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Comparison of two model environmental burdens with massive light non-aqueous phases liquids (LNAPL) pollution – the extent of pollution identified by geological survey vs. reality uncovered by remediation

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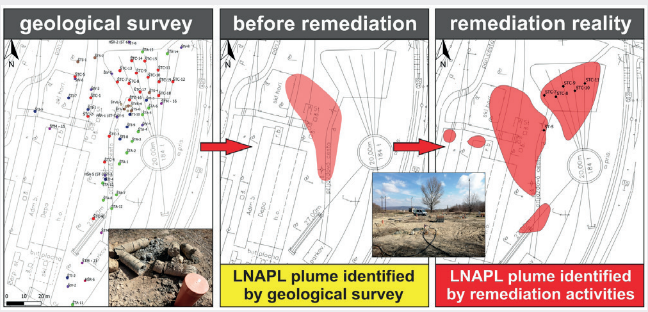
Abstract: The paper deals with the results of exploration and remediation in two railway operations. Locomotive depots in Štúrovo and Leopoldov belonged to heavily polluted sites with the occurrence of light non-aqueous phases liquids (LNAPL) on the groundwater table. Remediation began on the sites in 2018. The results of the pre-remediation surveys did not indicate the presence of large volumes of pollution in the form of free phase, however, during the remediation LNAPL flowed into new wells. At the same time, the spreading of LNAPL accumulations and the progressing of pollution in dissolved form by groundwater has not been confirmed. Comparison of surveys and remediation points to various facts that must be considered when evaluating the degree of pollution of the site. It is necessary to perceive the whole space of the railyard as possible source of pollution. Remediation project should not be based solely on the presence of LNAPL. Its presence and the risk it poses must be verified. Outcomes of activities, based on limited data, may in that case differ from the remediation goals.

Key words: remediation, light non-aqueous phases liquids, locomotive depot, environmental burden

Graphical abstract



Highlights

- Distribution of LNAPL on two sites is evaluated
- Pre-remediation survey and remediation outcomes are compared
- Vast differences in pollution plumes were discovered
- Remediation decision making must include detailed LNAPL characteristics

Introduction

The basis for planning of a remediation is usually a detailed site survey. It mostly results in accurate information on the nature and spatial distribution of the pollution. Selected sites, locomotive depots in Leopoldov and Štúrovo (Fig. 1), have a long history of repairs of traction rolling stock. Both were already in operation in the 1950s. During transition from steam to diesel traction, both depots switched to maintenance of diesel locomotives.

During operations, leakage of oil-based operating fluids (diesel, lubricants) may have occurred, either due to leaks from single walled tanks and fittings or improper handling. Both sites have been examined in detail in the past (Štúrovo depot – Polák, 1987; Solymosiová et al., 1988; Leopoldov depot – Vrana, 2008) and since 2008 groundwater monitoring has been carried out on both sites.

In Štúrovo, four boreholes in the vicinity of underground storage tanks were identified, in which light non-aqueous phases liquids (LNAPL) thicknesses up to 870 mm were present for a long time (Kostolanský et al., 2017a). In Leopoldov, LNAPL was observed only in one borehole located near the fuel dispensing point (LEV-1 borehole). The assumed sources of pollution were fuel pipelines or leaks from pumping fuel (Kostolanský et al., 2017b). In 2017, both sites were included in the group of 14 railway sites where the Ministry of Environment of Slovak Republic was approved for the implementation of remediation. In the information system of environmental burdens, the sites were registered as confirmed environmental burdens – NZ (029) / Štúrovo-Rušňové depo, Cargo, a. s. (SK/EZ/NZ/601) and HC (1844) /

