Geologia Croatica
Journal of the Croatian Geological Survey and the Croatian Geological Society

2025 | 78/2 | 141–149 | 9 Figs. |

www.geologia-croatica.hr

Historical maps as a tool in the interpretation of urban topsoil geochemistry: A case study from the Roman city of Sisak, Croatia

Ajka Pjanić[1,*], Goran Durn[2], Josip Halamić[1]

[1] Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia; (*corresponding author: apjanic@hgi-cgs.hr; jhalamic@hgi-cgs.hr)
[2] Faculty of Mining, Geology and Petroleum Engineering, University in Zagreb, Pierottijeva 6, Zagreb, Croatia; (goran.durn@rgn.hr)

doi: 10.4154/gc.2025.09

Article history:
Manuscript received: December 10, 2024
Revised manuscript accepted: March 6, 2025
Available online: June 30, 2025

Keywords: Roman Siscia, geochemical maps, historical maps, PTEs

Abstract

Topsoil geochemistry maps of the city of Sisak were compared with historical maps to explain the geochemistry of the topsoil. Historically, three periods of Sisak's development can be distinguished: 1) the Celtic and Roman period; 2) the Medieval period, and 3) the industrial era during the 20th century. Comparison of the geochemical maps with the historical maps reveals 1) the accumulation of elements in the soil and their preservation over 2,000 years; 2) the influence of infrastructural interventions on the geochemical composition of the topsoil and 3) the high rate of accumulation of potentially toxic elements in the topsoil due to rapid industrialisation on purely arable land.

1. Introduction

According to the UNITED NATIONS (2024), 55% of the world's population lived in urban areas in 2018 and it is expected to increase to 68% by 2050. A large number of people living in a small, limited urban area has a severe impact on the environment. Modern lifestyles lead to significant pollution. Urban geochemical mapping provides information on the concentration, dispersion and distribution of potentially toxic elements (PTEs) and other pollutants in the urban ecosystem (WONG et al., 2006; LONG & LYONS, 2020). Such data are substantial for the assessment of contamination and potential environmental and health risks. Urban soils are, in the broadest sense, soils that have developed in urban areas. They are exposed to strong anthropogenic influences and play an important role in the ecosystem (O'RIORDAN et al., 2021). Urban soils are an ideal reservoir for the storage of PTEs, they accumulate them over time and therefore they often have elevated concentrations of potentially toxic elements (WONG et al., 2006; ŠORŠA et al., 2017).

Urban geochemical studies conducted as part of the geochemical mapping of cities in different parts of the world aimed to determine the concentration and spatial distribution of PTEs and other pollutants in soil or dust. Research methods differ from city to city, making it very difficult to correlate the results obtained in different cities (BIRKE & RAUCH, 2000; GLENNON et al., 2014; TARVAINEN et al., 2018). Therefore, a European project of the EuroGeoSurveys Geochemistry Expert Group project (EGS-GEG) "URban GEochemistry in Europe – Soil, Children, Health (URGE)" was launched to assess the environmental quality of urban topsoil using harmonized geochemical mapping in cities (DEMETRIADES & BIRKE, 2015a, b). As part of the URGE project, a geochemical survey of the urban soils of the city of Sisak and its surroundings was carried out.

The geochemical maps of the city of Sisak area were generated using descriptive statistics of the concentration of individual elements in the topsoil (ŠORŠA & HALAMIĆ, 2014), as well as using multivariate statistical analyses of the entire set of chemical elements and pH, including factor analysis (ŠORŠA et al., 2017) and discriminant analysis (ŠORŠA et al., 2018a). Interpretation of the obtained geochemical maps considers the geological background, the pedological development and the anthropogenic influence. The geological and pedological influence on soil chemistry was visible on various geochemical maps of the area (PIKIJA, 1987a, b; HUSNJAK, 2012; ŠORŠA et al., 2017, 2018a, b, 2023). The anthropogenic influence is permanent and has been over a period of about 2,000 years, having a significant impact on the soil, as can also be seen on geochemical maps (ŠORŠA et al., 2017). Anthropogenic activities can also be observed on historical maps. The numerous studies in old urban areas have focused on the study of environmental changes over time, landscape evolution through the creation of anthropogenic landforms, urban development under the influence of the geological-geomorphological characteristics of the area, and the urban geomorphology of a historical cities (AMATO et al., 2013, 2017; AUCELLI et al., 2021; MANDARINO et al., 2021). The aim of this study was to present the use and significance of historical maps for the interpretation and cartographic representation of geochemical mapping data of topsoil in the cities.

2. Materials and methods

2.1. Description of the study area

Sisak is a city in central Croatia at 45°29' N and 16°20' E (Fig. 1). The wider surroundings of Sisak are lowlands with a groundwater table between 2 and 4 m below the surface. The deposits consist mainly of fine-grained Quaternary alluvial sediments and loess. These are carbonate clastic sediments of

