ISSN 2720-3581

JOURNAL OF GEOTECHNOLOGY AND ENERGY

FORMERLY AGH DRILLING, OIL, GAS

2023, vol. 40, no. 3

WYDAWNICTWA AGH

KRAKOW 2023

ISSN 2720-3581

JOURNAL OF GEOTECHNOLOGY AND ENERGY

FORMERLY AGH DRILLING, OIL, GAS

2023, vol. 40, no. 3

WYDAWNICTWA AGH

KRAKOW 2023

The "Journal of Geotechnology and Energy" (formerly "AGH Drilling, Oil, Gas") is a quarterly published by the Faculty of Drilling, Oil and Gas at the AGH University of Krakow, Poland. Journal is an interdisciplinary, international, peer-reviewed, and open access. The articles published in JGE have been given a favorable opinion by the reviewers designated by the editorial board.

Publisher

AGH University Press

Linguistic corrector: *Aeddan Shaw*
Technical editor: *Kamila Zimnicka*
Desktop publishing: *Munda*
Cover design: *Paweł Sepielak*

ISSN: 2720-3581
DOI: https://doi.org/10.7494/jge

Journal website: https://journals.agh.edu.pl/jge

Wydawnictwa AGH (AGH University Press)
al. A. Mickiewicza 30, 30-059 Kraków
tel. 12 617 32 28, 12 636 40 38
e-mail: redakcja@wydawnictwoagh.pl
www.wydawnictwo.agh.edu.pl

CONTENTS

Journal of Geotechnology and Energy | vol. 40 | no. 3 | 2023 | pp. 5–12

https://doi.org/10.7494/jge.2023.40.3.6041

Łukasz Łukańko

AGH University of Krakow, Faculty of Drilling, Oil and Gas
ORCID: 0000-0003-0689-7931
Corresponding author: lukanko@agh.edu.pl

Jan Macuda

AGH University of Krakow, Faculty of Drilling, Oil and Gas
ORCID: 0000-0002-8180-8014

ASSESSING THE IMPACT OF EXPRESSWAY CONSTRUCTION AND OPERATIONS ON GROUNDWATER INTAKE

Date of submission:
20.08.2023

Date of acceptance:
7.09.2023

Date of publication:
29.09.2023

https://journals.agh.edu.pl/jge

Expressways represent significant public investments contributing to the socio-economic development of a country. However, their construction and operations exert detrimental effects stemming from the road surface onto the adjacent groundwater environment.

To mitigate these adverse environmental consequences, extant legal restrictions are factored in during the expressway design phase, accompanied by the implementation of modern technical and organizational solutions. As a pivotal legal instrument, the environmental impact assessment is mandated in the procedural framework for obtaining approval on environmental conditions during expressway construction. The precision in evaluating the negative impact of an expressway on distinct environmental elements hinges on the depth of the assessment, influencing the nature and extent of planned protective measures.

In many instances, supplementary environmental risk assessments are conducted to bolster the investment process. This study aims at discerning the specific impact of expressway construction on nearby groundwater intake. To achieve this, an exhaustive assessment of contaminant migration times from the land surface to the aquifer and within the aquifer itself was executed. Subsequently, a proposal for aquifer monitoring was formulated based on the findings to enable the early detection of potential shifts in groundwater quality, facilitating timely preventive interventions.

Keywords: expressway, environmental impact, pollution migration, groundwater impact

1. Introduction

Expressways represent significant public investments contributing to the socio-economic development of a country. However, their construction and operations exert detrimental effects on various environmental elements, notably impacting both the groundwater and surface water in their proximity. Liquid and solid pollutants emanating from vehicular activities are systematically washed from the road surface into the adjacent groundwater environment.

To mitigate these adverse environmental consequences, existing legal restrictions are factored in during the expressway design phase, accompanied by the implementation of modern technical and organizational solutions. As a pivotal legal instrument, the environmental impact assessment is mandated in the procedural framework for obtaining approval on environmental conditions during expressway construction. However, the precision in evaluating the negative impact of the expressway on individual environmental elements hinges on the depth of the assessment, thereby influencing the nature and extent of planned protective measures.

