

LID Approach to Railway Track Drainage: Determination of Heavy Metal Content in the Embankment of Railway

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Abstract

Along with the increase in global pollution, every part of the urban system, including facilities for the transport of people and goods, is becoming increasingly interesting for the study. The first serious research into the impact of railway traffic on the environment appeared after the year 2000. So far, there have been few studies, the main shortcoming of which is a lack of understanding about pollutant migration. With this in mind, in this paper, an investigation and control of the railway track with regard to the presence, content and migration paths of heavy metals was provided. For the research purposes, X-ray fluorescence spectrometry and optical emission spectrometry with induced coupled plasma were used. It was found that the maximum allowable values were exceeded for cadmium, cobalt, copper, zinc, nickel, vanadium, barium, chromium and iron. In the course of determining the amount of these elements in the railway track, there was also evidence of significant metal infiltration into the lower layers. This indicated the ability of heavy metals to migrate, even through mechanically compacted soil. Detailed knowledge of these issues is of huge importance, which enables the selection of adequate techniques to prevent the migration of heavy metals into the lower layers of the ground and the surrounding soil, among which the elements of Low Impact Development technology stand out in recent years, which could find a very wide and effective application in railway engineering.

Keywords

railway, environmental pollution, storm water contamination, soil contamination, XRF spectrometry, ICP-OES spectrometry

1 Introduction

The impact of railway traffic with the accompanying infrastructure on the environment has been gaining importance in recent years. According to studies, substances emitted by railway traffic pose a risk of soil and water pollution [1, 2]. When discussing pollution, the primary topic would be substances and particles that are the result of railway superstructure element wear and rinsing, as well as railway vehicle and superstructure elements maintenance [3].

The most recent research revealed the existence of data on sampling and testing methods, which confirmed the presence of pollutants [4], prominent among them being the heavy metals such as iron, copper, zinc, manganese and chromium, polycyclic aromatic hydrocarbons (PAHs) and herbicides [4, 5]. The presence of these contaminants was confirmed in the surrounding soil, which certified

the theory of pollutant migration, and the increased possibility of their transport raises additional concerns [6]. The mechanism and route of migration is still unknown, because the number of studies so far is too small to draw conclusions about it [2, 7]. So far, lots of researches have been conducted on the detection of pollutants, like heavy metals and the possibility of their removal [8]. When it comes to pollution caused by railway traffic, similar considerations must be made. To properly approach finding solutions for pollution reduction, it is necessary to identify the types of pollutants.

As one of the solutions for removing heavy metals and other pollutants from rainfall runoff, elements of Low Impact Development (LID) technology have been proposed [9, 10]. In addition to the control of the runoff volume

and reduction to the surface runoff, the functionality of LID elements has been assessed based on the reduction of heavy metals concentration in runoff and drainage of rainwater [11]. LID elements, precisely because of this property, represent one of the possible solutions to the described problem [12]. In general, these are various filtering systems that, to a large extent, filter rainfall and prevent runoff contaminants from reaching recipients and ground waters in a completely natural way [13]. Some LID solutions can be adapted to the needs of railway roadbed drainage by modifying previously tested solutions on elements of urban areas and highway channels [14]. Self-sustainable drainage systems are widely present and, in addition to LID, the literature often use the terms such as SUDS (Sustainable Urban Drainage System), BMP (Best Management Practice) and WSUD (Water Sensitive Urban Design) [15, 16].

Considering all the above, in this paper, an investigation and control of the single-track railway with regard to the content of heavy metals, as well as their migration, was provided. For the research purposes, X-ray fluorescence (XRF) spectrometry and optical emission spectrometry with induced coupled plasma (ICP-OES) were used. Although the use of ICP-OES spectrometers is widespread [17–24], by inspecting the available research, no data on the application of the ICP-OES spectrometer for the purpose of measuring the concentration of heavy metals in the railway track were found.

The aim of the examination was to determine the presence of heavy metals in the zone that is affected by drainage, but also in the railway embankment itself. It was assumed that the highest concentration of heavy metals would be in places with more intense runoff flow, and therefore a significant migration of metals was expected in those places. At the same time, one should not ignore the ability of metal to infiltrate into the soil under the railway track [25, 26]. By determining the condition of the railway embankment, it is possible to identify the need to analyze surrounding areas, in order to determine the wider impact of pollution [2, 5, 6], as well as the potential impact on the quality of ground waters. An important feature of heavy metals is that they are cumulative, do not break down in the natural environment and contribute to the accumulation of harmful substances in the food chain [27].