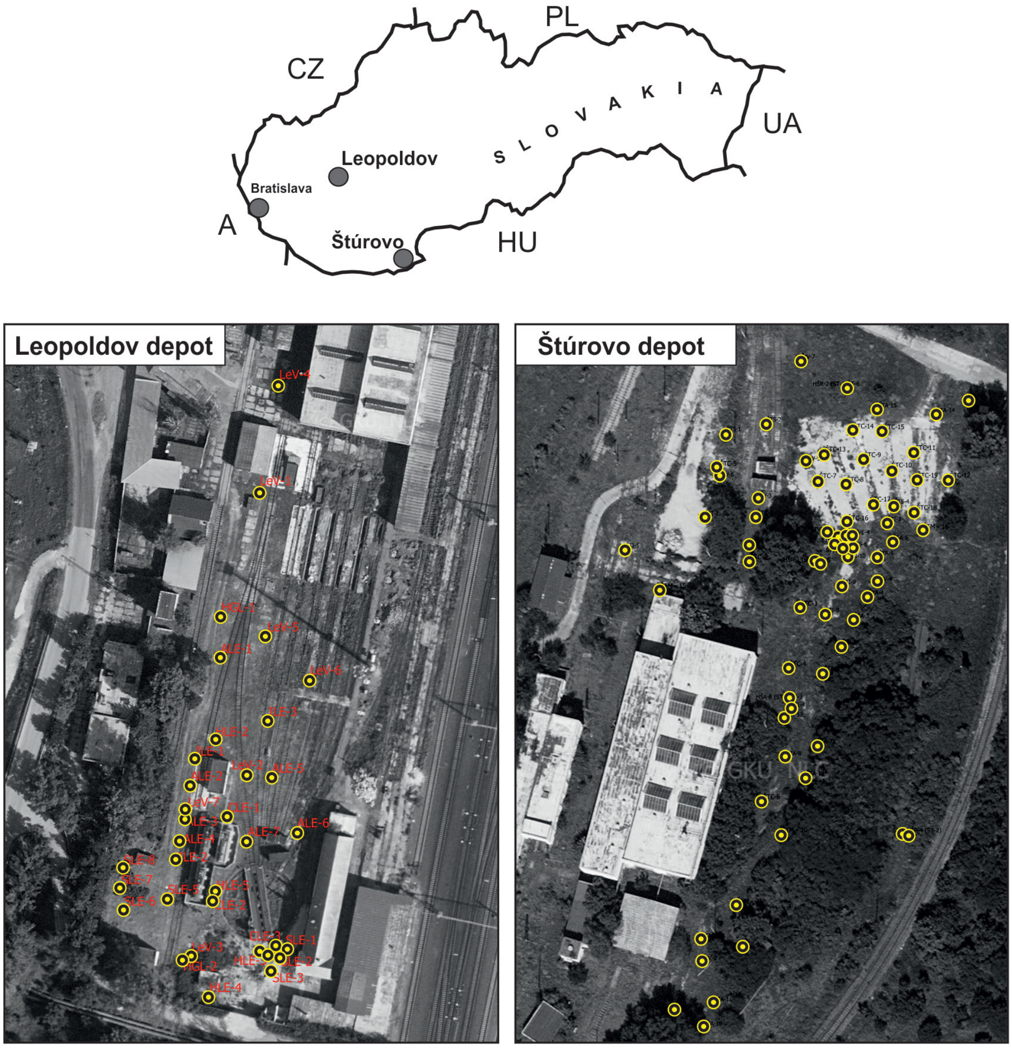


Fig. 1. Schematic map of model locomotive depots with the location of realized geological and remediation objects

Leopoldov-Rušňové depo, Cargo, a. s. (SK/EZ/HC/1844). The depot in Štúrovo has been out of operation since 2008, operation in Leopoldov is limited at present.

The first step of remediation was the pre-remediation survey which led to update of the risk assessment. Atmogeochemical measurements (detection of VOC´s in soil vapor) were carried out as a part of the survey, which primary focused on the drilling of soil probes and hydrogeological wells from which soil and groundwater samples were collected. Primary concentrations of organic substances – NEL-IR (non-polar extractable substances – infrared spectrum), NEL-UV (non-polar extractable substances – ultraviolet spectrum), C_{10}–C_{40} (total petroleum hydrocarbons via GC-FID), BTEX (benzene, toluene, ethylbenzene, xylenes), CAH (chlorinated aliphatic hydrocarbons), PAH (polycyclic aromatic hydrocarbons), and PCB (polychlorinated biphenyls) – were determined in the samples and the extent of contamination was continuously adapted based on the new information obtained during the geological survey. Concentrations of BTEXs, CAHs, PAHs and PCBs were low, or under the laboratory detection limit.

The results of the survey in Leopoldov identified extensive soil pollution in the vadose zone (0.0–1.0 m below ground surface (bgs) at max. 2 320 mg.kg^{-1} C_{10}–C_{40}, 3.0–5.0 m bgs max. 6 160 mg.kg^{-1} C_{10}–C_{40}) and in the saturation zone (5.0–7.0 m bgs up to 5 690 mg.kg^{-1} C_{10}–C_{40}) and in groundwater (up to 6.76 mg.l^{-1} C_{10}–C_{40}). Pollution consisted of oil substances (diesel), identified mainly in the area under the turntable and under the above-ground fuel tanks. The occurrence of LNAPL was confirmed during the survey only in the original LEV-1 well (Tupý et al., 2019). In the newly built wells only an oil sheen was observed at the groundwater head. The assumed sources of pollution were handling areas of filling and discharging of fuel, operating place of oil-mill and above-ground fuel tanks.

Survey in Štúrovo depot identified very extensive soil contamination at the top of the saturation zone with the content of C_{10}–C_{40} in soils up to 17 200 mg.kg^{-1}. The maximum concentration of C_{10}–C_{40} in groundwater was up to 7.71 mg.l^{-1}. The occurrence of LNAPL was observed only in old wells on area of about 700 m^2. The assumed source of pollution were three underground single walled fuel storage tanks – USTs (Urban et al., 2019).

Based on the results of pre-remediation survey, the main planned remediation operations focused to the pumping and treatment of groundwater in oil separators and the pumping of LNAPL out from the created hydraulic depressions. In Leopoldov, the removal 2 000 m^3 of polluted soils was also planned. The paper deals with the results of exploration and remediation activities on above mentioned sites. Other techniques used for LNAPL plume estimation are described in case studies in papers by Dippenaar et al. (2005), Steyl et al. (2012) or Mineo et al. (2022).

Geological situation at model sites

Leopoldov

According to Vass (2014) the investigated territory belongs to the Danube Basin, Blatné Depression, belonging to the Váh river floodplain and lies on Quaternary fluvial sediments. Lithofacially it is built by undivided fluvial loams or sandy to gravel loams. More lithological and lithofacial information are presented by Maglay et al. (2005) and Maglay et al. (in press).

