200 / PVC / 2014 |
| 18 | Public building | S, G | 200 / PVC / 2016 |
| 19 | FEE parking lot – gully | S | – / m / nd |

*Source:* own elaboration.
SFH – single-family housing; MFH – multi-family housing; S – services; G – gastronomy; MP – manufacturing plant.

In the case of sanitary and combined sewer systems, sediments samples were taken from the bottom of the sewer through sewer manholes, while in the case of stormwater sewers, rain gullies were additionally the object of study. The method of sediments collection was selected adequately to the design of the facilities, the collection was carried out during normal operation of the sewer system, that is, the sediments was under the layer of sewage (except for the stormwater sewer system, where only one stormwater inlet contained stormwater). Sediments were collected into prepared 250 ml screw-cap bottles, in number of 3 sub-samples for each sampling points, filled to capacity – so that there was no air in the containers – and transported as quickly as possible to the Laboratory of Environmental Analysis.

**Preparation of samples for testing.** The collected sediments were dried with dry air. Aqueous extracts were then prepared at a dilution of 1:10 in accordance with PN-EN 12457–2:2006 [29] in the procedure described in a previous paper [30]. During the study, 5 ml of nitric acid (V) (65%) was added to each digestion vessel containing an aqueous extract of sediments. Nitric acid is a strong oxidant and is used to break down organic material, as well as dissolve metals. The prepared extracts were mineralized in an Anton Paar Multiwave 3000 microwave mineralizer. Mineralizations were carried out according to the manufacturer's guidelines, with a maximum pressure of 80 bar and a temperature of 250 °C.

The concentration of the metals arsenic, nickel, lead, chromium, copper, zinc and cadmium in aqueous extracts from sediments was measured using a JY 238 Ultrace spectrophotometer (Jobin Von Horiba, France) with inductively coupled plasma optical emission spectrometer (ICP OES; Jobin Von Horiba, France). Argon (purity: 99.996%; (Air Liquide S.A., São Paulo, Brazil) was employed as the plasma source, nebulization medium, and auxiliary gas in the inductively coupled plasma optical emission spectrometry (ICP-OES) apparatus. The ICP-OES apparatus is integrated with a solid-state radiofrequency (RF) generator operating at 40 MHz. The optical system features a distinctive echelle configuration, coupled with a segmented-array charge coupled device (CCD) detector. Post- microwave-assisted wet digestion, sample introduction was achieved using a low-flow GemCone nebulizer, which was linked to a peristaltic pump, facilitating the conveyance of sample solutions to the nebulization chamber. Subsequently, the sample solutions were channeled into the plasma, produced within a single slot quartz torch, through an alumina injector with a 1.2 mm diameter.

The specific parameters and conditions utilized for the instrumentation are delineated in Table 2. The choice of emission lines was predicated on such criteria as abundance, analytical sensitivity, and potential spectral interferences. It warrants emphasis that prior to the quantification of carbon, the gaseous compounds rich in carbon were meticulously eliminated. This was achieved by purging the digestates and the calibration standards with Ar for a duration of 2 minutes at a flow rate of 0.1 $L\ min^{-2}$. All experimental measurements were conducted in triplicate. In the conducted experimental series, individual detection thresholds were systematically determined for each set of measurements. For all metallic elements under investigation, these thresholds did not exceed 10 $\mu g\ L^{-1}$ [31].

**Statistical elaboration of research results.** The similarities between the sediment samples collected from various sewer system types, i.e. stormwater, sanitary, and combined sewer system, were determined via the multidimensional scaling

**Table 2.** Specific parameters and conditions utilized for the instrumentation

| PARAMETER | ICP-OES |
|---|---|
| Plasm flow rate ($\mathrm{L \cdot min^{-1}}$) | 12.0 |
| Auxiliary gas flow rate ($\mathrm{L \cdot min^{-1}}$) | 1.0 |
| Nebulizer gas flow rate ($\mathrm{L \cdot min^{-1}}$) | 1.0 |
| Analytes | Emission line |
| As | 189.042 |
| Cd | 228.802 |
| Cr | 267.716 |
| Cu | 324.754 |
| Ni | 221.647 |
| Pb | 220.353 |
| Zn | 213.856 |