2 Materials and methods

2.1 Study area

The study area was on the arterial railway line Niš–Preševo-border with the Republic of North Macedonia, at the section Belotinac–Medjurovo, Serbia (Fig. 1) [28], from



Fig. 1 Map of the south corridor railway line with the marked section Niš–Brestovac [28]

km 253+072.00 to km 253+283.00. The last known piece of data, referring to the previous railway overhaul back to 1965 year, included both the superstructure and the substructure. The electrical traction has been used from 1974 year until the present time. The rails are on the ballast, so the superstructure consists of the ballast, wooden sleepers with rails and type K fastenings. In the period since the reconstruction until now, only individual superstructure elements were replaced, whereas the railway roadbed did not undergo any substantial repairs.

For the selection of the positions of cross-sections, the crucial circumstance was that at that moment, for the purposes of reconstruction, the existing elements and layers of the superstructure, as well as the railway embankment itself, were removed. The chosen location was evaluated as favorable for research, because the investigated cross-sections for sampling were located in the embankment, which excluded the influence of the contents that can flow from the surrounding soil during heavy rainfall. Sampling locations on the cross-sections were chosen according to the way of drainage from the railway track [29], as presented in Fig. 2.

In addition to the requirement that the observed cross-sections should be in the embankment, the goal was also that the examined cross-sections should be as far as possible from each other (at a distance of more than 100 m), in order to avoid possibly the same influences. Bearing in mind that the reconstructed part was 211 m long and the length of the section in the embankment was less than 200 m, this allowed two relevant cross-sections to be observed in the research (cross-sections 1 and 2, given in Fig. 3).

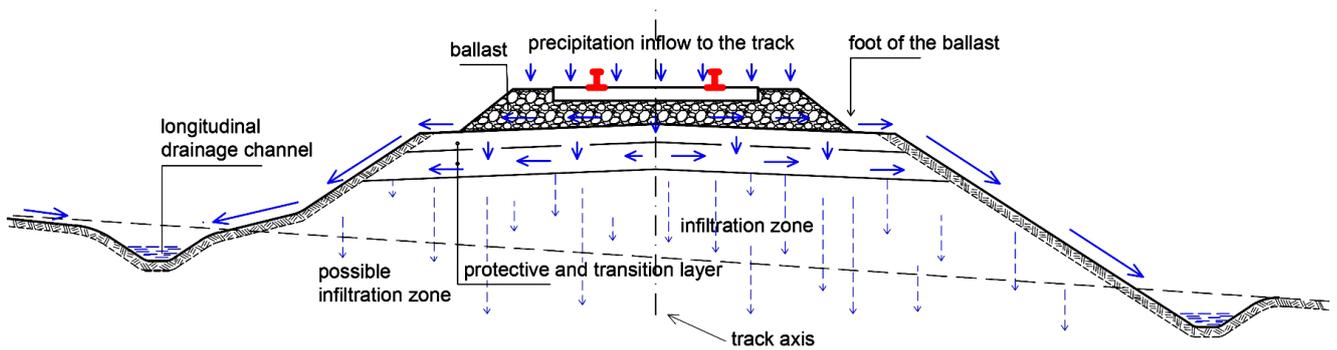


Fig. 2 Rainfall evacuation path from the railway track



Fig. 3 Position of the examined cross-sections (cross-section 1 and cross-section 2)

2.2 Soil sampling

In terms of the position of the route in relation to the terrain and arrangement of the surrounding areas, two cross-sections under investigation differed only in terms of

the embankment height. The soil samples were collected during the removal of the superstructure and embankment during the railway reconstruction activities, whereby the sampling was done with an appropriate hand tools.

The position and depth of sampling locations as well as sample labeling are shown in detail in Fig. 4. Eight samples per cross-section were collected, i.e. a total of 16 samples. The marked sample locations 1', 2', 3', 4', 5', 6', 7', 8' correspond to the cross-section No. 1, whereas the marks 1'', 2'', 3'', 4'', 5'', 6'', 7'' and 8'' correspond to the cross-section No. 2.

The first series of sampling was performed at the position of the railway track's vertical axis, both immediately beneath the ballast (samples 1' and 1'') and at the depth of $1.3 \text{ m} \pm 10 \text{ cm}$ (samples 2' and 2''). In addition, samples were taken right below the ballast's foot (samples 3', 3'', 4' and 4'') as well as at the depth of $1.3 \text{ m} \pm 10 \text{ cm}$ from the foot of the ballast (samples 5', 5'', 6' and 6''). The following positions examined were the ditches at the foot of the embankment (samples 7', 7'', 8' and 8''), as the final points of the water evacuated from the track [30], whereas after that, the water was evacuated longitudinally, parallel to the track axis.