Alluvial sediments of the Váh river in broader area reach a thickness of 7–10 m. On the surface, there are clays and sands of variable thickness (1–4 m), below them there is a continuous layer of gravel and sand (Valušiak, 1987). Exploration works (wells LEV-1 to LEV-7) verified the lithological conditions in the area of the locomotive depot up to a depth of 12 m below ground level (Vrana, 2008). Below the backfill layer, 0.5 m thick, locally up to 2.8 m, there is a clay-sandy layer (sandy clay, loamy sand) 1.6 to 1.8 m thick. Below is developed a sandy layer with an admixture of gravel to a depth of approx. 4.5–5 m, below which sandy gravels occur.

The Neogene sediments do not outcrop to the surface anywhere within the Quaternary alluvial basement in the immediate vicinity. The underlying Neogene is built of Pontian sediments with a predominance of variegated clays with positions of fine, medium, loamy-clay sands and locally with gravel lenses (Valušiak, 1987). The basement of the gravel-sand layer is formed by impermeable clay and was verified in the area of the locomotive depot at a depth of 10 to 11 m below the ground. Representative geological profile of locality Leopoldov with massive contamination is presented in Fig. 2.

Štúrovo

The area of interest is located on the eastern edge of the Štúrovo-Mužla Terrace with poorly divided terrain between the valley floodplains of the Hron and the Danube rivers. The terrace is built of Quaternary sediments – gravel-sand facies approx. 3–4 m thick, with well-worked layers of all

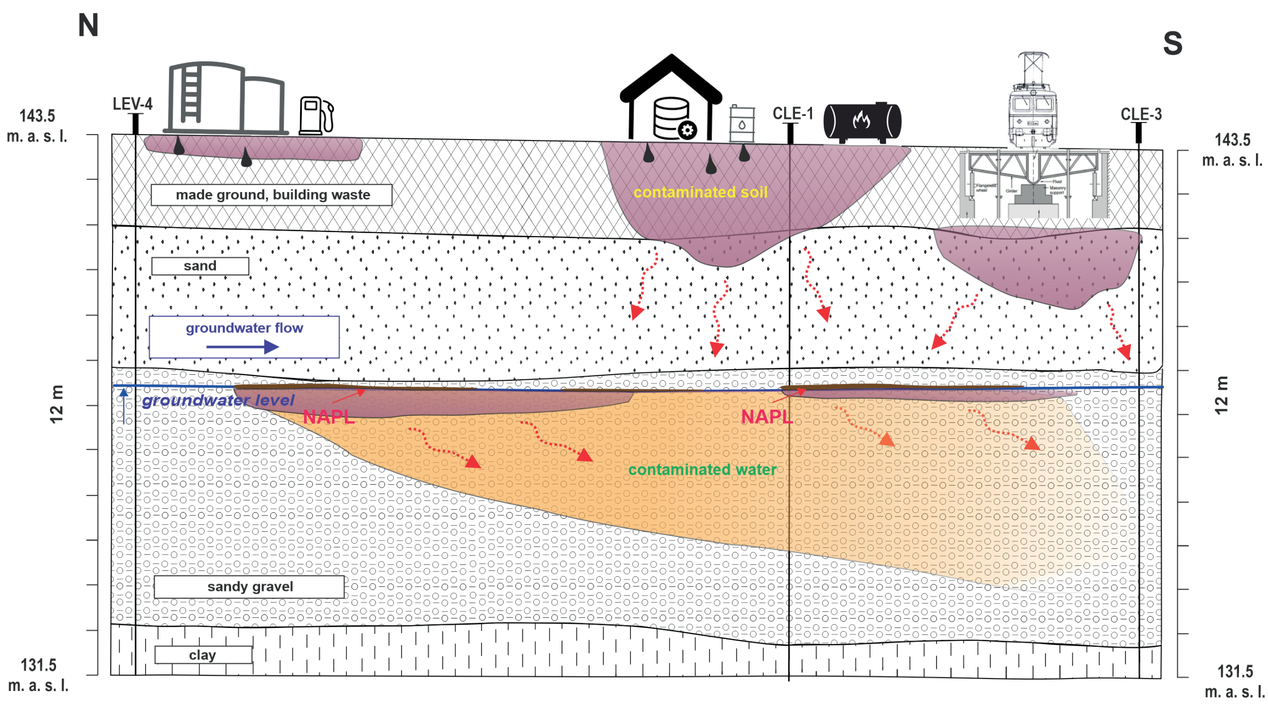


Fig. 2. Leopoldov depot – geological situation at model site in cross section with contamination.

grain size categories. Pebbles consist of quartz, quartzite, more rarely of granitic rocks. The occurrence of the sandy fraction is variable in percentage content and grain size. In the overburden of sandy gravels, the loess, loess clays and clays of considerable thickness occur, approx. 8–10 m thick. The base of the terrace consists of clayey-sandy sediments of the Neogene and Paleogene. More detailed lithological and lithofacial information are presented by Nagy et al. (1998). Representative geological profile of locality Štúrovo with massive contamination is on the Fig. 3.

From a geological point of view, the localities differ considerably. In Leopoldov, under a layer of material accumulation up to 3.0 m thick, a great water bearing gravel layer occurs. The Váh floodplains in the wider area reach a thickness of 7–10 m. The survey verified the lithological conditions of the area up to a depth of 12 m below the ground surface in the locomotive depot. Below the 0.5 m thick bacfill layer (locally up to 2.8 m) a clayey-sandy layer (sandy clay, loamy sand) with thickness of 1.6 to 1.8 m is located. Below is a sandy layer with gravels up to a depth of ca. 4.5–5 m, below this layer sandy gravels occur (Tupý et al., 2019).