This challenge becomes particularly apparent when assessing the negative impact of a designed road on the aquatic environment. Consequently, this article provides a practical example illustrating the calculation of migration times for pollutants from the land surface to the aquifer and within the aquifer itself. Leveraging the results of these calculations, the article proposes aquifer monitoring as a proactive measure for the early detection of potential changes in groundwater quality, facilitating prompt and effective preventive interventions.

2. Technical characteristics of the groundwater intake

This study investigates the hydrogeological characteristics and operational parameters of a groundwater intake system comprising four wells S-1, S-2, P-2, and P-3 (Fig. 1). The wells, situated at depths ranging from 17 to 20 m below sea level, draw water from an aquifer composed of gravels with pebbles [1, 2, 4, 5, 17, 18]. The study analyses key parameters, including aquifer thickness, filtration coefficient, and depression funnel radius, to assess the efficiency and sustainability of the groundwater extraction system.

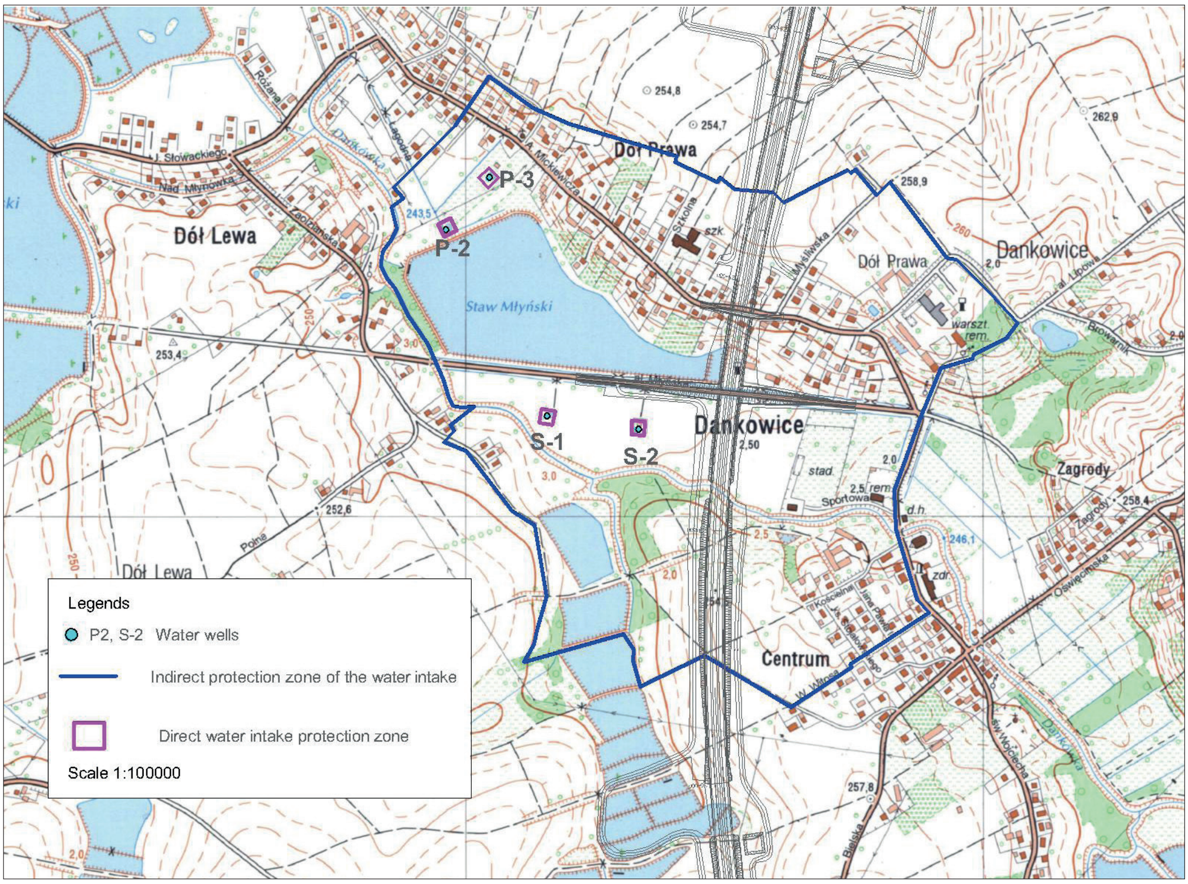


Fig. 1. Water well location in the vicinity of an expressway [4, 5]