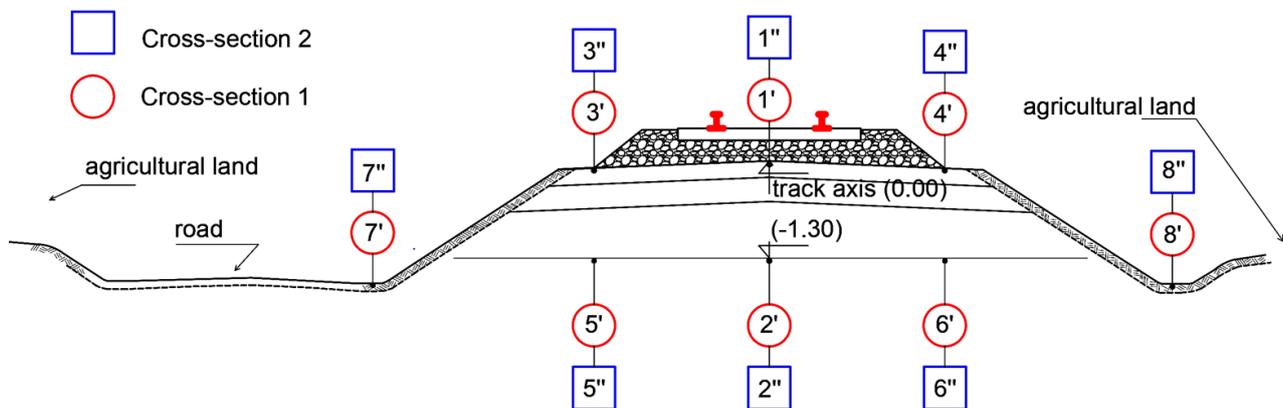


Fig. 4 Typical cross-section of the railway and locations from where samples were collected

2.3 Methods

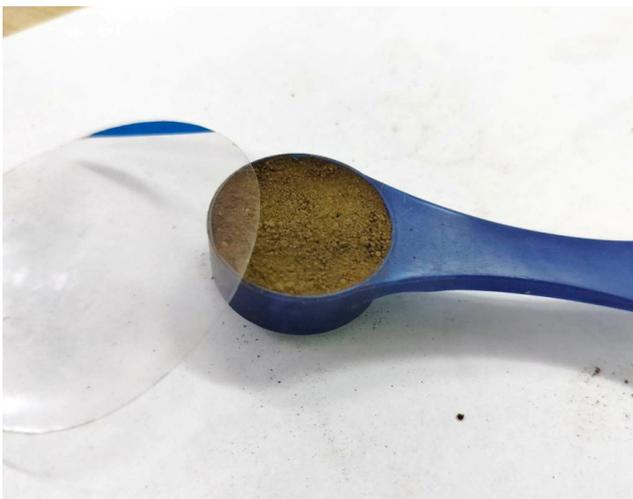
2.3.1 Methodology I: Examination of samples using XRF spectrometer

Scanning of samples in the first testing cycle was performed using a hand-held X-ray fluorescence (XRF) spectrometer (made by LANScientific, model RTU-XRF7460), in the Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of University of Niš (Fig. 5 (a)).

The device features with the Mg-U detection range. The scanned samples were in a loose state, prepared according to the recording instructions (Fig. 5 (b)). Each of the samples was scanned three times for the duration of 30 seconds. It was decided that the output list of results would be in widely accepted units of ppm (mg/kg). Further data processing was done in Excel. The final value adopted was the mean value of all recordings of a specific sample (a minimum of three scans per sample).



(a)



(b)

Fig. 5 XRF spectrometry: (a) hand-held XRF spectrometer; (b) sample prepared for analysis

2.3.2 Methodology II: Examination of samples using ICP-OES spectrometer

The procedure of determining traces and types of metal in the mentioned samples was performed on the ICP-OES (optical emission spectrometry with induced coupled plasma) spectrometer (iCAP 6000 series, manufactured by Thermo scientific company), in the Laboratory for Analytical and Physical Chemistry of the Faculty of Sciences and Mathematics of University of Niš. The operating parameters of the spectrometer are given in Table 1.

This examination technique requires samples in the form of a solution. The solutions were prepared for the analysis using water and hydrochloric acid (HCl) [31]. In this case, the hydrochloric acid should have the effect of washing away soil due to acid rain. This contributed to the experiment's genuine resemblance to natural conditions. In this instance, each sample weighed approximately 5 g. Exact data on the weight per sample are provided in Table 2.

Measurements were performed on the samples in dry and loose state. After measuring, each of the samples was added 25 ml of deionized water. After adding deionized water, solutions were mixed using magnetic mixers at 850–1400 rpm. The mixing speed was variable, because of the different sizes of mixing containers and magnets. The mixed solutions were left to settle and clear up. After two days, hydrochloric acid (35% g.r.) was added, 10 ml per solution. Another mixing cycle was performed, after adding the hydrochloric acid (Fig. 6 (a)). After the repeated

Table 1 Operating parameters for ICP-OES spectrometer

RF power (W)	1150
Analysis pump rate (rpm)	50
Flusc pump rate (rpm)	100
Nebulazer gas flow rate (L/m)	0.7
Coolant gas flow rate (L/m)	12
Auxilliary gas flow rate (L/m)	0.5
Observation mode	axial
Rinse time (s)	30