method. Multidimensional scaling enables reduction of the dimensionality characterizing multidimensional data, as well as visualizing the differences among observation groups. Torgerson [32] presented a method for determining whether observations are similar or not. Usually, non-metric multidimensional scaling is employed with ordinal-type variables, when differences between measurements cannot be calculated [33], or when the values measured are expressed in different units. The applied non-metric multidimensional scaling algorithm is also known as the Kruskal-Shepard algorithm, described in [34]. This involves the minimization of the Standardized Residual Sum of Squares (STRESS) parameter, a two-step algorithm. The first step, which is achieved iteratively, involves establishing a monotonic relationship characterizing the distances between observations. In turn, the second step consists in achieving the smallest possible dimensionality of the transformed data [35]. The iterative procedure corresponds to moving points in a k dimension ($1 \leq k \leq n - 1$), where n denotes the number of variables describing the objects, so that the newly-established inter-point distances subjected to transformation in a permissible manner, minimize the STRESS parameter [36]. In line with the article [37], the STRESS values below 0.15 indicate that the original data was rescaled optimally.

The R package, version 2022.7.0.548 [38] implemented in the RStudio environment [39], was used to perform the multidimensional scaling and create each graph related to NMDS. The presented calculations were carried out using the different software libraries. The tidyverse package created in 2016 by Wickham and the RStudio team comprises other libraries. The graphs were created using the ggplot2 package [40]. The MASS package, described in [41] and published in the CRAN archive in 2009, comprises functions which are used for non-metric multidimensional scaling, i.e. the Shepard and isoMDS function. The latter was employed to reduce the dimensionality characterizing the original data.

## RESULTS AND DISCUSSION

Table 3 shows the comparison of concentrations of the heavy metals cadmium, chromium, copper, nickel and lead in the water extracts from sediments from various sewer systems: stormwater drain inlet sediments traps, as well as stormwater sewer, sanitary sewer and combined sewer channels. The concentration of arsenic in samples from the sediments was measured. No arsenic was detected in the analyzed samples.

The presented concentrations of heavy metals in the sediments from specific sewer systems, in accordance with their increasing concentration of metals in aqueous extracts from sediments, can be ranked as follows:

- sediments from the sediments traps of stormwater sewer inlets:
  zinc → copper → nickel → chromium → lead → cadmium;
- sediments from stormwater sewer channels:
  zinc → copper → chromium → lead→ nickel → cadmium;
- sediments from sanitary sewers and combined sewer system:
  zinc → copper → lead→ chromium → nickel → cadmium.

Analysis of the heavy metal content of sediments from various sewer systems provides key information about potential environmental risks. As the presented series indicate, the content of heavy metals in sediments is variable.

The wide variety of heavy metals observed at different sampling sites suggests that identification of important sources of contamination should be carried out continuously. Huber et al. (2016) noted that a combination of several interacting factors results in heavy metal contamination of runoffs, and these factors should be detailed at each monitoring site. They classified these factors as land use and point sources of pollution, and rainfall parameters, among others.

In the conditions of the analyzed different sewer systems, despite some variability in the content of individual heavy metals in sediments, it is clearly visible that in all systems zinc

**Table 3.** Comparison of results of metals concentration analysis in sediments taken from different sewer systems

| | CONCENTRATIONS OF METALS [mg/kg] | | | | | |
|---|---|---|---|---|---|---|
| | Cadmium | Chromium | Copper | Nickel | Lead | Zinc |
| Sediments from stormwater sewer inlet sediments traps | 0.21±0.001 | 0.71±0.20 | 12.83±0.15 | 3.67±0.21 | 5.20±0.02 | 72.17±1.41 |
| Sediments from stormwater sewer system | 0.014±0.001 | 0.56±0.05 | 19.69±0.06 | 0.72±0.01 | 0.31±0.07 | 25.8±0.65 |
| Sediments from sanitary sewer system | 0.01±0.001 | 0.42±0.14 | 2.10±0.40 | 0.27±0.01 | 1.41±0.39 | 12.83±0.18 |
| Sediments from combined sewer system | 0.012±0.001 | 0.38±0.04 | 28.57±0.14 | 0.28±0.07 | 0.48±0.04 | 48.50±0.27 |
| Permissible leaching limits specified in the Regulation[1] | 1 | 10 | 50 | 10 | 10 | 50 |
| Industrial wastewater discharged into receiving water[1] | 0.0005 | 0.05 | 0.1–0.5 | 0.5 | 0.1–0.5 | 0.2 |
| Surface water of good quality[2] | 0.0005 | 0.05 | 0.02 | 0.01 | 0.01 | 0.3 |