3. Technical characteristics of the proposed expressway

The analysed section of the proposed expressway will traverse a newly planned corridor passing through the indirect protection zone of the underground water intake, agricultural areas, forested regions, and zones with dispersed development. It will be characterized by the following parameters [3, 13]:
- technical class: S 2/2 with a reserve for 2/3,
- design speed: V_p = 100 km/h,
- authoritative speed: V_m = 110 km/h,
- load: 115 kN/m²,
- normal section type: dual carriageway,
- carriageway width: 2 × 3.50 m,
- dividing lane width: 12 m with 2 × 0.5 m bands (with provision for a third lane),
- width of emergency lane: 2.50 m,
- width of hard shoulder: minimum 1.60 m,
- crown width: minimum 35 m.

For the designed section of the expressway within the zone of indirect protection of the underground water intake, a sealed rainwater drainage system has been planned [3, 13]. Its purpose is to collect water from the road surface, dividing strip, and shoulders. Rainwater and snowmelt will be directed outside the intermediate protection zone and undergo treatment to meet the legally required standards before discharge into the environment [3, 13]. Additionally, sealed roadside ditches will be implemented on both sides of the road to manage rainwater and snowmelt runoff from the embankments of the expressway.

The projected vehicle traffic for the first year of use along the section of the designed road in the intermediate zone of the intake is expected to be 35,934 vehicles per day [3].

4. The characterisation of the geological and hydrogeological conditions

The geological structure of the area comprises Carboniferous, Tertiary (Neogene), and Quaternary formations. The older subsoil consists of productive Carboniferous formations, lying at a depth of approximately 400 m. Lithologically, these formations are composed of claystone, siltstone, and sandstone accompanying coal seams [15].

Tertiary (Neogene) formations are represented by Miocene sediments, known as the Skawina strata, primarily consisting of clays, siltstones, with thin inserts of dust and sand. Their thickness varies, ranging from 350 to 380 m, depending on the floor formation of the Carboniferous formations [15].

Quaternary formations, directly on Miocene formations, include Pleistocene and Holocene sediments. Pleistocene sediments, associated with the Krakow glaciation, consist of a continuous layer of sand and gravel, with pebbles and gravels at the bottom. The average thickness of Pleistocene sand and gravel formations is about 7 m. Above these formations, cohesive and organic Holocene soils are found, with thicknesses varying from approximately 5.0 to 7.5 m [15]. The geological cross-section in the vicinity of the planned expressway is presented in Figure 2.

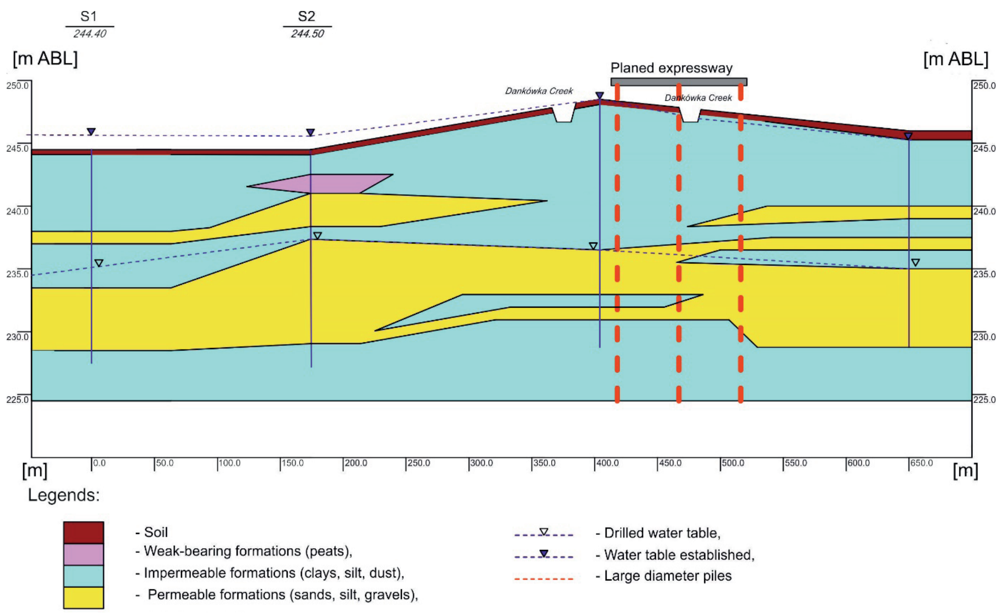


Fig. 2. Geological cross-section in the vicinity of the planned expressway [3, 15]