Table 2 The exact weights of the testing samples

Sample	Weight [g]	Sample	Weight [g]
1'	5.0490	1''	5.0568
2'	5.0832	2''	4.9909
3'	5.0144	3''	5.0150
4'	5.0367	4''	5.0383
5'	5.0283	5''	5.0611
6'	5.0137	6''	5.0128
7'	5.0941	7''	5.0708
8'	5.0897	8''	5.0445

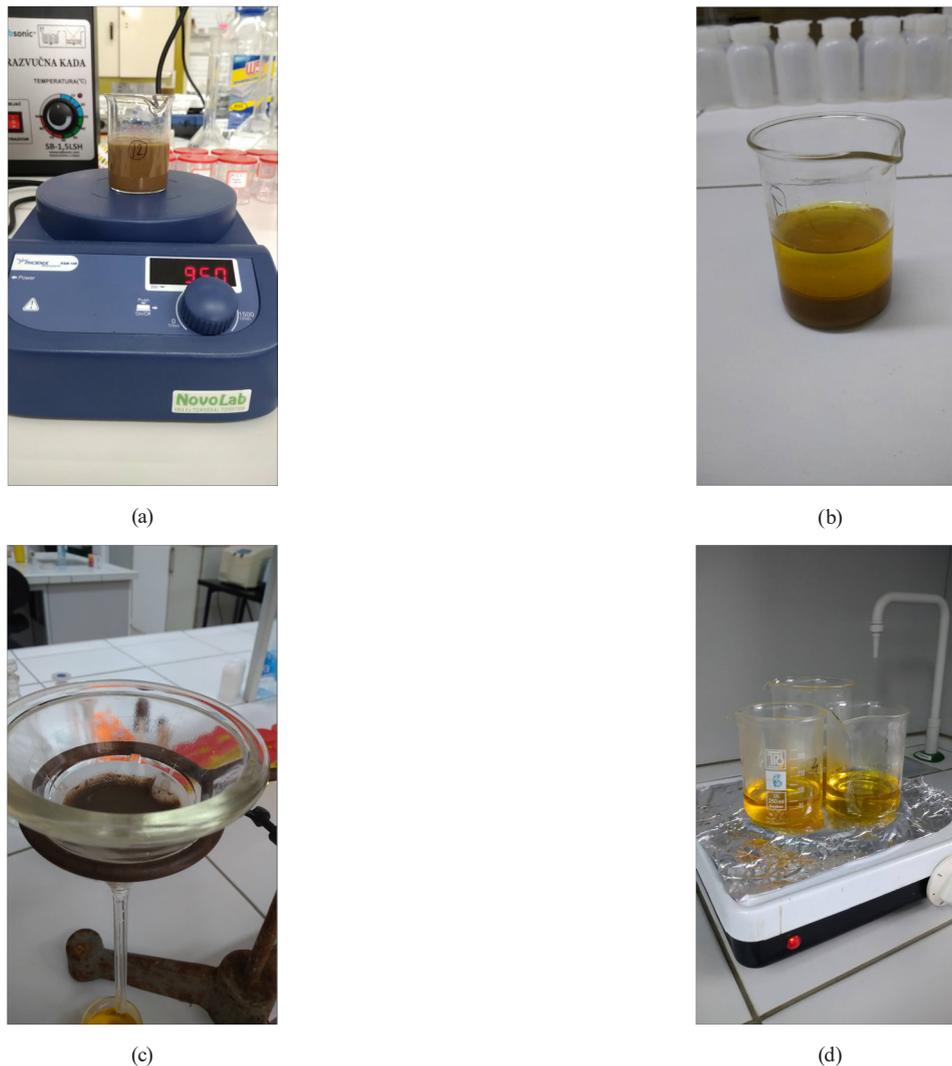


Fig. 6 Filtrate preparation process for ICP-OES testing: (a) mixing the soil sample with water and HCl; (b) appearance of the settled solution; (c) filtering the solution; (d) heating the filtrate

settling of the solutions (Fig. 6 (b)), the procedure further consisted of filtering the solutions through the filter paper and rinsing with deionized water (Fig. 6 (c)). The filtered content was heated to a volume of 25 ml and prepared for analysis in the ICP-OES spectrometer (Fig. 6 (d)).

3 Results and discussion

Test results from both procedures were analyzed according to maximum allowable concentration of hazardous metals (Maximum allowable concentration (MAC) according to the national regulations of the Republic of Serbia [32] and according to the values recommended in the European Union (EU) countries [33, 34]). The values specified in the EU Directive represent the recommended range of allowable chrome, nickel, copper, zinc, cadmium, lead and mercury values. This directive is not binding, but every country can implement corrections, most often in agreement with the pH value of the

observed soil of a country or area [34]. Concentrations of the metals not included in the EU Directive were considered according to MAC. The maximum allowable concentration of polluting, harmful and hazardous metals in the soil are shown in Table 3.