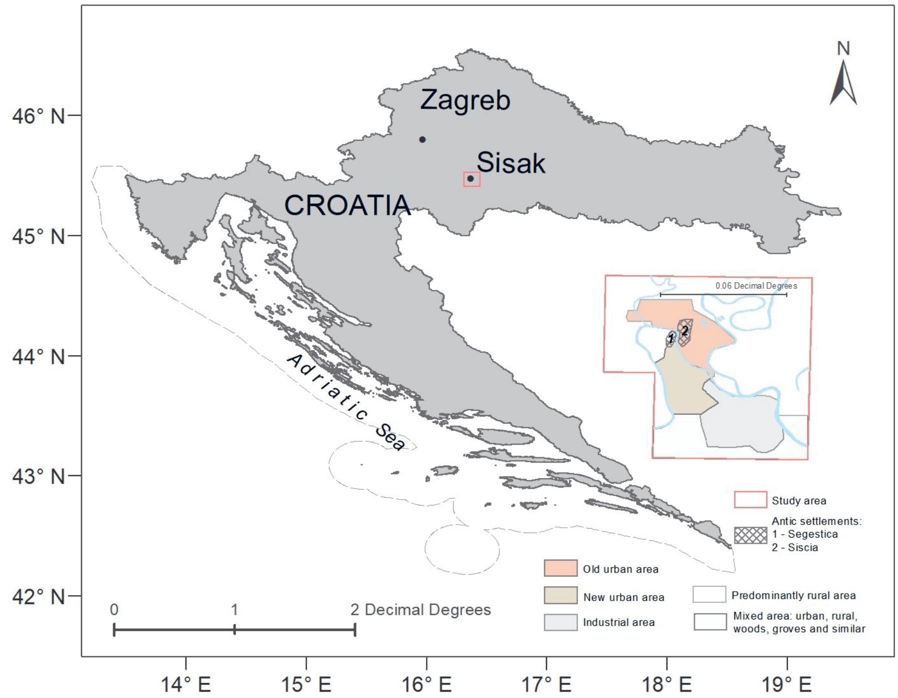

Figure 1. Geographical location of the research area.

the Sava River in the east, siliciclastic sediments of the Kupa and Odra Rivers in the west and north, and loess deposits in the central part, within the large meander of the Kupa River (PIKIJA, 1987a, b). The urban part of the study area is dominated by technogenic soils (urban soils), while in the rural part of the study area hydromorphic soils, mainly gley soils prevail (HUSNJAK, 2012; ŠORŠA et al., 2023). The climate in Sisak is a "moderately warm rainy climate, without extreme dry periods" (LISAC & HERIĆ-NEKIĆ, 1995). The average annual precipitation is 872 mm and most of it falls during the warm season. The study area includes the urban part of the city of Sisak and the adjacent rural surroundings (Fig. 1).

2.2. Development of the city of Sisak

There are three important periods in the development of the city of Sisak that have had the most influence on the type and concentration of PTEs in the topsoil of the study area:

2.2.1. Period 1 – The Celtic and Roman period (the ancient settlements of Segestica and Siscia)

The development of settlements in the floodplains of the Kupa, Sava and Odra Rivers began due to their favourable location. It was an important transportation hub between Pannonia and Dalmatia as well as between the Roman Empire and the East. The Celts most probably arrived in this area in the IV century BC and founded the settlement of Segestica (Segestika) on the right bank of the Kupa River, together with the local Illyrian population. In the 1st century BC, the Romans conquered the area of Sisak and founded the settlement of Siscia on the left bank of the Kupa River (Fig. 2a, b). Over time, Segestica and Siscia were united (SLUKAN ALTIĆ, 2004) and therefore, the designation Siscia is used in this paper for both settlements. Under the influence of the Celtic tradition, the first production and sale of metal in the Sisak region was recorded in Segestica. In 262 AD, mints, for minting money for the entire Roman Empire, were established in Siscia, which were active for over 140 years (BUZOV, 2009).

2.2.2. Period 2 – the Medieval period

During the Middle Ages, the inhabitants of the Sisak region were mainly engaged in agriculture. The city of Sisak was located on the boundary with the Ottoman Empire. It was more of a village than a city (Fig. 2c). The entire present-day old part of the city of Sisak (the former ancient Siscia) was surrounded by the Sisak stream (Sisački potok), which is marked on the historical map as *Alter Stadt Graben* (Fig. 2b). At the end of the 18th and in the 19th century, as part of urban infrastructural development, water bodies were also managed which includes the filling of the *Alter Stadt Graben* in 1876.

2.2.3. Period 3 – the industrial era during the 20th century

Due to intensive industrialization in the 1950s, Sisak became one of the more powerful industrial cities in the former Yugoslavia. The most important branches of industry were heavy industry (metallurgy, refinery, chemicals, textiles, food production and, to a lesser extent, the wood processing industry). The most intensive industrial development took place in the 1970s, which began to stagnate in the 1980s and has now almost disappeared. The heavy industry facilities were mainly located in the south in the newly developed part of the city of Sisak (Fig. 2d, e).

2.3. Sampling, chemical analyses and quality control

Sampling was carried out in accordance with the URGE manual (DEMETRIADES & BIRKE, 2015b). A total of 144 topsoil composite samples and 7 field duplicates were collected. One composite sample consisted of five subsamples taken at the corners and in the centre of a 2 × 2 m square. The sampling