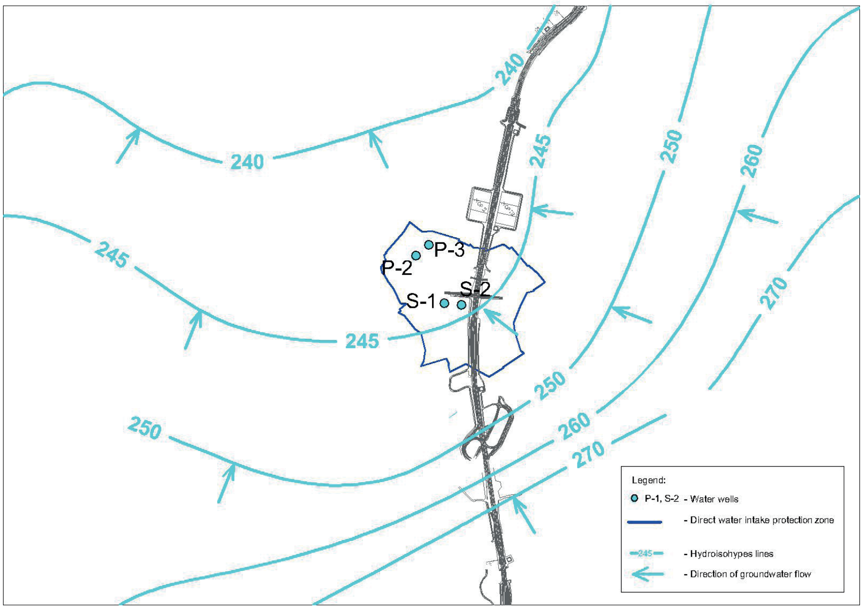


Fig. 3. The diagram shows the direction of groundwater flow [10]

Three main aquifers associated with permeable formations – Quaternary, Tertiary (Neogene), and Carboniferous – were identified in the area. Due to the impact of the planned expressway, the Quaternary aquifer, consisting of two layers of sand and gravel separated by layers of clay or dust, is crucial for analysis [9, 11, 15].

The hydrogeological map, based on current measurements from dug and drilled wells in the area, indicates that the water table generally follows the terrain configuration. It approaches the surface in downgradient areas and remains several metres below the terrain surface in upgradient areas. Groundwater flows from the south and southeast towards the north and northwest, i.e., toward the Vistula River, the primary drainage base, and locally towards smaller watercourses, as shown in Figure 3 [10]. The wells of the analysed water intake are unfavourably situated in the direction of water flow from the planned expressway location. Hydraulic gradients are generally low, ranging from $I = 0.002$ to $I = 0.01$ [1, 2].

5. Assessment of the migration time of contaminants from the land surface to and in the aquifer

To assess the migration time of potential pollutants that may infiltrate the aquifer due to the operation of the planned expressway in the indirect protection zone of the discussed water intake, calculations were conducted for both the time of seepage of pollutants from the land surface and the time of migration of pollutants within the aquifer. The time of seepage from the land surface to the groundwater was determined using the N.N. Bindeman method, modified by T. Macioszczyk [12, 16].

Calculations of the vertical migration time (t) of pollutants were conducted following the relationships outlined by Małecki [11, 12, 14, 16]:

$$t = \frac{m}{V_a} \left[\text{year}\right] \tag{1}$$

where:
- m – thickness of the aeration zone [m],
- V_a – seepage velocity [m/year].

$$V_a = \frac{1}{W_o} \cdot \sqrt[3]{\omega^2} \tag{2}$$

where:
- W_o – volumetric moisture content [–],
- ω – annual effective infiltration [m/year].

$$\omega = P \cdot w \tag{3}$$

where:
- P – annual rainfall [m/year],
- w – precipitation rate [–].

$$t = \frac{m \cdot W_o}{\sqrt[3]{(P \cdot w)^2 \cdot k}} \tag{4}$$

where:
- k – filtration coefficient of rocks in the aeration trephine [m/year].