[1] Regulation of the Minister of the Environment of 18 November 2014, on conditions to be met when introducing sewage into waters or into the ground, and on substances particularly harmful to the aquatic environment

[2] Regulation of the Minister of the Environment of 11 February 2004 on the classification for presenting the status of surface and groundwater, method of conducting monitoring and method of interpreting the results and presenting the status of these waters (*Journal of Laws,* No. 32, item 284).

and copper predominate in quantity, and cadmium is found in minimal quantities. The variability of the remaining 3 analyzed elements is obvious, but according to averaged data, the following row in content of heavy metals is characteristic for analyzed samples:

zinc → copper → nickel → lead→ chromium → cadmium.

In particular, these factors have a decisive impact on the dynamics of pollutant emissions to the receiver [19].

**Cadmium.** The highest average concentration of cadmium, 201 μg/kg, was observed in the sediments from stormwater inlets. In the sediments from sanitary sewers and combined sewers, cadmium concentrations were below detection levels. Cadmium may be present in sediments for several reasons. Firstly, due to industrial contamination, as many industrial processes emit cadmium into the environment, especially in the metallurgical industry, the manufacture of nickel-cadmium batteries, as well as the recycling of plastics and electronics. Secondly, cadmium is used in various consumer products, such as paints, pigments and stabilizers in plastics [42]. When these contaminants or products enter the sewer system, cadmium is deposited in the sediments. In the sediments samples tested, cadmium concentrations were negligible, so it can be assumed that it is not a problem in the study area. Relating the results obtained to similar ones described in literature sources, it can be said that cadmium was observed in the sediments from street inlets in Luleå (Sweden) at a level of 0.04 mg/kg, while in the city centre the cadmium content was 0.1 mg/kg [27].

**Chromium.** Chromium concentration was highest in the sediments from the stormwater sewer inlet sediments traps, reaching 0.7 mg/kg. Chromium concentrations did not exceed the permissible content in water extracts, as specified in the Regulation of the Minister of Economy of 16 July 2015 on the admission of waste to landfills [26] at any of the points tested. Chromium (Cr) may be present in sediments for several reasons. Many industrial processes use chromium in various forms, for example, hexavalent chromium (Cr(VI)) is used in electroplating processes, the manufacture of paint and wood preservation pigments, and in the production of certain chemicals. If these wastes are improperly handled, or if there are leaks of chromium at industrial sites, it can infiltrate into the sewer system. Some metal pipes may contain chromium as a component of stainless steel, but this is the case mainly at industrial sites where there is a problem of chemically-aggressive wastewater. Corrosion of these pipes can cause chromium to be released into the wastewater. Some products used in homes, such as paints cleaners and cosmetics, can contain chromium [43].

**Copper.** Copper had a significantly higher concentration in the sediments from the combined sewer system, which was 28.57 mg/kg, compared to the other types of sediments. This result can be explained by the type of roofing of nearby buildings, often made of copper sheets [44]. The presence of copper in sediments can be problematic for several reasons. Copper is a heavy metal that can be toxic to aquatic organisms in high concentrations. Therefore, it is worth conducting a thorough investigation to determine the source of copper and possibly take remedial measures.

Copper can also appear in sediments from causes other than stormwater runoff from roof slopes covered with copper sheeting. One reason is industrial pollution, especially by the industries related to metal production and processing, such as metalworking plants, electroplating plants or plants that produce intermediate copper products. Another cause is corrosion of pipes in water supply systems made of copper, which over time can lead to the release of copper into the water supply. However, these are rare cases in European countries and in Poland. In addition, some pesticides and fungicides contain copper; hence, their residues can be flushed from green spaces during rainfall. In some water supply systems, copper is added to water as an antimicrobial agent. Domestic users can also introduce copper into the sewer system through products such as paints, cosmetics and cleaning products [45].

**Nickel.** Nickel concentrations were relatively low in all sediments types, with the highest average of 3.67 mg/kg in the sediments from stormwater sewer inlets. Nickel is a naturally occurring element in the environment, but it is also widely used in industry. There are several sources that can contribute to the presence of nickel in sediments. Industries, especially those associated with metal production, such as in metallurgy, electroplating and battery manufacturing, emit nickel into wastewater. Corrosion of water pipes and fittings made of metals containing nickel can lead to the release of the element into water. The burning of fuels can also introduce nickel into the atmosphere, which then settles on the ground and is flushed into sewers. Many industrial processes, such as oil refining, steel production and chemical manufacturing, use nickel, and residues from these processes can also end up in wastewater [14].