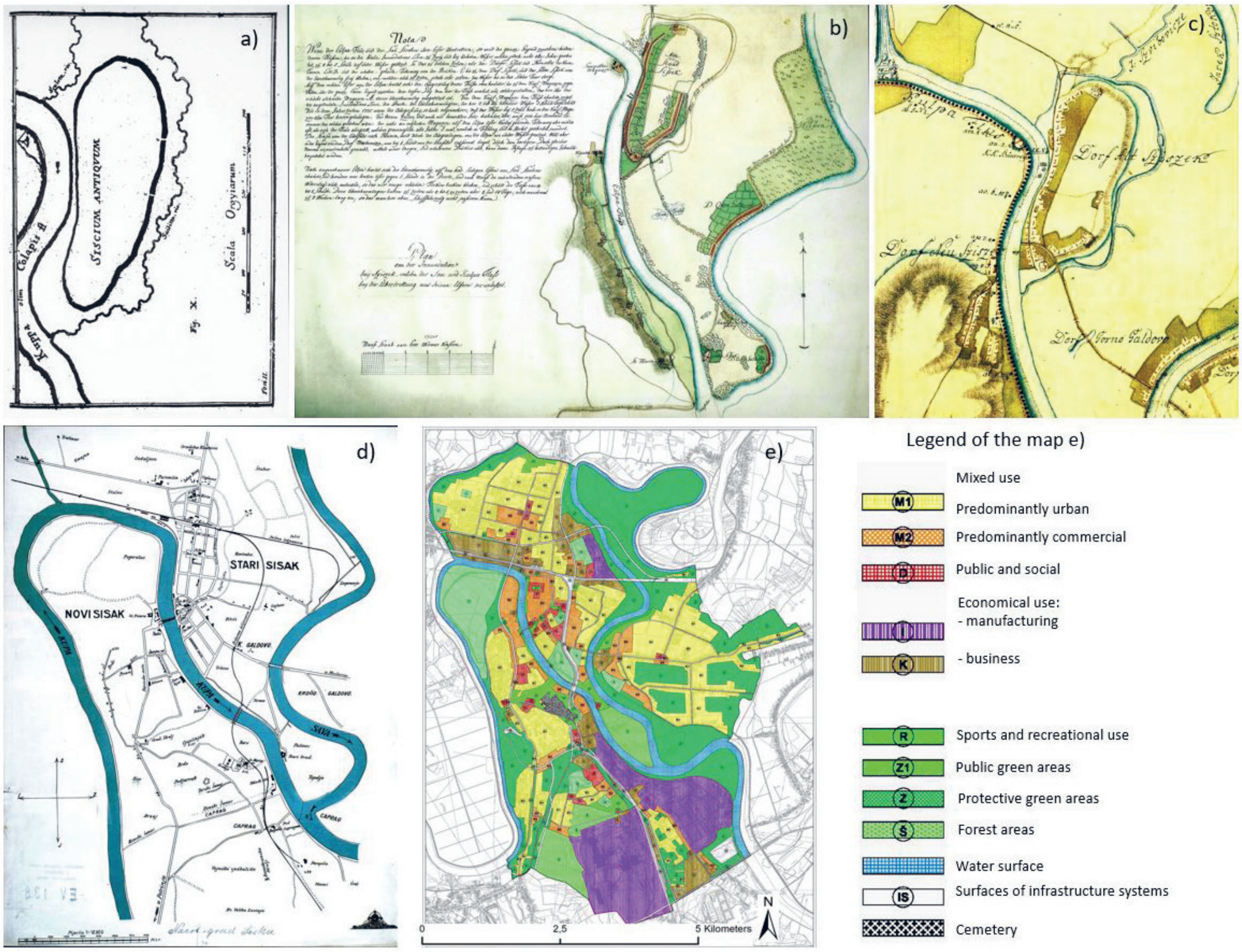

Figure 2. **a)** Remnants of the Roman Siscia on the plan of Ferdinando Marsigli dating from 1726 (after SLUKAN ALTIĆ, 2004); **b)** Hydrographic map of the Sisak area with the Siscia (*Alte Stadt Sissek*) and the Kontroba Trench (*Alte Stadt Graben*) from 1783 (Cartographic Collection of the War Archives in Vienna, after SLUKAN ALTIĆ, 2004); **c)** Detail of the Military (*Dorf Neu Sziszek*) and Old Sisak (*Dorf Alt Sziszek*) on the plan by Ignjat Pongrac from 1793 (Cartographic Collection of the State Archive in Zagreb; SLUKAN ALTIĆ, 2004); **d)** City of Sisak on the map from 1901 (Cartographic Collection of the State Archives in Zagreb); **e)** on the urban plan from 2002 (GUP, 2002).

grid was 0.5 × 0.5 km in the urban and industrialized areas and 1 × 1 km in the adjacent rural areas covering the entire area of Sisak (≈ 65 km^2). Samples were analysed for 53 elements using ICP MS. Quality control was performed both in the field and in the laboratory. A detailed description of the sampling and laboratory analyses as well as the quality control procedures for topsoil samples was explained in other publications (ŠORŠA et al., 2017; ŠORŠA et al., 2018a, b).

2.4. Data treatment and presentation

2.4.1. Historical maps

Historical maps are a valuable tool for understanding the urbanisation process of cities in the past. These maps are often very detailed and highlight important features such as city walls, rivers, channels, roads, railroads, factories, etc. The city of Sisak was first recorded on the two most famous medieval maps from the 13th century, the Ebstorf map from Ebstorf Abbey and the Hereford Mappa Mundi from Hereford (SLUKAN ALTIĆ, 2003; LOLIĆ, 2023). Since Sisak has belonged to different states during its long existence, the cartographic documentation is kept in various institutions such as the Regional Cadastral Office in Sisak, the Chapter Archive in Zagreb, the War Archive in Vienna, the University Library in Bologna, and the National Library in Budapest (SLUKAN ALTIĆ, 2004; LOLIĆ, 2023). The overview of the collection of historical cartographic records of Sisak has been published in several books and articles (SLUKAN ALTIĆ, 2004; LOLIĆ, 2023). The historical maps of the city of Sisak have recorded different periods in the city's past: the ancient Segestica and Siscia, the transportation network, changes in infrastructure, changes in hydrography, urban and industrial development. The historical maps of Sisak show the human fingerprint on the past urban landscapes of the city and were therefore a valuable tool for understanding the topsoil geochemical maps.