The calculated time of vertical migration of contaminants from the land surface to the groundwater in the area of the designed road ranges between 5 and 23.1 years.

The analysis of contaminant migration time in the aquifer considered two scenarios [12]:
– variant I: decommissioned wells,
– variant II: exploitation of water by bored wells.

To determine the time for the migration of contaminants from the roadside ditch of the designed expressway in the scenario where both intake wells are decommissioned, the equation derived from Darcy's law was utilized. Through the transformation of Darcy's law, the formula for the migration velocity of contaminants in groundwater was obtained [12, 16]:

$$V = k \cdot I \tag{5}$$

where:
V – pore debris flow rate [m/day],
k – filtration coefficient – 26.52 m/day,
I – hydraulic gradient – 0.007 [–].

Taking into account the porosity of the aquifer rocks, the formula for flow velocity takes the form:

$$V_{actl} = \frac{V}{n_0} \tag{6}$$

where:
V_{actl} – actual pore contaminant velocity [m/day],
V – contaminant flow velocity in pores [m/day],
n_0 – effective porosity of aquifer – 0.2.

To transform both equations, we derive the formula for the velocity of contaminants in the aquifer:

$$V_{actl} = \frac{k \cdot I}{n_0} = \frac{26.53 \cdot 0.007}{0.2} = 0.93 \text{ m/day} \tag{7}$$

The migration time of contaminants in groundwater was determined based on the equation:

$$t = \frac{L}{V_{actl}} = \frac{125.6}{0.93} = 136 \tag{8}$$

where:
t – migration time of contaminants in groundwater [day],
L – path travelled by groundwater – 125.6 m,
V_{actl} – actual pore contaminant flow velocity – 0.93 m/day.

Assuming a groundwater velocity of 0.93 m/day in the second aquifer captured by the wells, contaminants migrating with the groundwater are projected to reach well No. S-1, located 300 m away from the roadside ditch, in approximately 323 days.

The time of migration of contaminants in groundwater, while exploiting wells S-1 and S-2 was determined using the method developed by A. Kleczkowski [7, 8]. The calculations were conducted under the following assumed conditions [7, 8]:
– the aquifer is considered unconfined, isotropic, and homogeneous,
– water movement is steady, with water particles following the current lines,
– the pumping rate and groundwater flow are constant,
– contaminants do not sorb or react with the rock,
– dispersion of contaminants in the pore medium can be neglected (reciprocating flow).

A coordinate system was established based on hydroisohips, with the *y*-axis perpendicular to the direction of water flow (parallel to the hydroisohypse), and the *x*-axis directed upstream of the natural groundwater flow. The system's origin is positioned in the axis of the wellbore (Fig. 4).

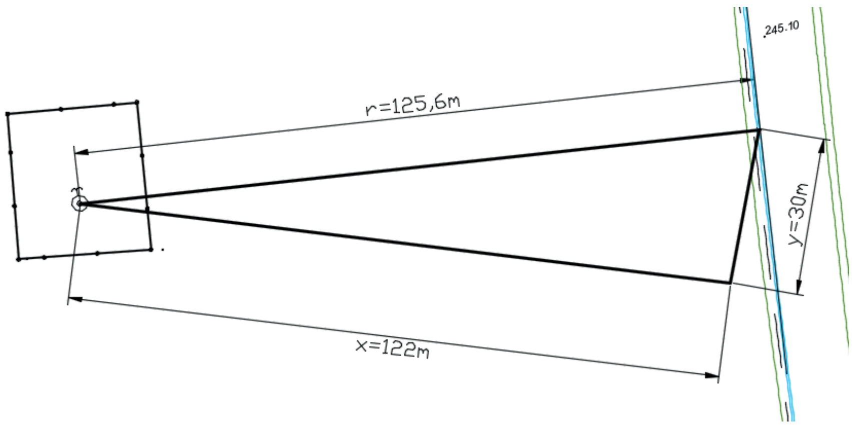


Fig. 4. Method of determining the values of *x*, *y* and *r* using the Kleczkowski method [8]

To determine the migration time, the first step involves calculating the unit discharge of the natural groundwater stream and the auxiliary value r_0. The unit discharge q of the natural groundwater flux is determined by the formula [8]:

$$q = k \cdot m \cdot I = 26.52 \cdot 7 \cdot 0.007 = 1.3 \text{ m}^3/\text{day} \qquad (9)$$

where:
k – aquifer filtration coefficient – 26.52 m/day,
m – thickness of aquifer – 7 m,
I – hydraulic gradient – 0.007 [–].