**Lead.** Lead concentrations in different types of sediments were similar, with the highest value of 5.20 mg/kg in the sediments from stormwater sewer inlets. Lead can be present in sediments for a variety of reasons. One reason is the use of old pipes and connections in water supply systems, where lead pipes are quite common. Although many of these pipes have been replaced, lead residue can enter the water supply when water flows through the remaining sections of the pipes. In addition, industrial pollution in some places introduces lead into the water, especially when factories that use lead do not properly manage their waste. Lead has also been an ingredient in many consumer products, such as paint, and the residue from these products can end up in the sewer system.

Historically, lead was a component of gasoline (petrol), leading to its emission into the atmosphere when the fuel was burned. Although lead has been phased out of the fuel, its traces can remain in soil and water. Because of its toxicity to humans and the environment, monitoring and managing the presence of lead in water and sediments is crucial [46].

**Zinc.** The highest average concentration of zinc, 72.17 mg/kg, was observed in the sediments from stormwater sewer inlets. The explanation for this situation is most likely that much of the roofing and roof gutters are made of galvanized sheet metal, from which zinc leaches and finds its way into storm and combined sewers. Zinc is also present in sediments for other reasons, but this applies mainly to sanitary and combined sewers.

One of the reasons mentioned is human consumption and excretion, as dietary supplements and some medicines contain zinc necessary for biological functions in the body. Excess zinc ingested is excreted through urine and stool, resulting in its presence in wastewater. In addition, zinc is used in many industrial processes, including electroplating, the manufacture of paints, lubricants, cosmetics and other products, and residues of these substances can enter the sewage system located in the areas with industrial and service activities. Zinc can also originate from natural minerals in the environment, or from products such as paints used on buildings; rain can flush zinc from these surfaces into the sewer system. Many steel structures are coated with zinc during the plating process to protect them from corrosion. Over time, zinc can erode and infiltrate into stormwater that is diverted to the sewer system. Finally, zinc is an ingredient in many consumer products, such as shampoos, toothpastes and cosmetics, and residues from these products can enter the sewer system during daily activities [47].

## RESULTS

The content of heavy metals in water extracts from sediments was analyzed. The obtained results were also compared with concentration limits for industrial wastewater dischargedinto receiving waters and Class 1 surface waters. Water extracts allow assessment of the content of contaminants in sediments, including heavy metals, organic substances, pathogenic microorganisms and other chemical compounds. By analyzing water extracts, the potential environmental impact of sediments can be assessed, particularly if the sediments is to be disposed of. Understanding which substances are likely to seep into groundwater or surface water is key to ensuring environmental safety. Water extracts can be used to test how microorganisms can break down organic contaminants in sediments. This is important, especially when considering biological methods for sediments and sludges treatment or stabilization. The proposed methodology is an alternative method for determining metals in sediments. No publications on the analysis of water extracts from sediments have been reported in the available scientific literature, although research on leaching of heavy metals from sludges has been conducted on a large scale [48–50]. Such an approach is lacking in sediments research. In view of the above, the present authors postulate the introduction of the proposed methodology to more studies in this area.

The concentration of copper in water extracts from sediments exceeds the permissible levels for industrial wastewater (0.1–0.5 mg/kg) and surface water of good quality (0.05 mg/kg). Zinc contents in the water extracts of sediments from stormwater sewer inlets exceed the permissible leaching limit (50 mg/kg). These concentrations exceed the permissible levels for industrial wastewater (0.2 mg/kg) and surface water of good quality (1 mg/kg).

The obtained data were interpreted using non-metric multidimensional scaling (NMDS), which is a method for analyzing data in multiple dimensions without the assumption of fitting to the normal distribution. Hence, in the field of human risks of heavy metal, community ecology and environmental studies, NMDS is one of the key ordination methods in use [51] This method allows comparison of data from different groups in one space, which proves useful for comparative research. Multidimensional scaling (MDS) is an increasingly employed algorithm in environmental research as it is a reliable method for comparing similarities and differences between obtained data. Gu et al. (2023) employed NMDS to examine how sediment properties affected the concentrations of trace metals available for the diffusive gradients in thin films (DGT) technique. The results showed that sediment properties significantly impacted most of the trace metals available for DGT [52].