3.1 Results obtained by XRF spectrometer analysis

The results of the XRF spectrometer analysis contained up to 35 heavy metals. The discussion includes heavy metals that exceeded the permitted limits.

The comparison with the prescribed MAC revealed that the amount of *vanadium* (V) was two to four times higher than allowed in both considered cross-sections (Fig. 7 (a)).

Chromium (Cr) in a number of samples was above the limit, although the highest concentrations were present in the surface layers, especially at the foot of the ballast (sample 3") and in the channel next to the country road (sample 7') (Fig. 7 (b)).

Table 3 Maximum allowable concentration of heavy metals in soil

Metal (symbol)	MAC* (ppm)	EU Directive** (ppm)
Cadmium (Cd)	0.8	1.0–3.0
Chromium (Cr)	100	100
Copper (Cu)	36	50–140
Nickel (Ni)	35	30–75
Lead (Pb)	85	50–300
Zinc (Zn)	140	150–300
Mercury (Hg)	0.3	1.0–1.5
Arsenic (As)	29	–
Barium (Ba)	160	–
Cobalt (Co)	9.0	–
Molybdenum (Mo)	3.0	–
Antimony (Sb)	3.0	–
Beryllium (Be)	1.1	–
Selenium (Se)	0.7	–
Thorium (Th)	1.0	–
Vanadium (V)	42	–

* Concentrations allowed by the Regulation on the maximum concentrations of polluting, harmful and hazardous substances in soil in the Republic of Serbia [32]

** European Union Directive 86/278/EEC [33, 34]

Even though there is no prescribed maximum for *iron* (Fe) concentration, it is interesting to comment on the results. The increase in Fe concentration with depth was an intriguing observation. It was clearly observed by comparing the amount of Fe in sample 1" at a smaller depth and in the samples at greater depths (samples 2", 5" and 6" according to Fig. 4), where a higher Fe concentration was recorded on the samples collected from deeper layers.

Cobalt (Co) and *nickel* (Ni) had excess values in both considered cross-sections (Fig. 7 (c) and Fig. 7 (d)). Here the maximum concentrations of both metals were registered under the foot of the ballast (sample 3"), on the embankment side that faces the rural road. It can also be noted that Co (Fig. 7 (c)) exhibited more excessive concentration than Ni (Fig. 7 (d)).

Copper (Cu) was in excess of MAC, and its concentration was the highest in the samples collected at the foot of the ballast (samples 3' and 3") and in the ditch on the side of the country road (sample 7') (Fig. 7 (e)).

Zinc (Zn) in certain positions exceeded the MAC, and it was even twice as high as MAC at the foot of the ballast (samples 4' and 4"), on the side facing the farmland. It was hard to detect regularity in the distribution of Zn according to the maximum values (Fig. 7 (f)).

Barium (Ba) by far exceeded the allowable concentrations, at places 3.5 times in excess of the prescribed limit.

The sample from drainage channel (sample 8') stood out, whereas no particular regularity of Ba migration in other positions was observed (Fig. 7 (g)).

Other metals of concern, as severe pollutants, were within allowable range, such as *mercury* (Hg), *lead* (Pb), *arsenic* (As) and *selenium* (Se).

The *allowable concentrations according to EU Directive* were exceeded in case of nickel (Ni), copper (Cu) and zinc (Zn), which was compared to MAC in Fig. 7 (d)–(f). Since according to EU Directive, there are no limitations for V, Cr, Co and Ba, diagrams for these heavy metals were presented only according to MAC. Aside from the EU Directive, the EU member states set the maximum permitted concentrations for Cr. There is a similar situation for As, which is not relevant since there were no excess values according to MAC.

The maximum amplitude values, based on an analysis of diagram peaks (Fig. 7 (a)–(g)), were shown to correspond to the positions at the foot of the ballast (samples at locations 3 and 4) and drainage ditches (samples at locations 7 and 8).

3.2 Results obtained using ICP-OES procedure

The amount of each metal in the sample was determined by calculating the metal concentration using the mean value of three measurements per sample, as follows:

$$E_x = \frac{Avg_x \cdot 25}{m} \text{ [ppm]} \quad (1)$$

where:

- x – metal designation;
- E_x – concentration of metal x in the sample;
- Avg_x – mean value of the metal according to the results obtained by the process of ICP-OES;
- m – exact mass of the sample;
- 25 – multiplication factor representing the volume of each filtrate (in ml), after heating during the sample preparation process.

Equation (1) refers to the gravimetric factor that is often used in geochemistry to determine the concentration of metals in ppm units [35].