The auxiliary value of r_0 is calculated from the formula [8]:

$$r_0 = \frac{Q}{2\pi q} = \frac{672}{2 \cdot 3.14 \cdot 1.3} = 82.3 \text{ m} \qquad (10)$$

where:
Q – discharge of well No. 2 – 627 m^3/day.

On the basis of Minkin's nomogram, from the graph for the values x/y = 122/30 = 4.0 and r/r_0 = 125.6/82.3 = 1.5 it is possible to read the value of the dimensionless time t for the pollutant to reach the well, which is 3.7. The actual time for the pollutant to reach the well (t) from the expressway ditch according to the formula will thus be [8]:

$$t = \frac{\tau \cdot n_0 \cdot m \cdot r_0^2}{Q} = \frac{3.7 \cdot 0.2 \cdot 7 \cdot 6773}{672} = 54 \qquad (11)$$

where:
t – actual time for the pollutant to reach the well [day],
n_0 – effective porosity of the aquifer – 0.2.

Calculations of contaminant migration in the aquifer reveal that the groundwater flow time from the ditch of the designed expressway to well No. 2 is 54 days. The groundwater flow velocity in the aquifer was determined based on the method by Kleczkowski [7, 8].

For well S-1, the migration velocity is assumed to be similar to that for well S-2 with a velocity of v = 2.32 m/day. Given that the well is 300 m from the roadside ditch, and assuming well S-2 will be decommissioned, contaminants are expected to flow into the intake after a period of 130 days.

$$t = \frac{L}{v} = \frac{300}{2.2} = 129.3 \text{ day} \qquad (12)$$

6. Groundwater risk assessment in the area of the analysed water intake

The degree of vulnerability of water to contamination is determined by assessing the approximate time it takes for contaminants to reach an aquifer from the land surface. By understanding the vertical migration time of contaminants from the land surface to individual aquifers, it becomes possible to evaluate the level of threat to the exploited groundwater intakes situated closest to the planned expressway. Table 1 illustrates the hazard classes and resistance of groundwater to contamination according to Kleczkowski [7].

After analysing the results of the vertical seepage time from the ground surface to the first and second aquifers in the considered area of the indirect groundwater intake protection zone, it is evident that the first aquifer belongs to the first or second groundwater hazard class [6]. However, since water from this aquifer is not being extracted, it is not relevant to the overall analysis.

Regarding the second aquifer, classified as a usable aquifer with a migration time of contaminants ranging from 5 to 22.5 years depending on the threat's location, it is considered to be of medium groundwater vulnerability. Both its vulnerability class and resistance to pollution are classified as medium.

Table 1. Classes of threat and resistance of groundwaters to pollution [7]

The average time of water migration from of land surface to the top of the aquifer [years]	Symbol class	Hazard class of groundwater	Vulnerability class groundwater to contamination	Resistance class of groundwater to pollution
<2	A1	very severely under threat	very high	very low
2–5	A2	high risk	high	low
5–25	B	moderately endangered	medium	medium
25–100	C	low risk	low	high
>100	D	practically not threatened	very low	very high

Another method used in Poland to define groundwater vulnerability is the classification by the Polish Geological Institute in the Hydrogeological maps of Poland on a scale of 1 : 50,000. According to this method, three degrees of vulnerability to groundwater pollution are distinguished [10]:
– very high: <5 years,
– high: 5–25 years,
– medium: 25–50 years.

In accordance with the above, the first aquifer in the indirect protection zone of the Dankowice groundwater intake is classified as having a very high degree of susceptibility to contamination, whereas the second exploited one is classified as having a medium degree of susceptibility to contamination.

7. Summary

The calculations for the migration time of contaminants from the land surface to the aquifer indicate that the aquifer, from which groundwater is withdrawn by wells S-1 and S-22, is well isolated by a layer of clay. The vertical migration time of contaminants from the ground surface to wells S-1 and S-2 was determined to be 23 and 21.5 years, respectively. For the designed monitoring wells, allowing observation of changes in groundwater quality due to the operation of the designed expressway, the migration times are 14.5 and 22.5 years, respectively.