The base of gravel-sandy layer is built by impermeable clays and was verified in the locomotive depot at a depth of 10 to 11 m below the ground surface. The main collectors of groundwater are Quaternary gravel-sandy sediments, which reach a thickness of about 10–15 m in the studied area (Tupý et al., 2019).

The coefficient of hydraulic conductivity of gravel sandy sediments ranges from 1 to 2.10^{-3} m.s^{-1}. From a hydraulic point of view, the groundwater in the Quaternary sediments is unconfined. General direction of groundwater flow is from north to south.

The situation is considerably different in Štúrovo. Geological conditions in the locomotive depot were verified by new wells to the depth of 15 m below ground surface. Below the top 0.5–3.8 m thick backfill layer, there is an impermeable layer consisting of silty clay and silt. Under these, from a depth of 7.8–9.8 m sandy gravels 1.7–4.0 m thick (in average about 2.5 m) occur. Below the impermeable clays occur (Auxt et al., 2009; Urban et al., 2019). Groundwater at the site of interest is in sandy gravels of fluvial origin. It is filled up with infiltrated rainwater. The height of the water column is very variable and depends not only on the infiltrated amount of precipitation, but also on the character of the bedrock and the overall natural conditions. Transmissivity also varies, hydraulic conductivity coefficient ranges inbetween 10^{-4} to 10^{-5} m.s^{-1}, aquifer is confined.

Methods

The removal of pollution from both sites was based on a similar principle. The pumping and infiltration wells with a diameter of 200 mm were drilled and the groundwater pumping started. After groundwater treatment in the oil separator, it was infiltered via several wells back into the aquifer. In Štúrovo, it was enough to pump water of

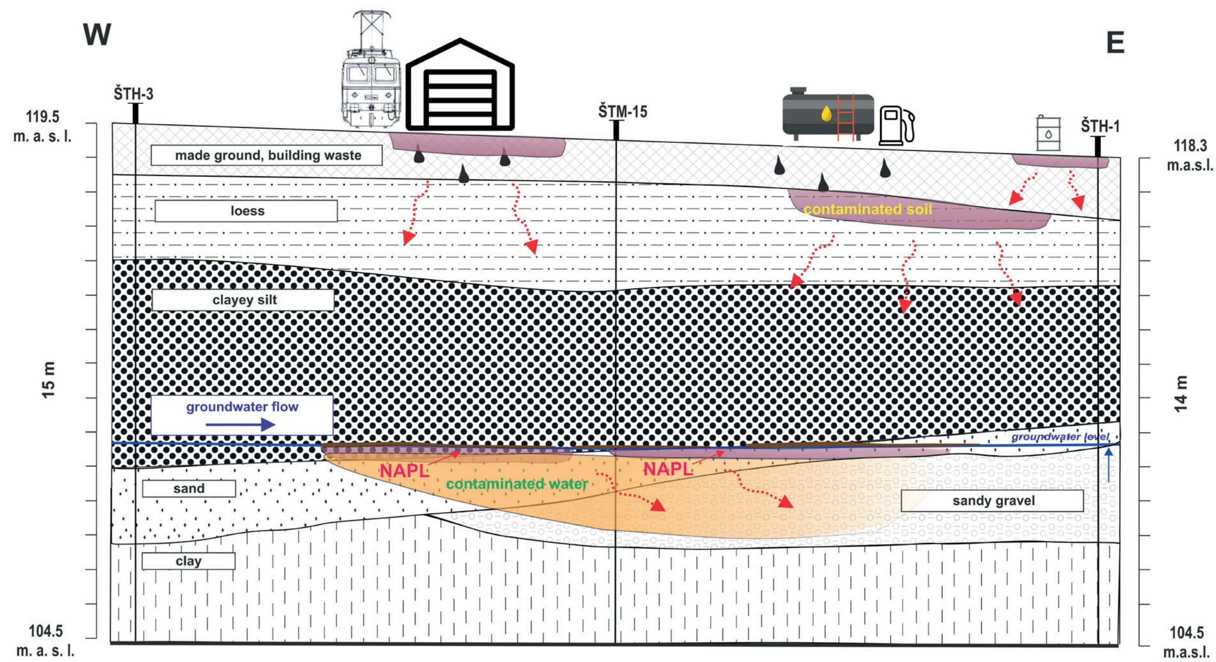


Fig. 3. Štúrovo depot – geological situation at model site in cross section with contamination.

about 0.5–1.0 $l.s^{-1}$ to create optimal depression cones, into which pollution flowed. On the contrary, in Leopoldov, the lowering of groundwater levels in the wells was achieved by pumping more than 3.0 $l.s^{-1}$. In addition, in Štúrovo there was not sufficient groundwater inflow into the pumped wells, and therefore it was necessary to gradually reduce the pumping capacity.

Remediation was carried out for approximately 2 years at both sites. These included supplementary methods to remove residual pollution such as air-sparging, soil washing and enhanced biodegradation by bacterial strains isolated from the contaminated soil in Štúrovo. In 2021, the turntable and the polluted soils below it were removed in Leopoldov (Fig. 4). The excavation was carried out about 2 m below groundwater level. Subsequently, LNAPL was skimmed from the water table. Groundwater samples were analysed at the accredited laboratory ALS Czech Republic, s. r. o., Na Harfě 336/9, Praha 9, Czech Republic. The "CZ_SOP_D06_03_151 (ČSN EN ISO 9377-2)" method for detection of extractable compunds in the hydrocarbon range C10–C40 (gas chromatography with flame ionisation detector) was utilized.