2.4.2. Geochemical maps

The geochemical maps of the single elements were created using two techniques: as dot maps and Inverse Distance Weighting (IDW) maps. In the dot maps technique, a point symbol is drawn at the sampling sites to emphasise the concentration at that point. The symbol is a dark grey filled circle that increases in size as the class increases. The class limits for dot maps are represented by the 5th, 10th, 25th, 50th, 75th, 90th and 98th percentiles. This is the most accurate technique for visualising the spatial distribution of elements in urban areas. To make the geochemical maps clearer and more user-friendly, additional maps were created with the same data as the dot maps as their “background”. The IDW method was used to generate the “background maps” and it was chosen because of the heterogeneity of the topsoil in the urban area, which is the reason for the large variability of the concentration values at the sampling sites. The IDW method emphasises the value at a single site. The class limits for IDW maps were every two percentiles. The coloured surface layer was generated by IDW interpolation with a moving average window cell size of 600 m radius, a weighting power of 2, and the nearest neighbour function to include at least 3 sampling sites. The final geochemical maps for each element are shown as growing grey dark dots overlaid on a coloured surface map.

The multi-element geochemical maps were created using the Kriging technique. This method was chosen for the visualisation of the factor values in order to highlight regional trends in the study area. A continuous colour-scale with 50 gradations from dark blue (lowest class) to red (highest class) was used for presenting single element “background” and multi-element geochemical maps. The projection of the maps is WGS 1984.

All data collected in the study, such as topsoil sample analysis results, fieldwork records, topographic, land use, geological, pedological and historical maps, are managed in ArcGIS ver. 10.2.1 from ESRI. The geochemical maps were created using the Geostatistical Analyst extension of this software. The statistical processing of the analytical data for the maps was prepared using the IBM SPSS Statistics software package.

3. Results and discussion

The interpretation of geochemical maps of the spatial distribution of single elements and of multi-element maps as a result of statistical processing is related to the lithological and pedological background and the anthropogenic influence. However, some geochemical phenomena, such as unexpected higher concentration of elements or associations of elements in certain urban areas, cannot be explained using the geological and pedological maps alone, but only with the input from the historical maps.

3.1. Period 1 – the Celtic and Roman period

Geochemical maps can indicate the long-lasting historical development of the area. Since the cities were built in ancient times, traces of some elements such as Au, Ag, Cu, Pb were accumulated in the urban soils as indicated by their increased concentrations in the soil in the area.

According to the geochemical map of gold in topsoil in the city of Sisak, the measured concentrations of Au in the soils of the entire urban area of Sisak are not significant (Fig. 3; fig. 4 in ŠORŠA et al., 2017). However, the distribution of this element in the analysed samples provide some interesting phenomenon for the area. The highest concentrations and extreme values of Au were measured in ancient Siscia. These elevated Au concentrations in the soil indicate an anthropogenic input during the past two thousand years of human activity. The anomalous concentrations in the southern industrial zone are probably related to industrial activities (ironworks, refinery).

The geochemical map of the spatial distribution of copper in the topsoil layer shows an area with elevated concentrations

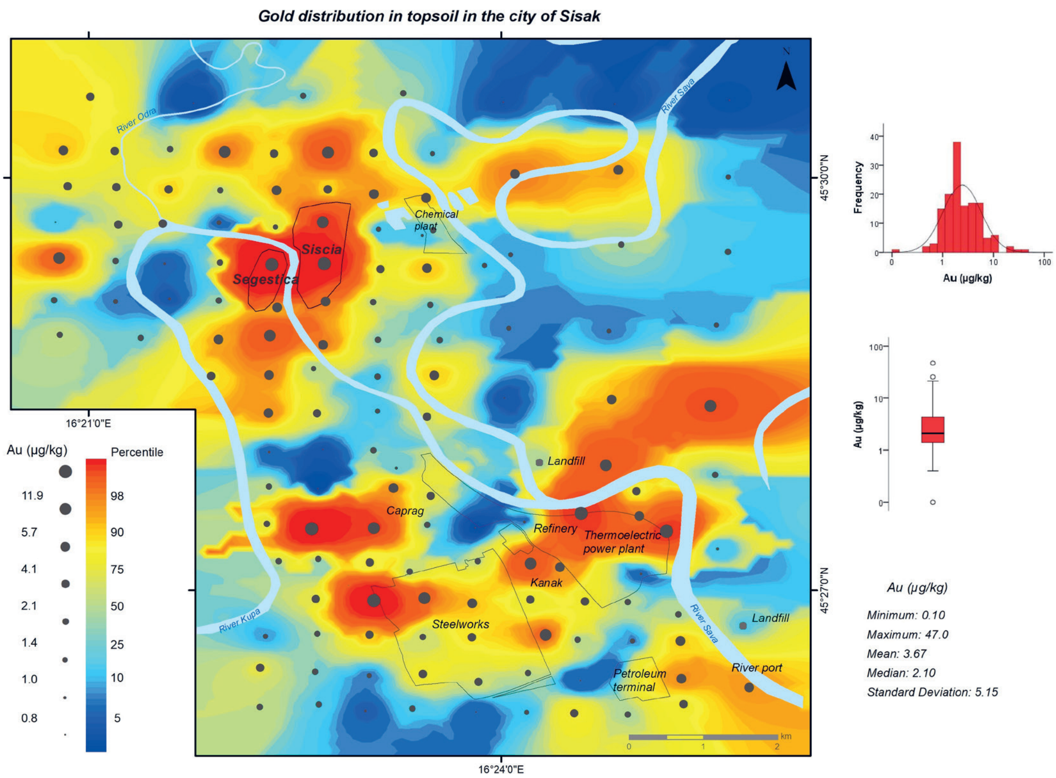

Figure 3. A geochemical map of the spatial distribution of Au in Sisak topsoil.