In the case of *copper* (Cu) (Fig. 8 (a)), variations by samples were observed, but also several excess values. In the case of cross-section 1, the value was almost doubled under the foot of the ballast (sample 3'). Another excess value was registered beneath the ballast's foot at a depth of 1.3 m (sample 6'). In the case of cross-section 2,

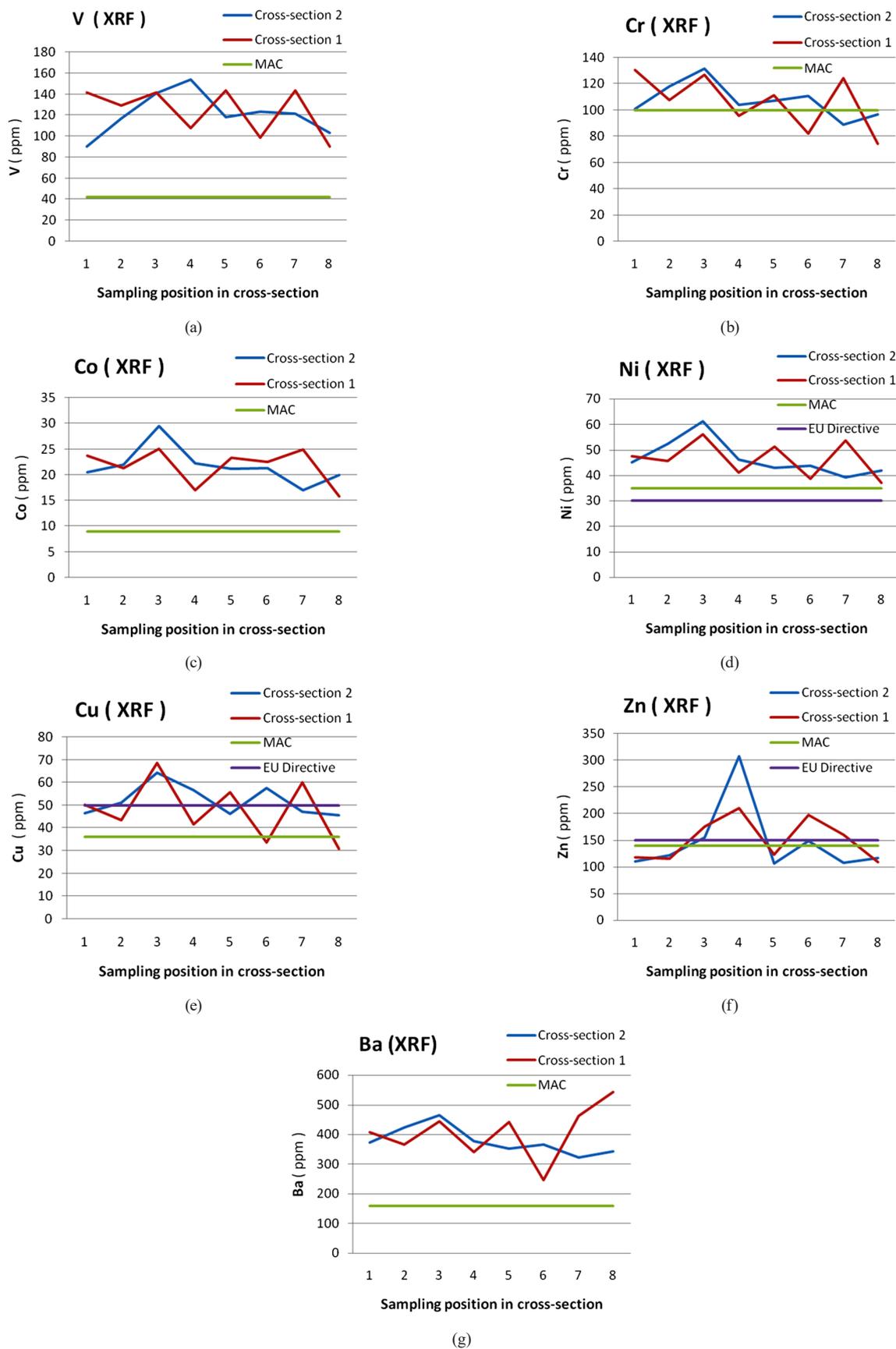


Fig. 7 Concentration of heavy metals on the cross-sections 1 and cross-section 2 in comparison with the maximum allowable values according to MAC and EU Directive, measured by XRF spectrometer: (a) vanadium - V; (b) chromium - Cr; (c) cobalt - Co; (d) nickel - Ni; (e) copper - Cu; (f) zink - Zn; (g) barium - Ba