Fig. 4. LNAPL in excavation pit at locality Leopoldov depot.

Results and discussion

Štúrovo

To start the remediation, the pumping out of LNAPL from the existing wells was realized. Almost 150 l of pollution was pumped from the ST-5 well at once. The initial step of remediation at both sites was to build a network of new wells. In Štúrovo, the drilling was carried out stepwise in 5 stages. In Leopoldov, the remediation wells were drilled in one stage (except for airsparging wells).

During drilling works in Štúrovo, spontaneous LNAPL inflows into new wells were observed. During the realization of wells (07/2019) at the margin of the assumed pollution cloud (identified in Urban et al., 2019), a relatively fast inflow of LNAPL into two new wells was observed.

In the next phase of drilling works (07/2020), a large area with another source of pollution at the site was identified. This source of LNAPL pollution was more quantitatively abundant as in the area around the underground storage tanks. The presence of pollution in the form of a mobile LNAPL was confirmed in the track area in front of the former roundhouse, that no longer exists today. The high degree of soil saturation by pollution was also confirmed by the immediate occurrence of LNAPL in new wells (up to a thickness of almost 1 000 mm). LNAPL was first pumped without supporting groundwater pumping (in several wells on the site, after the initial volume of the LNAPL was pumped out, it has not immediately inflowed again). High inflows of LNAPL in several new wells (STC-8, STC-10) were the impulse for starting groundwater pumping in adjacent wells (STC-7, STC-9, STC-11). Subsequently, LNAPL with a thickness of almost 1500 mm (STC-9) appeared in these wells (except STC-11). Approximately 2 m^3 of pollution was pumped from wells in the vicinity of underground reservoirs and more than 4 m^3 from wells in the railyard area. Thus, the source of pollution identified during the remediation (trailyard in front of the former depot building) was double abundant in terms of extracted LNAPL as the originally considered source of pollution (underground fuel tanks). In addition to the two main pollution sources, two smaller sources (fuel pipeline and repair pit) were identified at the site (Urban et al., 2021).

The remediation thus verified the pollution by LNAPL on an area approximately three times larger than originally expected (Fig. 5). The work of Macek and Milička (2021) evaluates the nature of pollution regarding its degradation and the result is the conclusion that the pollution comes from several different sources. Despite the fact, that the depot has been out of operation for more than 10 years, one of the collected LNAPL samples showed no obvious signs of degradation.

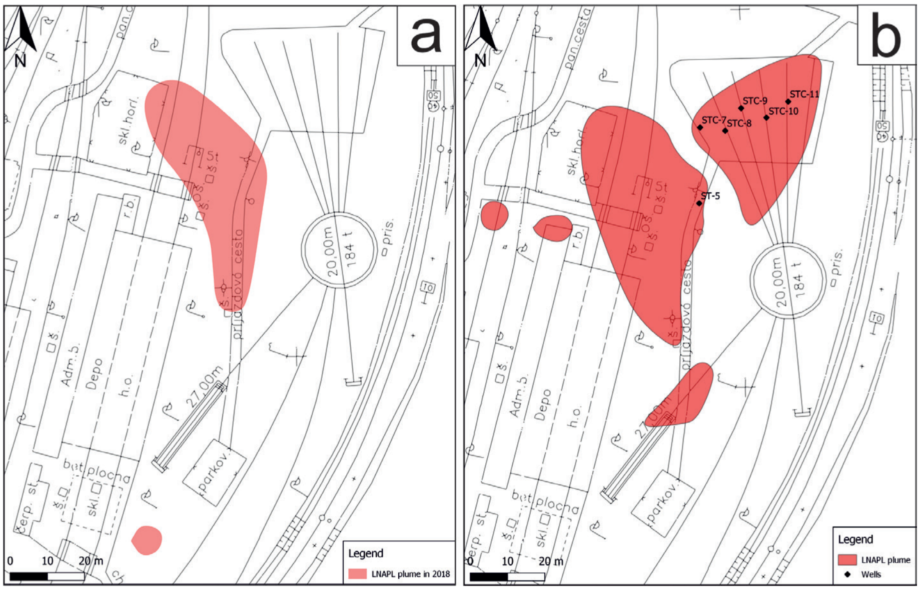


Fig. 5. LNAPL plume at model localities identified by remediation activities – a) Leopoldov depot (Tupý et al., 2022), b) Štúrovo depot (Urban et al., 2021).

The estimated age of pollution at the site is from 8 to 48 years.

Leopoldov

In Leopoldov, the remediation wells were drilled in one stage (except for airsparging wells). No significant spontaneous infiltrations of LNAPL were observed in the newly built wells (07/2019). Free phase was observed in 08/2019 in 9 wells (of 13) with a maximum layer thickness of 40 mm. After the start of remediation and the start of groundwater pumping in August 2019, significant inflows of pollution in the form of LNAPL were observed in the CLE-1 and CLE-2 wells. LNAPL flowed into the CLE-2 well immediately after it was pumped, reaching a thickness of almost 80 cm (approx. 25 l), which was the highest volume of all wells. Gradually, after the groundwater pumping from new drilled wells, LNAPL inflow was also observed in wells CLE-3, ALE-4, ALE-7, HLE-2 and ILE-2. The area around the turntable and above-ground fuel tanks thus proved to be much more polluted than originally expected. In total, more than 5 m^3 of LNAPL, and of LNAPL and groundwater mixtures, with high contents of emulsified petroleum substances, were pumped exclusively from boreholes in the turntable area and fuel tanks.