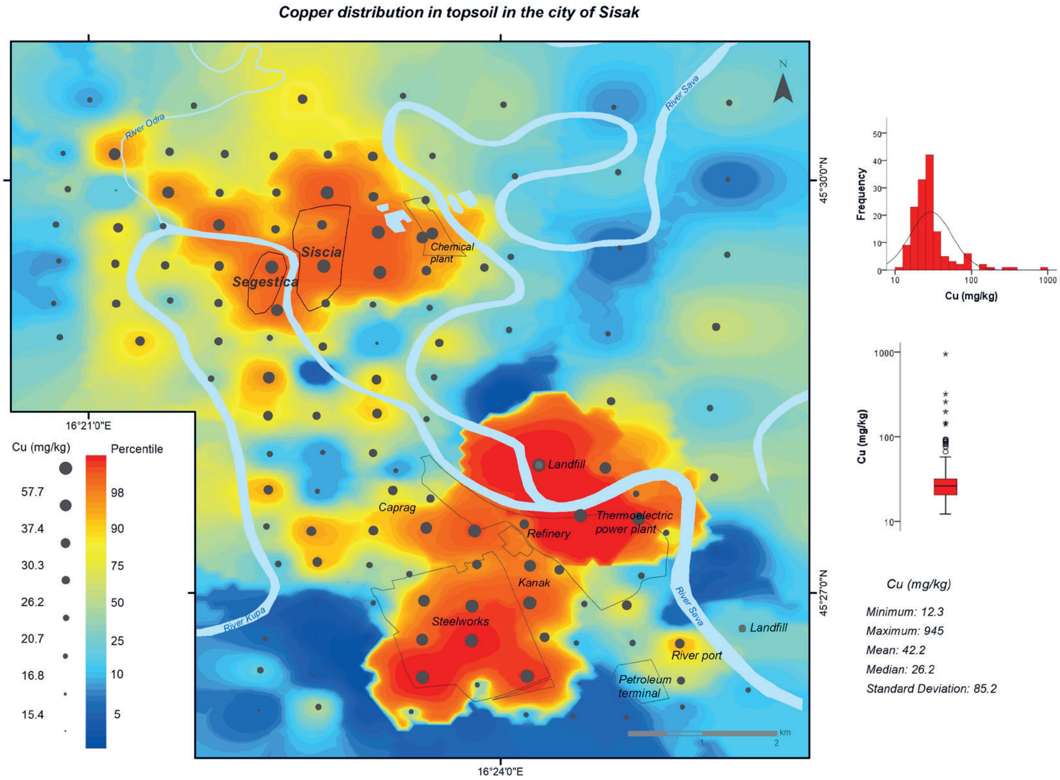

Figure 4. A geochemical map of the spatial distribution of Cu in Sisak topsoil (modified from ŠORŠA et al., 2018b).

of Cu in the soil in the ancient settlement of Siscia (Fig. 2a–c). These values are the result of the anthropogenic input of Cu into the soil at that time (smelters and mints, jewellery and various household and craft items). To the east of ancient Siscia, Cu levels are also elevated in the vicinity of the chemical plant, which can be linked to the production of pesticides. Other areas with elevated Cu levels are located along roads and railway lines and to the south in the industrial zone (Fig. 4). In addition to the industrial facilities, Cu was dispersed by the wind in the surrounding settlements and on agricultural land downwind on the left bank of the Sava River.

The map of the spatial distribution of lead in the study area shows that the Pb is predominantly of anthropogenic origin. The first area with extreme and anomalous Pb concentrations is located in the urban complex comprising the area of the Siscia (Fig. 2a, b). As Siscia was a centre for the minting of coins for the needs of the Roman Empire, Pb was released into the environment during the smelting of ores and the minting of coins. Lead was also a widely used metal in ancient times for water pipes (Fig. 5) and for many other commonly used items, so the high concentrations of Pb in the topsoil are related to this period and only a small part is more recent, e.g. along roads due to the combustion of fuel in vehicles. Another area with an elevated Pb content in the topsoil is located in the southern industrial zone, then it was dispersed by the wind to the surrounding settlements and to the agricultural areas on the left bank of the Sava River (Fig. 6).

Due to the largest factor score associated with the mints, factor 6 (FA6) can be interpreted as an anthropogenic factor: Roman mints (ŠORŠA et al., 2017). Multi-element geochemical maps show groups of elements Au, Ag, Hg, Pb, Bi and P associated with ancient Siscia (Fig. 7). Copper coins with Ag or Au coating were minted in smelters and mints throughout the Roman Empire, also in Siscia. The method of coating coins involved the use of mercury (INGO et al., 2006). The FA6 factor score is also elevated in the southern industrial zone due to heavy industry production.

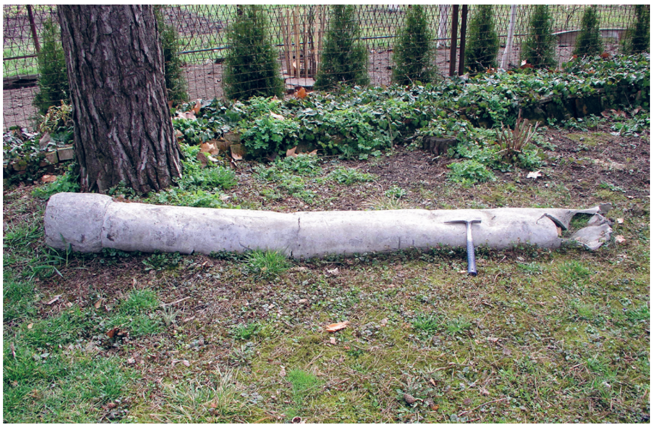

Figure 5. A lead water pipe from the Roman period kept in the City Museum in Sisak (photo: Josip Halamić).