Figure 1 shows the outcomes derived from the analytical and visual representation of measurement data, executed via the NMDS technique. The Figure facilitates a comparative assessment of the all analysed metal content in sediment samples procured from diverse sewer systems, namely, storm, sanitary, and combined sewers.

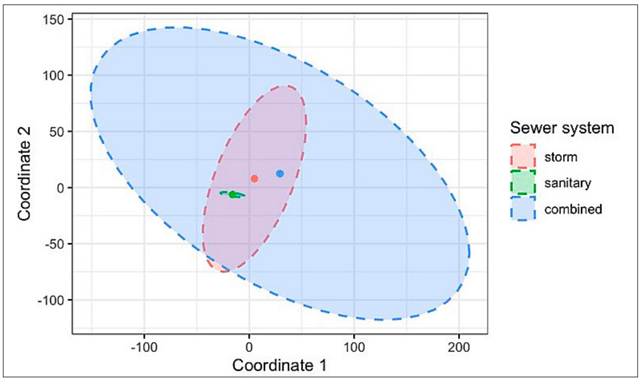

**Figure 1.** Analysis results and visualization of similarities between sediments in storm, sanitary and combined sewer systems, based on all analyzed metals concentration

In Figure 1, the ellipses symbolizing the 95% confidence of data from all analyzed metal concentrations overlap for each of the types of sewers, i.e. stormwater, sanitary and combined sewer systems. The sanitary sewer system, which is characterized by very low variability compared to the others, is completely included in the ellipse describing the variability of metal content in the stormwater and combined sewer systems. Simultaneously, the variability of metal content in the stormwater sewer system is not completely contained in the highest variability of the combined sewer system. The centre point of the sanitary system ellipse is located in the overlapping areas of the two other systems. Referring to the size of the area of the ellipsoids corresponding to the variability of the metals concentration in question, it can be concluded that the smallest variability was clearly characterized by the concentration of metals in the sanitary sewer system, and the largest in the combined sewer system.

The STRESS values of NMDS with different number of dimensions are shown in Figure 2. The STRESS of the bi-dimensional configuration of NMDS plot is approximately equal to 0.087, indicating good rescaling of the multidimensional original data, and no need for the addition of more dimensions.

The data obtained showed similarity in quantitative values regarding the content of the studied heavy metals for all kind of analyzed systems. The amplitude of the content of individual elements in the combined sewer system gives grounds for its systematic control, since the maximum risks occur in this system, whereas the overall content and variability in the other two systems are lower.

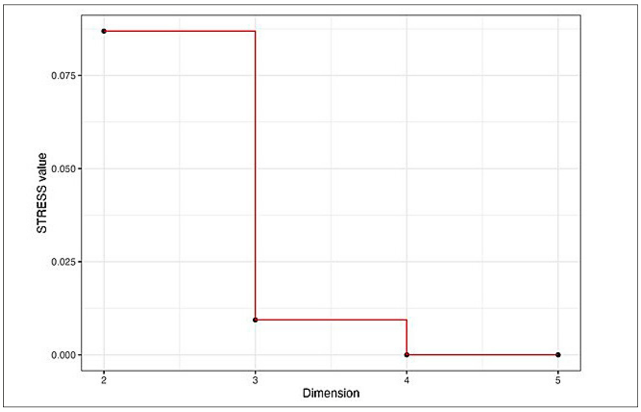

**Figure 2.** STRESS plot for non-metric multidimensional scaling

## CONCLUSIONS

Analysis of the presented data confirms that the content of heavy metals in sediments varies depending on the sampling location and type of sewer system. This means that the sources of emissions of these metals vary, thus indicating the need for detailed monitoring and analysis to identify them. The sediments from stormwater sewer have higher concentrations of most of the heavy metals tested compared to other sediments types. The sediments from sewer inlets had significantly higher zinc concentrations than those allowed by Regulation of the Minister of Environment of 18 November 2014. Based on the NMDS methods, it can be stated that the smallest variability of all analyzed metals concentration was observed in the sanitary sewer system, and the largest in the combined sewer system. Thus, control of the combined sewer system seems to be the most informative regarding the potential risks of exceeding current standards and, accordingly, environmental threats.