The distribution of the pollution identified during the remediation corresponds to the area identified by the pre-remediation survey. However, the concentration of pollution highly exceeds the original assumptions. The occurrence of LNAPL also in the area around the CLE-3 well behind the turntable (downgradient from the source) proved the high degree of soil and groundwater pollution in the studied area (Fig. 6). This fact was not discovered either by long-term monitoring work in the years 2008–2017 (Kostolanský et al., 2017b) or by the pre-remediation survey (Tupý et al., 2019). It should be noted that the monitoring wells (Kostolanský et al., 2017b) are located mainly in the railyard area, upgradient from turntable and UST. In the originally assumed pollution center, the situation was exactly reverse. Pollution was pumped out from the LEV-1 well (units of liters) and no repeated inflow was observed.

The aim of the paper is to point out the different pollution conditions at the sites, which were found before and during the remediation. During the surveys, no LNAPL was observed in the newly built wells; according to LSPA (2008), the presence of LNAPL in mobile form should by indicated by high levels of pollution in some soil samples (more than 10,000 $mg.kg^{-1}$ C_{10}–C_{40}). Nevertheless, during remediation of both sites, large volumes of pollution were pumped out of the wells (in Leopoldov approx. 5 m^3, in Štúrovo approx. 6.5 m^3). The high degree of pollution was evident in Štúrovo already at the beginning of the drilling works during the remediation. LNAPL flowed into some remediation wells spontaneously immediately after drilling.

During the remediation, several facts were observed, which were inconsistent with theoretical assumptions, based on the characteristics of pollutants and the properties of the geological environment. Laboratory analyses of groundwater samples from Leopoldov collected prior remediation (August 2019), showed low pollution concentrations in the CLE-2 well (compared to the results of other samples). They achieved approximately double IT criteria for NEL-IR and C_{10}–C_{40}, and the concentrations in samples from other wells (ALE-4, ALE7, ILE-1) exceed these values up to 20 times (Tab. 1). In the sample from the CLE-1 well, the concentrations of both parameters were below the ID criterion. However, the highest amount of LNAPL was during the remediation extracted from wells CLE-1 and CLE-2.

Fig. 6. LNAPL plume at model sites (Leopoldov depot) – a) identified by geological survey, b) identified by remediation activities (Tupý et al., 2022).

Tab. 1

Evaluation of groundwater contamination in Leopoldov – selected parameters and wells (Tupý et al., 2022; *ID/IT Criterion from Directive of Ministry of Environment of the Slovak Republic No. 1/2015-7, Anon, 2015).

Well	NEL-IR [mg.l^{-1}]	C_{10}–C_{40} [μg.l^{-1}]
CLE-1	0.119	216
CLE-2	2.22	1 230
ALE-4	2.33	5 600
ALE-7	8.67	7 060
ILE-1	5.05	11 700
ID Criterion*	0.5	250
IT Criterion*	1	500

In Štúrovo the inflow of LNAPL was observed into wells outside the two main contamination clouds, probably due to preferential pathways and the realization of remediation pumping of groundwater from the wells. On the other hand, the inflow of LNAPL into the well in the assumed center of the pollution (under removed USTs) did not occur after its drilling, neither after the start of groundwater pumping and the subsequent depression of its level. LNAPL appeared in this well spontaneously about half a year after its completion despite the fact, that there was no pumping of groundwater from other wells in its vicinity. This may be the result of natural changes in the groundwater level within the changes of the seasons. The volume of LNAPL calculated according to the Directive of the Ministry of Environment of the Slovak Republic No. 1/2015-7 (Anon, 2015) was significantly overestimated for Štúrovo (10.5 m^3 of pollution on an area of 700 m^2). The formula used does not contain any correction in terms of soil or free product properties (Hall et al., 1984; de Pastrovich et al., 1979); moreover, due to the confined aquifer, the values measured in the field do not correspond to reality, but are highly overestimated (Hawthorne et al., 2011). Also, the soil pores are not completely saturated with pollution. According to API (1998), the pores in coarse-grained materials as sandy gravels in both localities are saturated with pollution in the range of 10–56 %. Considering 270 measurements carried out in the research, only in 17 % of the samples was observed the pore saturation by more than 10 %.

Generally, we can say that despite the large volume of pollution that was found in the porous media, there was no spread of the LNAPL, nor contamination dissolved in groundwater. This is consistent with the research of Rice et al. (1995). The authors examined LNAPL contamination clouds at 271 sites with underground storage tanks; their spreading was demonstrated in only 8 % of examinated cases. Similarly, no spread of pollution in dissolved form in groundwater has been reported. During the long-term monitoring of both sites no increased values of oil substances dissolved in groundwater were observed. The reason may be the out washing of more soluble parts of groundwater pollution in the past (Kostolanský et al., 2017a, b). In groundwater samples from wells located approximately 10 m (or even less) from the LNAPL clouddowngradient, only minimal pollution concentrations were observed during the remediation. Pollution in dissolved form was identified only in wells where LNAPL was observed (thickness in order of mm to cm). A more detailed analysis of these samples (treatment of the samples with non-polar silica gel) revealed that part of the contaminant identified by laboratory analyses as petroleum, refers not to petroleum hydrocarbons. These results are likely influenced by pollution degradation products (polar substances) preferentially dissolved in groundwater and detected by C_{10}–C_{40} analysis (Lang et al., 2009; Zemo et al., 2017; Bruckberger et al., 2018).