3.2. Period 2 – the Medieval period

The interpretation of the geochemical maps of the spatial distribution of Cr, Ni, Co, Fe, V, Ce, Ga, La, Nb, Rb and Tl (ŠORŠA & HALAMIĆ, 2014) was questionable in Siscia. As expected, the concentrations of these elements were elevated in the industrial zone in the south, in the alluvium of the Kupa and Odra Rivers, but concentrations were also elevated around

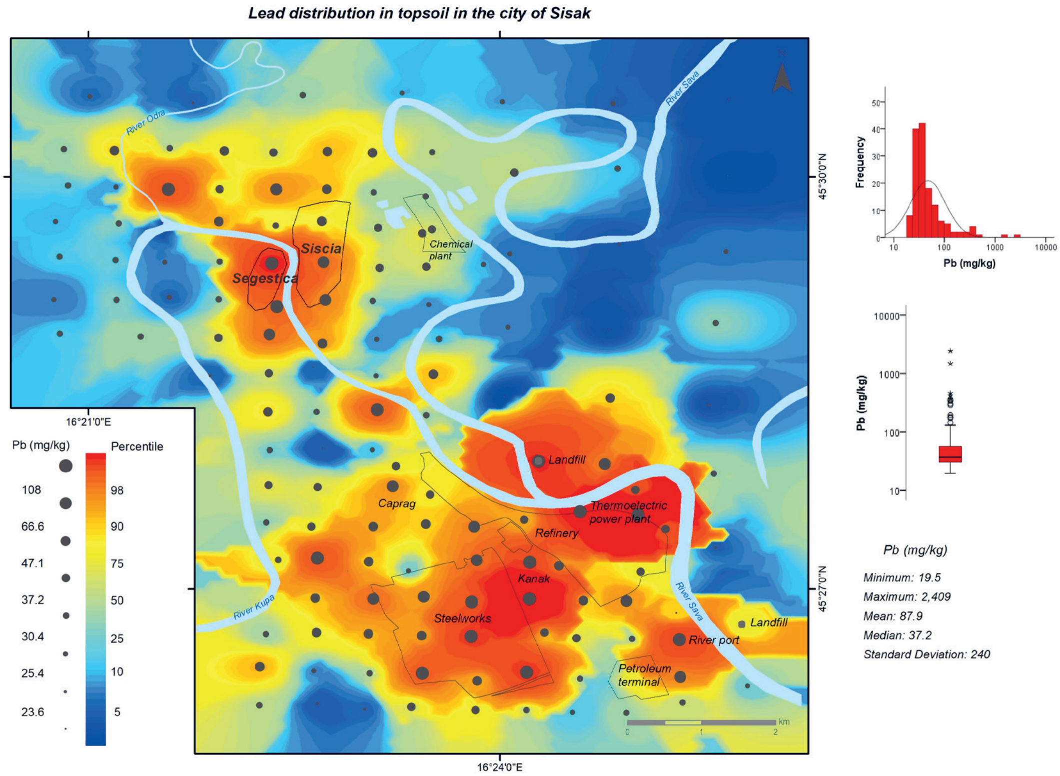

Figure 6. A geochemical map of the spatial distribution of Pb in Sisak topsoil (modified from ŠORŠA et al., 2018b).