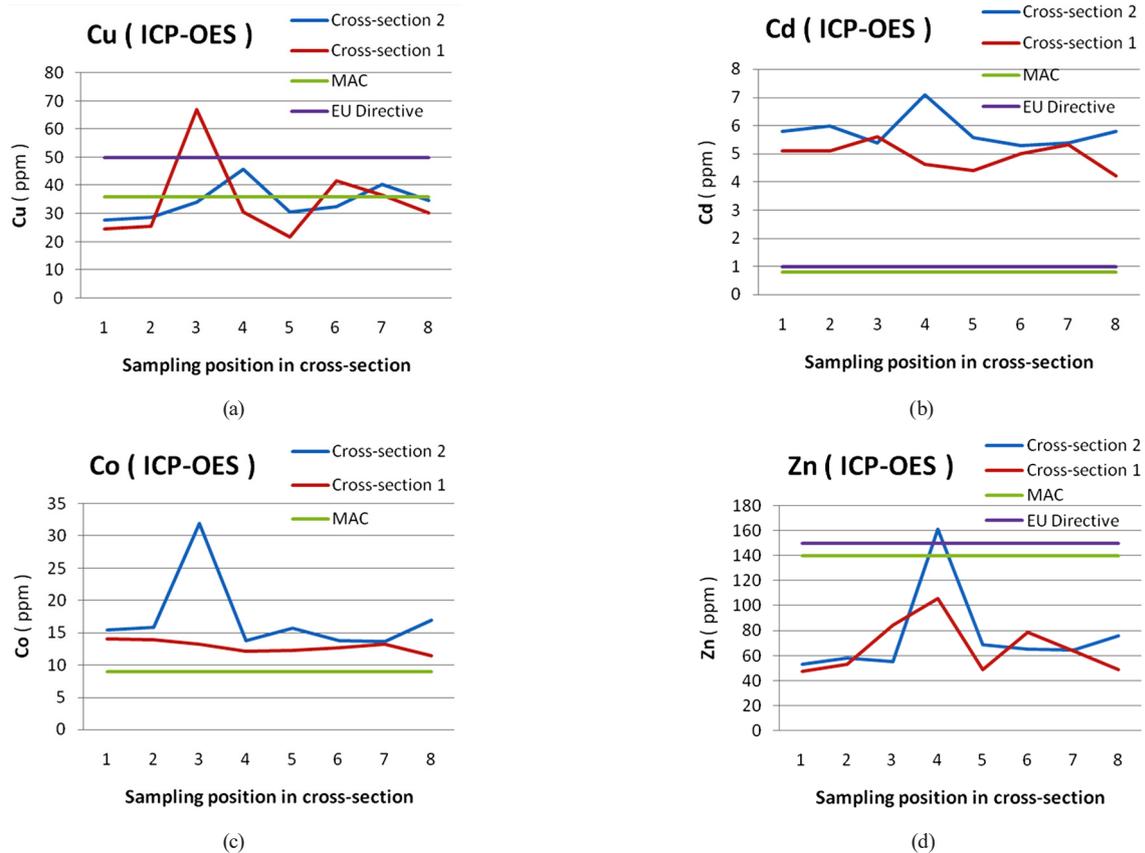


Fig. 8 Heavy metal concentration on cross-sections 1 and cross-section 2 with exceeded maximum allowable values according to MAC and EU Directive, measured by ICP-OES: (a) copper - Cu; (b) cadmium - Cd; (c) cobalt - Co; (d) zink - Zn

exceeded values were registered under the foot of the ballast (sample 4") and in the channel (sample 7"). It is interesting that Cu showed the lowest concentration in the track axis, regardless of depth (samples 1', 1", 2' and 2"). It could be concluded that Cu is prone to migration and follows the path of water evacuation from the railway track and through the embankment itself.

Cadmium (Cd) exceeded the permissible limit value five to nine times (Fig. 8 (b)). No pattern in migration of Cd across the embankment body was observed.

Cobalt (Co) was also present in unallowable quantities (Fig. 8 (c)), with a special reference to the sample under the ballast's foot (sample 3"). Other samples also showed the excess Co content, by about 30% to 50% of the allowed value. When comparing samples, except for above mentioned (sample 3"), there were no significant amplitude peaks. Cross-section number 2 displayed greater values in this instance.

Positions under the foot of the ballast (samples 4' and 4") stood out in terms of *zinc* (Zn) concentration, where cross-section 2 (sample 4") experienced the maximum concentration (Fig. 8 (d)).

Nickel (Ni) with the allowable limit of 35 ppm (Table 3), did not reach the limit value, but was very close to it, so

the presence of this metal should not be neglected. Other metals identified by the ICP-OES analysis were within the permitted limits.

The results highlighted the concentration of *iron* (Fe). What particularly attracted attention was the very close proximity of the sample values. In particular, it was noted that the Fe content ranged between 1987.5–2128.5 ppm, with a 7% difference between the maximum value and the minimum value. The fact that the difference in Fe concentration at track axis (samples 1' and 1"), on the one hand, and the point 1.3 m below the track axis (samples 2' and 2"), on the other hand, was insignificant, supports the claim of metal migration. This apparently slight variation leads to the conclusion that Fe is spread rather uniformly throughout the railway embankment and that migration rates are high both in the embankment itself and in the side ditches. An interesting observation was that the lowest concentration of Fe was under the ballast's foot (samples 3', 3", 4' and 4") and in the channel (samples 7', 7", 8' and 8"), which was the opposite compared to most of the heavy metals discussed previously.