Conclusion

The distribution of pollution found in the pre-remediation survey at both sites was significantly different from the findings obtained by the remediation. New abundant sources of pollution have been identified at both sites. During the remediation, more than 1 m^3 of pollution was extracted from the newly drilled wells. Pollution in the vicinity of above-ground storage tanks in Leopoldov can be attributed to leakage from them or to the leakage from the diesel pipeline. The occurrence of pollution in Štúrovo is discontinuous, therefore its probable source are not only USTs, but also massive leaks in the railyard during the operation of the depot. The extracted volume of pollution, as well as the rate of spontaneous re-inflow of LNAPL into the boreholes, suggests the local high degree of saturation of the rock pores by the pollution.

In the case of historic railway sites, it is therefore necessary to consider not only well-defined sources of pollution e.g. such as oil and fuel housekeeping and distribution, but also the whole space of the railyard as possible source. Pollution at examined sites is of different nature (diesel, lubricating oil) as well as different degrees of degradation. This fact indicates continuous leaks during the active period of operation. The suggestion for the implementation of remediation should not be based solely on the identification of LNAPL in wells on the site, as it is in accordance with the Directive of the Ministry of Environment of the Slovak Republic no. 1/2015-7. The assessment of the contamination degree must be verified, for example, based on experimental extraction of LNAPL from wells and the continuity of repeated inflow, and (or) on long term evaluation of LNAPL thickness in wells. Costs and duration of remediation activities, projected based on limited data, are thus very hard to estimate and contain high risk of discovering important new facts related to site contamination.

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Porovnanie dvoch modelových environmentálnych záťaží s rozsiahlym znečistením fázou ropných látok – rozsah znečistenia identifikovaný geologickým prieskumom vs. sanačná realita

Prezentovaná štúdia sa zaoberá výsledkami geologických prác v dvoch modelových železničných prevádzkach. Pre tento typ lokalít je charakteristický častý výskyt znečistenia vo forme voľnej fázy ropných látok (VFRL) na hladine podzemnej vody. Je to výsledok únikov veľkého objemu znečistenia (najčastejšie nafty) do životného prostredia.

Vybrané lokality, železničné depá v Leopoldove a Štúrove, majú dlhodobú históriu opráv hnacích koľajových vozidiel. Obe boli v prevádzke už v 50. rokoch 20. storočia a patrili k silne znečisteným prevádzkam s výskytom VFRL na hladine podzemnej vody. Lokality boli v minulosti podrobne preskúmané a od roku 2008 sa na oboch vykonávalo monitorovanie podzemnej vody. V Štúrove boli v okolí podzemných nádrží na pohonné hmoty (PHM), predpokladaného zdroja znečistenia, identifikované 4 vrty, v ktorých sa dlhodobo vyskytovala VFRL s hrúbkou až 870 mm (Kostolanský et al., 2017a). V Leopoldove bola VFRL pozorovaná iba v jednom vrte, ktorý sa nachádza v blízkosti výdajného miesta na PHM (vrt LEV-1). Predpokladaným zdrojom znečistenia boli potrubné rozvody na PHM, resp. úniky pri prečerpávaní PHM (Kostolanský et al., 2017b). Obe lokality boli v roku 2017 zaradené medzi 14 železničných lokalít, na ktorých Ministerstvo životného prostredia Slovenskej republiky (MŽP SR) schválilo realizáciu sanačných prác. Cieľom článku je poukázať na rozdielne stavy znečistenia lokalít, ktoré sa zistili pred sanáciou a počas sanácie.

V roku 2018 sa začali realizovať geologické práce na oboch lokalitách. Prvým krokom bolo uskutočnenie predsanačného prieskumu s aktualizovanou analýzou rizika znečisteného územia. Ťažiskom prác bola realizácia prieskumných a hydrogeologických vrtov, z ktorých sa odoberali vzorky zemín a podzemnej vody. Výsledky predsanačných prieskumov nepoukazovali na prítomnosť veľkého objemu znečistenia vo forme voľnej fázy, no počas realizácie sanačných prác dochádzalo k natekaniu menšieho objemu VFRL do vrtov (hrúbka vrstvy v jednotkách centimetrov). Zároveň sa nepotvrdilo rozširovanie mrakov VFRL a šírenie znečistenia v rozpustenej forme podzemnou vodou.

Výsledky prieskumu v Leopoldove identifikovali rozsiahle znečistenie zemín v pásme prevzdušnenia a nasýtenia, ako aj podzemnej vody ropnými látkami (naftou). Znečistenie bolo identifikované hlavne v priestore pod točňou a pri nadzemných nádržiach na PHM. Výskyt VFRL sa počas prieskumu potvrdil iba v pôvodnom vrte LEV-1 (Tupý et al., 2019). Prieskum v štúrovskom depe identifikoval plošne rozsiahle a výrazné znečistenie zemín pásma nasýtenia a podzemnej vody. Výskyt VFRL bol pozorovaný iba v starých vrtoch na ploche približne 700 m^2. Predpokladaným zdrojom znečistenia boli podzemné jednoplášťové nádrže na PHM (Urban et al., 2019).