The article presents results obtained with a method for universal determining contaminants in water extracts from sediments, applicable to various urban environments. The study investigated different types of sewer systems, namely storm, sanitary, and combined, providing a foundation for the adoption of the presented method in other urban areas with similar systems. It is important to consider local factors determining sewer catchments, such as the type of industry, population density, materials used for infrastructure and sealing surface of sub-catchments, as well as environmental conditions, as they may impact the level and type of pollution.

A future study should be conducted to determine recommendations for sewer system monitoring, which may include establishing monitoring points, analyzing pollution sources, employing non-metric multidimensional scaling statistical methods, and different statistical models for creating soft sensors useful for monitoring purposes.

Further research could include examining other physicochemical properties of sediments, organic substances content, and microplastics in various urban environments, to compare results and better understand the impact of local conditions on the composition and behavior of pollutants. In this context, it would be interesting to analyse the sediments and flushing waters removed from different sewer systems during cleaning and maintenance works. Additionally, the development and testing of electronic senses for examining sediments in sewage systems could be introduced.

## Acknowledgements

Funding source: Polish Ministry of Education and Science within Grant Nos. FD-20/IS-6/999, FD-20/IS-6/019, FD-20/IS-6/021, FD-20/IS-6/037.

## REFERENCES

1. Wang S, Shi X. Molecular mechanisms of metal toxicity and carcinogenesis. Mol Cell Biochem. 2001;222(1–2):3–9.
2. Beyersmann D, Hartwig A. Carcinogenic metal compounds: recent insight into molecular and cellular mechanisms. Arch Toxicol. 2008;82(8):493–512. doi:10.1007/s00204-008-0313-y
3. Cobbina SJ, Chen Y, Zhou Z, Wu X, Zhao T, Zhang Z, et al. Toxicity assessment due to sub-chronic exposure to individual and mixtures of four toxic heavy metals. J Hazard Mater. 2015;294:109–120. doi:10.1016/j.jhazmat.2015.03.057
4. Costa M. Review of arsenic toxicity, speciation and polyadenylation of canonical histones. Toxicol Appl Pharmacol. 2019;375:1–4. doi:10.1016/j.taap.2019.05.006
5. Gazwi HSS, Yassien EE, Hassan HM. Mitigation of lead neurotoxicity by the ethanolic extract of Laurus leaf in rats. Ecotoxicol Environ Saf. 2020;192:110297. doi:10.1016/j.ecoenv.2020.110297
6. Mazumdar M, Bellinger DC, Gregas M, Abanilla K, Bacic J, Needleman HL. Low-level environmental lead exposure in childhood and adult intellectual function: a follow-up study. Environ Health. 2011;10:24. doi:10.1186/1476-069X-10-24
7. Koedrith P, Kim H, Weon JI, Seo YR. Toxicogenomic approaches for understanding molecular mechanisms of heavy metal mutagenicity and carcinogenicity. Int J Hyg Environ Health. 2013;216(5):587–598. doi:10.1016/j.ijheh.2013.02.010
8. Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. Front Pharmacol. 2021;12(April):1–19. doi:10.3389/fphar.2021.643972
9. Obaideen K, Shehata N, Sayed ET, Abdelkareem MA, Mahmoud MS, Olabi AG. The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. Energy Nexus. 2022;7(January):100112. doi:10.1016/j.nexus.2022.100112
10. Obradović D, Šperac M, Marenjak S. Challenges in Sewer System Maintenance. Encyclopedia. 2023;3(1):122–142. doi:10.3390/encyclopedia3010010
11. Jin S, Zhang K, Cen C, Shuai Y, Hu T, Mao R. Odorous Substances in Urban Drainage Pipelines and the Removal Technology: A Review. Water (Switzerland). 2023;15(6):1–20. doi:10.3390/w15061157
12. Drapeau C, Delolme C, Chatain V, Gautier M, Blanc D, Benzaazoua M, et al. Spatial and Temporal Stability of Major and Trace Element Leaching in Urban Stormwater Sediments. Open J Soil Sci. 2017;07(11):347–365. doi:10.4236/ojss.2017.711025
13. Kye H, Kim J, Ju S, Lee J, Lim C, Yoon Y. Microplastics in water systems: A review of their impacts on the environment and their potential hazards. Heliyon. 2023;9(3):e14359. doi:10.1016/j.heliyon.2023.e14359
14. Egemose S, Sønderup MJ, Grudinina A, Hansen AS, Flindt MR. Heavy metal composition in stormwater and retention in ponds dependent on pond age, design and catchment type. Environ Technol. 2015;36(8):959–969. doi:10.1080/09593330.2014.970584
15. Hong N, Yang B, Tsang DCW, Liu A. Comparison of pollutant source tracking approaches: Heavy metals deposited on urban road surfaces as a case study. Environ Pollut. 2020;266:115253. doi:10.1016/j.envpol.2020.115253
16. Wang J, Zhang P, Yang L, Huang T. Adsorption characteristics of construction waste for heavy metals from urban stormwater runoff. Chinese J Chem Eng. 2015;23(9):1542–1550. doi:https://doi.org/10.1016/j.cjche.2015.06.009
17. Gunawardena J, Egodawatta P, Ayoko GA, Goonetilleke A. Atmospheric deposition as a source of heavy metals in urban stormwater. Atmos Environ. 2013;68:235–242. doi:https://doi.org/10.1016/j.atmosenv.2012.11.062
18. Cai K, Li C, Na S. Spatial distribution, pollution source, and health risk assessment of heavy metals in atmospheric depositions: A case study from the sustainable city of Shijiazhuang, China. Atmosphere (Basel). 2019;10(4):11–14. doi:10.3390/ATMOS10040222
19. Sakson G, Brzezinska A, Zawilski M. Emission of heavy metals from an urban catchment into receiving water and possibility of its limitation on the example of Lodz city. Environ Monit Assess. 2018;190(5). doi:10.1007/s10661-018-6648-9