The diagrams in Fig. 8 (a), Fig. 8 (b) and Fig. 8 (d) show a comparison of the maximum recommended values

according to MAC and the EU Directive for Cu, Cd and Zn, respectively. Co is not covered by the EU Directive, so it was shown only according to MAC. Otherwise, in the case of Cd (Fig. 8 (b)), in all the considered sections and locations, the registered values multiple times exceeded the prescribed limit of 1.0 ppm according to the EU Directive. Even considering the higher limit value of 3 ppm prescribed by the EU Directive (Table 3), which is the weaker criterion, the registered values still exceeded the recommended limit (even twice).

Analysis of the diagrams in Fig. 8 (a)–(d) demonstrated that there was a noticeable concentration of metal at the positions of the foot of the ballast in both cross-sections (samples at locations 3 and 4). In addition to these values, also important were positions near drainage channels (samples at locations 7 and 8), and in the middle of the track (samples at locations 1 and 2) only in the case of Cd.

According to the study of the values obtained by the ICP-OES and XRF spectrometers, it could be noted that the values detected by XRF spectrometer were significantly higher. The values obtained by ICP-OES procedure would be closer to those recorded by XRF spectrometer, if the solution was prepared exclusively with hydrochloric acid. In this way, the concentration of separated metals would be higher. Lower values obtained with the ICP-OES spectrometer can be explained by the fact that the soil sample was diluted with a mild solution (deionized water - HCl), and not with concentrated hydrochloric acid.

4 Conclusions

This paper presented the results of embankment examination regarding the presence and concentration of heavy metals, as well as their possible infiltration and paths of migration, on the main railway line Niš-Preševo, section Medjurovo-Belotinac, Serbia. The analysis of the test results determined the following:

- The presence of a large number of different heavy metals in the railway body was recorded as a result of railway traffic.
- The maximum allowable concentrations (MAC) for cadmium, cobalt, copper, zinc, nickel, vanadium, chromium and barium, prescribed for the Republic of Serbia, and the values for nickel, copper, cadmium and zinc, according to the EU Directive, were exceeded. Of these, cadmium, cobalt, copper and zinc according to the MAC, and cadmium, copper and zinc according to the EU Directive, were confirmed as metals prone to leaching in unallowable quantities.
- Although the concentrations of other metals were less than the recommended levels, it is important to take note of these values, because heavy metals have a tendency to accumulate.
- The cross-section of the track (i.e. embankment) exhibited a very uniform concentration throughout its body for the majority of polluting elements. On the basis of the discovery of concentration values at several locations, along the depth of the embankment, the migration of metals was confirmed.
- The study of the obtained data revealed that the drainage channels and feet of the ballast are the most polluted locations on open-air railways. This is important information considering future sampling for the purposes of examining the appearance, concentration and migration of pollutants, and therefore of applying the most suitable solution to prevent the migration of heavy metals into the lower layers of the ground and the surrounding soil. Namely, there is no need to wait for the railway to be reconstructed in order to carry out sampling, because reliable sampling can also be done on railways in service, since feet of ballast and drainage channels are the upper (surficial) layers of the track, and therefore easily accessible locations for sampling, without disrupting the functionality of railway lines.

These conclusions represent a starting point for additional research into the issue of heavy metal deposition on and around railway tracks.

The research provided above referred to the case of an open-air ballasted railway in an embankment. The presented soil testing procedure can also be applied to the railway in a cut. In that case, however, when the soil within the railway structure and the layers beneath it undergo examination, it is doubtful how the involvement of railroad traffic in pollution could be evaluated. Furthermore, the same sampling locations, described in the conclusion as relevant for open-air railway track, are equally significant for railway station track. The percentage of pollution in the station would most likely be higher due to the presence of a greater number of tracks. In addition, the given approach and principles in the selection of sampling locations can be applied to different types of railways (railway track on concrete base, for example), simply by following the path of water evacuation from the track. In the case of an open-air railway, this proved to be an excellent approach in identifying locations of significant pollution.

To prevent heavy metal migration along the railway track and along the sides of the railway track, as well as through drainage channels, it is recommended to use LID elements, which have achieved excellent results when used in different urban areas for road infrastructure drainage. Further research should be directed toward modernization and improving conventional railway drainage designs in accordance with contemporary environmental protection requirements and preventing heavy metal migration, first and foremost to freshwater resources, but also to surrounding arable agricultural land.

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Conflicts of interest

The authors declare no conflict of interest.

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