Calculations for the migration time of contaminants from a 2 m deep ditch were also performed, resulting in pollutant migration times of 5 and 12.7 years for the first and second aquifers, respectively. It is important to note that contaminants with a density lower than water, such as petroleum hydrocarbons, will not have the opportunity to migrate from the first aquifer to the second. Only substances readily soluble in water will be able to migrate to the second aquifer [12].

The horizontal migration time of contaminants in the second aquifer was calculated for two scenarios: during the exploitation of groundwater by wells S-1 and S-2 and in the case of their decommissioning. In the case of exploitation, it is 130 days for well S-2 and 130 days for well S-1, respectively. When both wells are decommissioned, the contaminant migration time in the second aquifer will be 136 and 323 days. This high rate of contaminant migration in the aquifer is influenced by the geological structure, with the aquifer being exploited primarily consisting of gravels and sands with a very high filtration coefficient (k = 26.52 m/day).

The calculations for contaminant migration emphasize that the vertical seepage time, ranging from 5 to 23 years depending on the calculation variant, predominantly influences the migration time of contaminants to groundwater. The potential migration of contaminants from the ditch to the aquifer exploited by wells S-1 and S-2 is estimated to be 5 years. Due to very small magnitudes (54 and 130 days), the time of horizontal migration of contaminants can be disregarded in the calculations, and it can be assumed that the total time of migration of contaminants to the wells equals the time of vertical migration.

Acknowledgments: The paper was performed within the framework of AGH University of Krakow statutory research grant No. 16.16.190.779 Faculty of Drilling, Oil and Gas, Department of Petroleum Engineering.

References

[1] *Dokumentacja hydrogeologiczna zasobów wód podziemnych ujęcia z utworów czwartorzędu w miejscowości Dankowice*. Przedsiębiorstwo Zaopatrzenia Rolnictwa w Wodę „Wodrol", Kraków 1974 [unpublished].
[2] *Dokumentacja hydrogeologiczna zasobów wód podziemnych ujęcia z utworów czwartorzędu w miejscowości Dankowice*. Przedsiębiorstwo Zaopatrzenia Rolnictwa w Wodę „Wodrol", Kraków 1982 [unpublished].
[3] *Dane Inwestora dotyczące budowy drogi ekspresowej S1 od węzła „Kosztowy II" w Mysłowicach do węzła „Suchy Potok" w Bielsku-Białej*. Generalna Dyrekcja Dróg Krajowych i Autostrad oddział w Katowicach, Katowice 2018 [unpublished].
[4] Jakimów W.: *Dodatek nr 2 do dokumentacji hydrogeologicznej i dodatku nr 1 ustalających zasoby eksploatacyjne ujęcia wód podziemnych, składającego się z dwóch studni S-1 i S-2, zlokalizowanego w miejscowości Dankowice*. Zakład Prac Geologicznych, Tychy 2016 [unpublished].
[5] Jakimów W.: *Dodatek nr 2 do dokumentacji hydrogeologicznej i dodatku nr 1 ustalających zasoby eksploatacyjne ujęcia wód podziemnych, składającego się z dwóch studni P-2 i P-3, zlokalizowanego w miejscowości Dankowice*. Zakład Prac Geologicznych, Tychy 2016 [unpublished].