V roku 2019 sa začala na oboch lokalitách sanačná etapa geologických prác. V Leopoldove neboli pozorované výrazné samovoľné náteky VFRL do novovybudovaných vrtov. Znečistenie vo forme fázy bolo pozorované v 9 vrtoch (celkovo z 13 novovybudovaných) s maximálnou hrúbkou vrstvy 40 mm. Po začatí sanačných prác a spustení sanačného čerpania podzemnej vody boli pozorované výrazné prítoky znečistenia vo forme VFRL, ktoré natekalo okamžite po odčerpaní, pričom hrúbka vrstvy VFRL dosahovala takmer 80 cm (pri vrte s priemerom paženia 200 mm ide o zhruba 25 l znečistenia). Bolo to najviac zo všetkých vrtov. Postupne, po realizácii overovacích čerpaní podzemnej vody z novovybudovaných vrtov, bolo natekanie VFRL pozorované aj v ďalších vrtoch. Oblasť okolo točne a nadzemných nádrží na PHM sa tak ukázala ako oveľa viac znečistená, ako boli pôvodné predpoklady. Spolu bolo v rámci sanačných prác odčerpaných a likvidovaných viac ako 5 m^3 VFRL, resp. zmesi VFRL a podzemnej vody s vysokým obsahom emulgovaných ropných látok, a to výhradne z vrtov v priestore pri točni a nádržiach na PHM (Tupý et al., 2022).

V Štúrove v niektorých novovybudovaných vrtoch boli pozorované okamžité samovoľné náteky VFRL. V priestore koľajiska pred dnes už neexistujúcou budovou depa sa potvrdila prítomnosť znečistenia vo forme mobilnej VFRL. Vysoký stupeň nasýtenia horninového prostredia znečistením sa potvrdil aj okamžitým (jednotky dní) objavením VFRL v nových vrtoch (do hrúbky takmer 1 000 mm). VFRL sa odčerpávala najskôr bez podporného čerpania podzemnej vody (vo viacerých vrtoch na lokalite po odčerpaní prvotného objemu VFRL už nedošlo k jej ďalšiemu dotekaniu). Z vrtov v okolí podzemných nádrží boli odčerpané zhruba 2 m^3 znečistenia, z vrtov v priestore koľajiska viac ako 4 m^3 (Urban et al., 2021). Zdroj znečistenia identifikovaný počas sanačných prác (koľajisko pred bývalou budovou depa) bol teda dvojnásobne výdatnejší z hľadiska odčerpanej VFRL ako pôvodne uvažovaný zdroj znečistenia (podzemné nádrže na PHM). Okrem uvedených dvoch hlavných zdrojov znečistenia boli na lokalite identifikované aj dva menšie zdroje (produktovod PHM a opravárenská jama). Sanačnými prácami sa tak overilo znečistenie VFRL na približne trojnásobne väčšej ploche, ako sa pôvodne predpokladalo. V práci Maceka a Miličku (2021) je vyhodnotený charakter znečistenia z hľadiska jeho degradácie. Výsledkom je zistenie, že znečistenie pochádza v viacerých rôznych zdrojov. Napriek tomu, že depo je viac ako 10 rokov mimo prevádzky, bola na lokalite odobraná vzorka VFRL bez zjavných známok degradácie. Odhadovaný vek znečistenia na lokalite je od 8 do 48 rokov.

Rozšírenie znečistenia identifikované v priebehu sanačných prác z hľadiska priestoru zodpovedá ploche identifikovanej predsanačnými prieskumami. Koncentrácia znečistenia však vysoko prekračuje pôvodné predpoklady. Počas prieskumov sa nezistila VFRL v novovybudovaných vrtoch (resp. v Leopoldove iba vo forme filmu), prítomnosť VFRL v mobilnej forme mohol podľa LSPA (2008) naznačovať iba vysoký obsah znečistenia v niektorých vzorkách zemín (viac ako 10 000 mg . kg^{-1} $C_{10} – C_{40}$). Napriek tomu bol na oboch lokalitách počas sanačných prác z vrtov odčerpaný veľký objem znečistenia vo forme VFRL. V rámci realizácie prác sa ukázali aj viaceré skutočnosti, ktoré boli v nesúlade s teoretickými predpokladmi založenými na charakteristikách znečisťujúcich látok a vlastnostiach geologického prostredia. V Leopoldove bola pred sanáciou koncentrácia znečistenia rozpusteného v podzemnej vode vo vrtoch CLE-1 a CLE-2 relatívne nízka (v CLE-1 nižšia ako ID kritérium smernice MŽP SR č. 1/2015-7), z týchto vrtov sa však počas sanácie odčerpal najväčší objem VFRL. V Štúrove bolo pozorované natekanie VFRL aj do vrtov mimo dvoch hlavných kontaminačných mrakov, pravdepodobne v dôsledku preferenčných miest a realizácie sanačného čerpanie podzemnej vody z vrtov. Natekanie VFRL do vrtu v centre znečistenia sa ale nezistilo po jeho odvŕtaní ani po spustení čerpania podzemnej vody a následnom znižovaní jej hladiny. VFRL sa v tomto vrte objavila samovoľne asi pol roka po jeho realizácii napriek tomu, že v jeho okolí sa nečerpala podzemná voda z iných vrtov. Porovnanie prieskumov a sanačných prác poukazuje na rôzne druhy neistôt, ktoré je nutné brať do úvahy pri vyhodnocovaní stupňa znečistenia lokality a plánovaní sanačných prác.

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