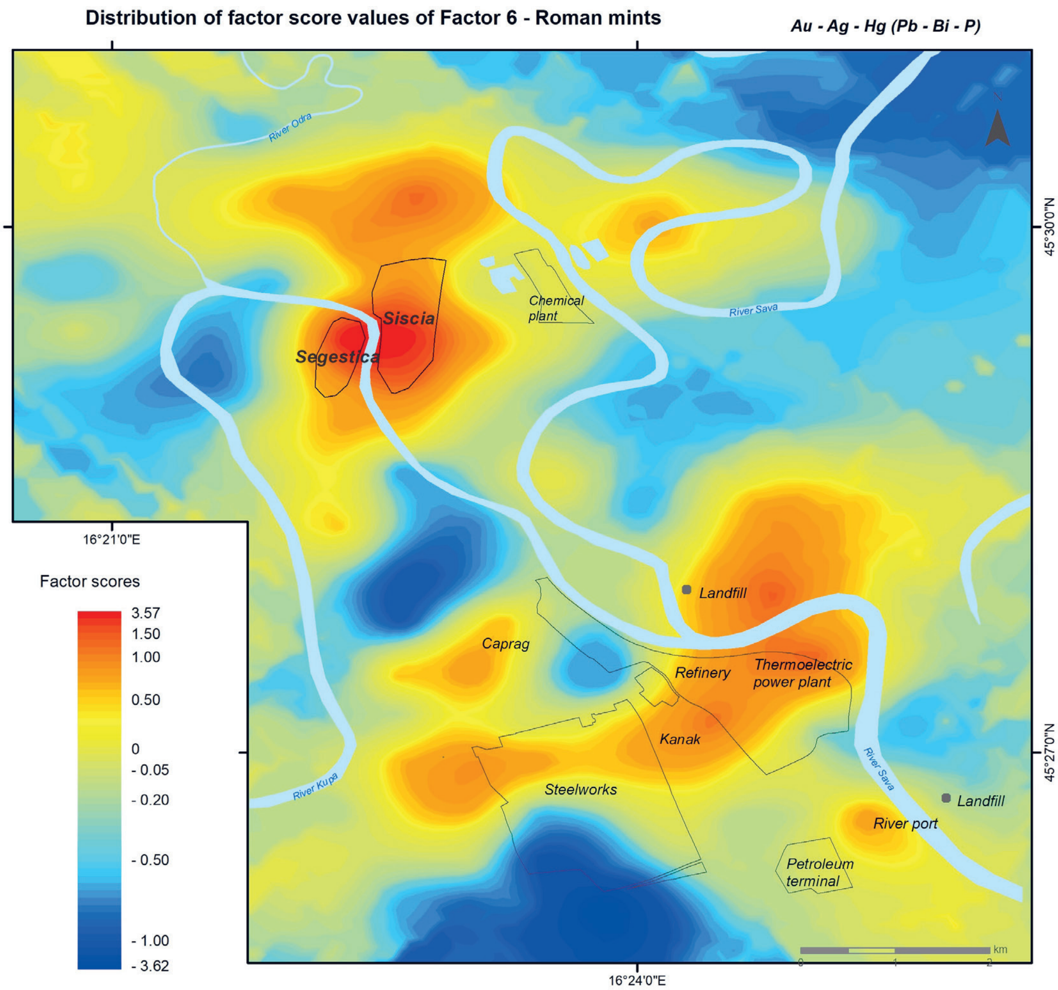

Figure 7. A geochemical map of the score of the factor analyses in Sisak topsoil – anthropogenic factor 6 – Roman mints (modified from ŠORŠA et al., 2017).

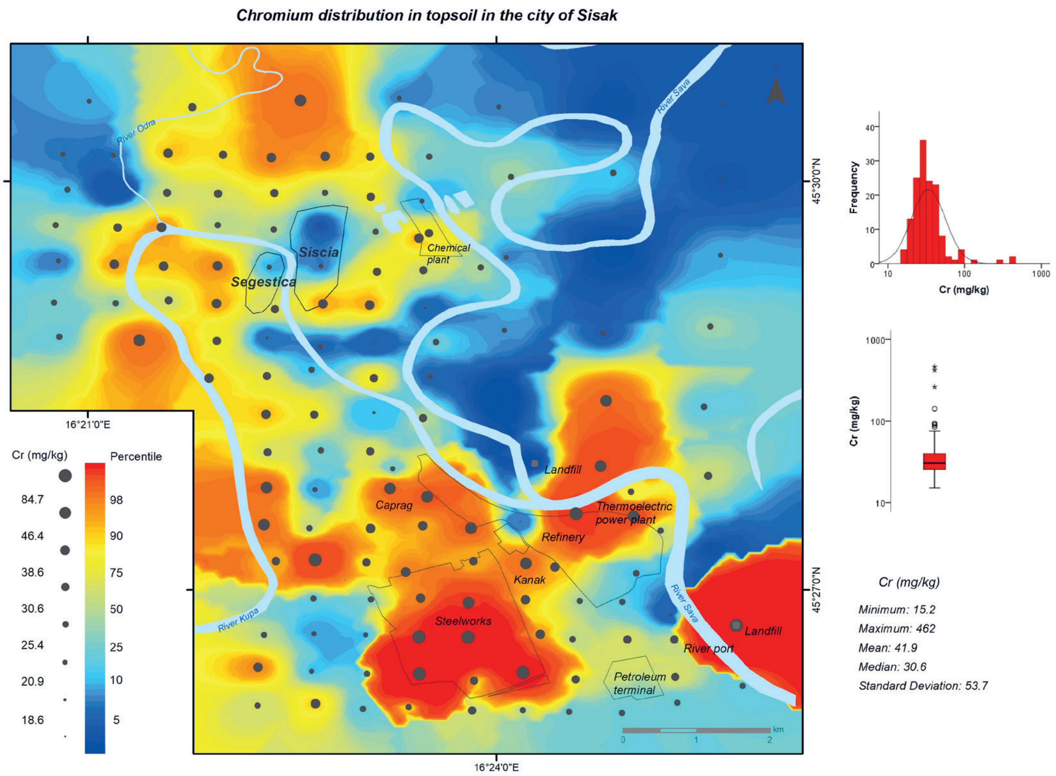

Figure 8. A geochemical map of the spatial distribution of Cr in Sisak topsoil.

Siscia. The satisfactory explanation for this was provided by the historical hydrographic maps, which showed the existence of the old Sisak stream around Roman Siscia, labelled on the map as *Alter Stadt Graben* (Fig. 2b, c), which was connected to the Kupa River and has the same alluvial parent material. Although the stream was filled in, 130 years ago, its impact on the geochemistry of the topsoil layer is still recognisable. Elevated levels of Cr were measured in soils formed on the alluvial sediments of the Kupa and Oder Rivers, which are of geogenic origin due to the weathering of basic and ultrabasic magmatic rocks in the hinterland (Fig. 8). The high Cr levels in the southern industrial zone and the surrounding urban and agricultural areas are the result of anthropogenic pollution.