20. McDonald S, Holland A, Simpson SL, Gadd JB, Bennett WW, Walker GW, et al. Metal forms and dynamics in urban stormwater runoff: New insights from diffusive gradients in thin-films (DGT) measurements. Water Res. 2022;209:117967. doi:https://doi.org/10.1016/j.watres.2021.117967
21. Marsalek J. Road salts in urban stormwater: an emerging issue in stormwater management in cold climates. Water Sci Technol. 2003;48(9):61–70. doi:10.2166/wst.2003.0493
22. Flanagan K, Blecken GT, Osterlund H, Nordqvist K, Viklander M. Contamination of urban stormwater pond sediments: A study of 259 legacy and contemporary organic substances. Environ Sci Technol. 2021;55(5):3009–3020. doi:10.1021/acs.est.0c07782
23. Regulation of the Minister of Climate of January 2, 2020 in the Waste Catalog. (J.L. 2020, Item 10).; 2020. https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20200000010/O/D20200010.pdf.
24. Waste Act (J.L. 2013 Item 21).; 2013.
25. Sikorska A. Stabilizacja osadów pochodzących z czyszczenia kanalizacji jako obowiązek nowoczesnej gospodarki obiegu zamkniętego (Stabilization of sludge from sewer cleaning as an obligation of a modern closed loop economy). Forum Eksploatatora. 2019;3(102):66–73.
26. Regulation of the Ministry of Economy and Labor on the Criteria and Procedures for Admission of Waste to Respective Landfill Types, Journal of Laws 2015, Item 1277.
27. Milik J, Pasela R. Analysis of concentration trends and origins of heavy metal loads in stormwater runoff in selected cities: A review. E3S Web Conf. 2018;44. doi:10.1051/e3sconf/20184400111
28. Bak Ł, Szelag B, Górski J, Górska K. The impact of catchment characteristics and weather conditions on heavy metal concentrations in stormwater-Data mining approach. Appl Sci. 2019;9(11). doi:10.3390/app9112210
29. PN-EN 12457-2:2006. Characterisation of Waste– Leaching– Compliance Test for Leaching of Granular Waste Materials and Sludges–Part 4: One Stage Batch Test at a Liquid to Solid Ratio of 10 l/Kg for Materials with Particle Size below 10mm.
30. Duda-Saternus S, Kujawska J, Wojtaś E, Kozłowska A, Jamka K, Szeląg B, et al. A simplified method for determining potential heavy metal leached from sediments of stormwater and combined sewer systems – importance for public health. Ann Agric Environ Med. 2023;30(3):455–461. doi:10.26444/aaem/170099
31. Coulibeuf C. Fast Elemental Determination of Environmental Samples with ICP-OES. Jobin Yvon S.A.S., Horiba Group Longjumeau, France
32. Torgerson WS. Multidimensional scaling: I. Theory and method. Psychometrika. 1952;17(4):401–419. doi:10.1007/BF02288916
33. Borg I, Groenen P. Modern Multidimensional Scaling. Springer New York; 2005. doi:10.1007/0-387-28981-X
34. Kruskal JB. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. Psychometrika. 1964;29(1):1–27. doi:10.1007/BF02289565
35. Shepard RN. The analysis of proximities: Multidimensional scaling with an unknown distance function. I. Psychometrika. 1962;27(2):125–140. doi:10.1007/BF02289630
36. Borg I, Groenen PJF, Mair P. Applied Multidimensional Scaling. Springer Berlin Heidelberg; 2013. doi:10.1007/978-3-642-31848-1
37. Dugard P, Todman J, Staines H. Approaching Multivariate Analysis. Routledge; 2022. doi:10.4324/9781003343097
38. R Core Team. R: A Language and Environment for Statistical Computing. Published online 2021.
39. RStudio Team. RStudio: Integrated Development Environment for R. Published online 2022.
40. Wickham H. Ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York; 2016.
41. Venables WN, Ripley BD. Modern Applied Statistics with S. Springer New York; 2002. doi:10.1007/978-0-387-21706-2
42. Briffa J, Sinagra E, Blundell R. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon. 2020;6(9):e04691. doi:10.1016/j.heliyon.2020.e04691
43. Sharma P, Singh SP, Parakh SK, Tong YW. Health hazards of hexavalent chromium (Cr (VI)) and its microbial reduction. Bioengineered. 2022;13(3):4923–4938. doi:10.1080/21655979.2022.2037273
44. Abraham J, Dowling K, Florentine S. Can copper products and surfaces reduce the spread of infectious microorganisms and hospital-acquired infections? Materials (Basel). 2021;14(13):1–27. doi:10.3390/ma14133444
45. Vardhan KH, Kumar PS, Panda RC. A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. J Mol Liq. 2019;290:111197. doi:10.1016/j.molliq.2019.111197
46. Jadaa W, Mohammed H. Heavy Metals – Definition, Natural and Anthropogenic Sources of Releasing into Ecosystems, Toxicity, and Removal Methods – An Overview Study. J Ecol Eng. 2023;24(6):249–271. doi:10.12911/22998993/162955
47. Wolf J, Sandstead Harold H., Rink L. Chapter 38 – Zinc. In: Nordberg GF, Costa MBTH on the T of M (Fifth E, eds. Academic Press; 2022:963–984. doi:https://doi.org/10.1016/B978-0-12-822946-0.00034-9
48. Li S, Fang B, Wang D, Wang X, Man X, Zhang X. Leaching characteristics of heavy metals and plant nutrients in the sewage sludge immobilized by composite phosphorus-bearing materials. Int J Environ Res Public Health. 2019;16(24). doi:10.3390/ijerph16245159
49. Rosli NA, Abdul Aziz H, Kueh ABH, Lim LLP, Zawawi MH. Leaching Behaviour of Synthetic Leachate through a Sewage Sludge and Red Gypsum Composite as Intermediate Landfill Cover. Sustain. 2023;15(5). doi:10.3390/su15054229
50. Kania M, Gautier M, Blanc D, Lupsea-Toader M, Merlot L, Quaresima MC, et al. Leaching behavior of major and trace elements from sludge deposits of a French vertical flow constructed wetland. Sci Total Environ. 2019;649:544–553. doi:https://doi.org/10.1016/j.scitotenv.2018.08.364
51. Gu YG, Huang HH, Liu Y, Gong XY, Liao XL. Non-metric multidimensional scaling and human risks of heavy metal concentrations in wild marine organisms from the Maowei Sea, the Beibu Gulf, South China Sea. Environ Toxicol Pharmacol. 2018;59:119–124. doi:https://doi.org/10.1016/j.etap.2018.03.002
52. Gu YG, Jiang SJ, Jordan RW, Huang HH, Wu FX. Nonmetric multidimensional scaling and probabilistic ecological risk assessment of trace metals in surface sediments of Daya Bay (China) using diffusive gradients in thin films. Sci Total Environ. 2023;867:161433. doi:10.1016/j.scitotenv.2023.161433