3.3. Period 3 – the industrial era during the 20th century

Factor 1 (FA1) is an anthropogenic factor with the highest factor score values of Mo, Zn, W, Sn, Sb, Cd, Mn, Cu, Pb, Cr, Fe, Ba, Ni, Ti, Na, Bi, S, Ag, In, As, U, Hg and V in the southern industrial zone. The elements (variables) associated with anthropogenic pollution from heavy industry have the highest factor loading, and therefore FA1 can be interpreted as Heavy industry. The highest values are located in the vicinity of the ironworks, refinery, the thermal power plant, the surrounding settlements and the agricultural land in the north-east, in the favoured wind direction of the industrial facilities (ŠORŠA et al., 2018b; Fig. 9). The value of the factor load is also increased to the north of Sisak (ancient Siscia), along the old road and railway, then along the Kupa River and in the southeast in the river port on the Sava River. In the ancient part of Sisak, PTEs have accumulated in the soil due to the long-term existence of settlement (over 2,000 years) (Fig. 2a–e). Elevated concentrations in the topsoil along the old roads and the railway can be interpreted with the help of historical maps (ČAKŠIRAN, 2011; Fig. 2d), on which we can see the beginning of the development of industry in the late 19th and early 20th century. The map in Figure 2d is from 1901 and on it the future southern industrial area is the village of Caprag without industrial facilities. On the 2002 map (GUP, 2002; Fig. 2e), the entire area is an industrial complex with settlements for the workforce in between. The elements with high factor loading values in FA1 are used in the metallurgy and chemical industries and released by the combustion of oil, fuel oil, coal and waste, then by exhaust fumes from vehicles, tyres and brakes on roads and railways, domestic waste, and sewage etc. As industrial development was intensive from the 1950s to the 1980s, the accumulation of trace elements in the topsoil is considerable.

4. Conclusions

The Sisak area is scientifically notable due to its unique development over 2,000 years. Three key phases of Sisak's development were identified: 1) the Celtic and Roman period; 2) the Medieval period; and 3) the modern industrial era. The origin of potentially toxic elements in the soil is clear since the Roman Siscia (north) and the modern industry (south) occupy different geographic areas. The city's medieval phase had minimal anthropogenic influence.

This allowed the tracing of: 1) the accumulation of elements in the soil and their preservation from the Roman period to the present; 2) the impact of infrastructural changes on topsoil composition; and 3) the rate of element build up due to rapid industrialization on formerly arable land.

A satisfying interpretation of the concentration and spatial distribution of chemical elements on geochemical maps in

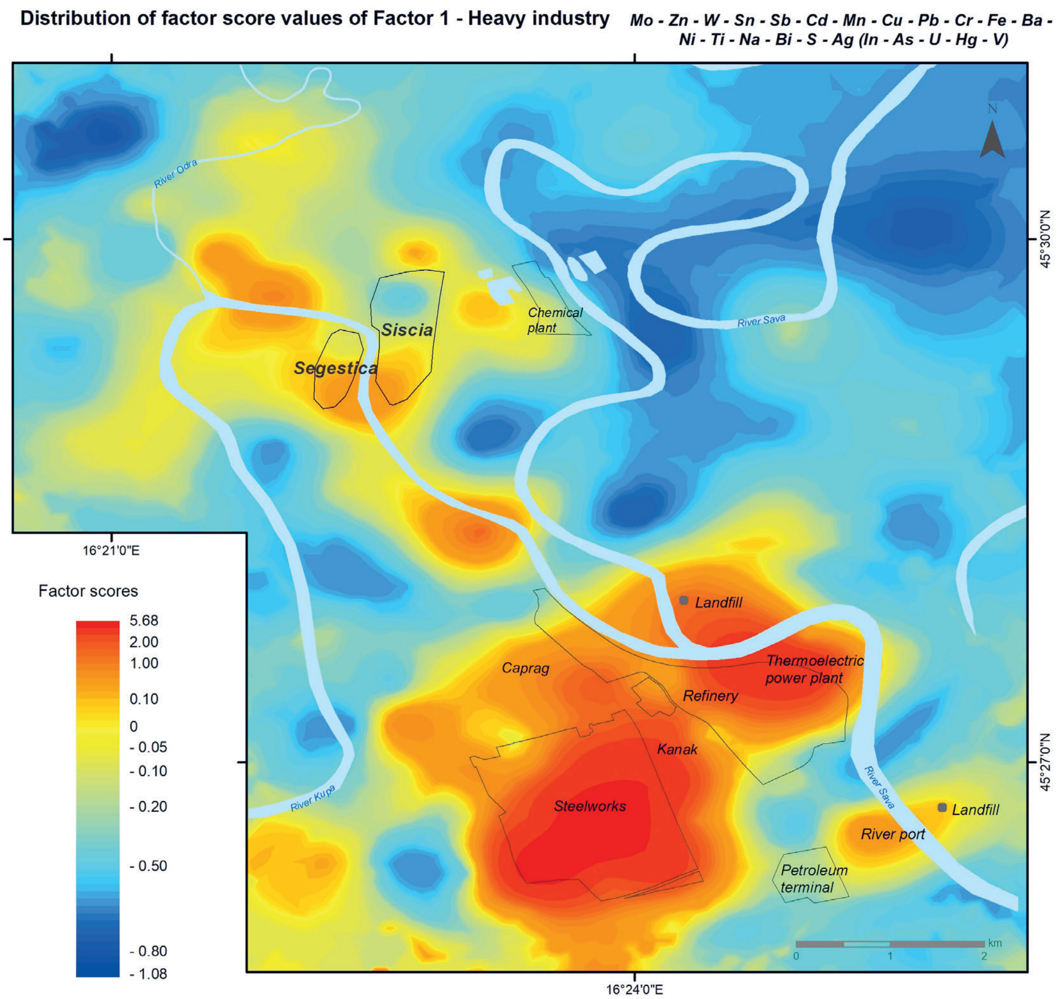

Figure 9. A geochemical map of the score of the factor analyses in Sisak topsoil – anthropogenic factor 1 – Heavy industry (modified from ŠORŠA et al., 2017).

urban areas can be obtained not only using geological and pedological maps, but also with the help of historical maps.

Acknowledgement

This study was financially supported by The Ministry of Science, Education and Sports, Republic of Croatia – Scientific Project: The Basic Geochemical Map of Croatia, Number 181-1811096-1181. We are grateful to associate editor Gevorg Tepanosyan and the anonymous reviewers for their thorough evaluations, which significantly improved the manuscript.

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