[6] Kacprzyk W.: *Praktyczne zastosowanie algorytmu oceny ryzyka w ocenie zagrożenia ludzi i środowiska w wyniku katastrofy transportowej z uwolnieniem substancji niebezpiecznych*. Zakład Polityki Ekologicznej, Instytut Ochrony Środowiska, Warszawa 2000.
[7] Kleczkowski A.: *Ochrona wód podziemnych w Polsce. Stan i kierunki badań*. Prace CPBP, z. 56. Warszawa – Kraków 1991.
[8] Kleczkowski A.: *Ochrona wód podziemnych*. Wydawnictwa Geologiczne, Warszawa 1984.
[9] Kondracki J., Richling A.: *Regiony fizycznogeograficzne (1 : 1 500 000)*. In: *Atlas Rzeczypospolitej Polskiej*, Warszawa: Główny Geodeta Kraju, 1994.
[10] *Mapa hydrogeologiczna Polski w skali 1 : 50 000: Arkusz Kęty*, t. 993. Państwowy Instytut Geologiczny, Warszawa 2000.
[11] *Mapa hydrogeologiczna Polski 1 : 50 000. Pierwszy poziom wodonośny. Wrażliwość na zanieczyszczenie i jakość wód. Objaśnienia. Arkusz Kęty*, t. 993. Państwowy Instytut Geologiczny, Warszawa 2013.
[12] Małecki J.J., Nawalany M., Witczak S., Gruszczyński T.: *Wyznaczanie parametrów migracji zanieczyszczeń w ośrodku porowatym dla potrzeb hydrogeologicznych i ochrony środowiska. Poradnik metodyczny*. Uniwersytet Warszawski. Wydział Geologii, Warszawa 2006.
[13] *Opracowanie koncepcji programowej dla zadania p.n. Budowa drogi ekspresowej S1 od węzła Kosztowa II w Mysłowicach do węzła Suchy Potok w Bielsku-Białej*. Multiconsult, 2018 [unpublished].
[14] Pazdro Z., Kozerski B.: *Hydrogeologia ogólna*. Wydawnictwa Geologiczne, Warszawa 1990.
[15] *Projekt robót geologicznych w celu określenia warunków geologiczno-inżynierskich i hydrogeologicznych dla zadania pod nazwą: „Budowa drogi ekspresowej S-1 od węzła Kosztowy II w Mysłowicach do węzła Suchy Potok w Bielsku-Białej" w granicach województwa śląskiego*. Pracownia Geologiczno-Inżynierska Sp. z o.o. Sp. k., Łódź 2018 [unpublished].
[16] Rogoż M.: *Metody obliczeniowe w hydrogeologii*. Wydawnictwo Śląsk, Katowice 2012.
[17] Sobol K.: *Dodatek nr 1 do dokumentacji hydrogeologicznej ustalającej zasoby eksploatacyjne ujęcia wód podziemnych, składającego się z dwóch studni S-1 i S-2, zlokalizowanego w miejscowości Dankowice*. Bielsko-Biała 2012 [unpublished].
[18] Sobol K.: *Dodatek nr 1 do dokumentacji hydrogeologicznej ustalającej zasoby eksploatacyjne ujęcia wód podziemnych, składającego się z dwóch studni P-2 i P-3, zlokalizowanego w miejscowości Dankowice*. Bielsko-Biała 2012 [unpublished].

Journal of Geotechnology and Energy | vol. 40 | no. 3 | 2023 | pp. 13–17

https://doi.org/10.7494/jge.2023.40.3.6040

Jan Macuda

AGH University of Krakow, Faculty of Drilling, Oil and Gas
ORCID: 0000-0002-8180-8014

Łukasz Łukańko

AGH University of Krakow, Faculty of Drilling, Oil and Gas
ORCID: 0000-0003-0689-7931
Corresponding author: lukanko@agh.edu.pl

GROUNDWATER CONTAMINATION BY BTEX HYDROCARBONS AND PHENOL AT FORMER GASWORKS SITES IN BYDGOSZCZ

Date of submission:
20.08.2023

Date of acceptance:
7.09.2023

Date of publication:
29.09.2023

https://journals.agh.edu.pl/jge

Abstract: This paper addresses the historical environmental impact of Bydgoszcz's 'Old Gasworks,' located on Jagiellońska Street on the Brda River—one of Poland's oldest and longest-operating gas production facilities. Municipal gas derived from dry coal distillation served both municipal and industrial purposes until 1973. However, the production process, marked by significant nuisances, particularly affected the ground and water environment. Pollutants, primarily organic compounds such as aromatic hydrocarbons, including PAHs (polycyclic aromatic hydrocarbons), and BTEX hydrocarbons (benzene, toluene, ethylbenzene, xylenes), phenol and mineral oil, entered the environment through equipment failures, leaks, and the improper storage of wastewater and technological waste.

One of the major sources of contamination was inadequately executed construction activities related to the dismantling of installations and the liquidation of sewage and waste storage tanks. This paper presents the findings of a comprehensive study focusing on hydrocarbon concentrations in groundwater at the 'Old Gasworks' in Bydgoszcz and proposes effective methods for treating the water environment.

Keywords: dry coal distillation, water pollution, aromatic hydrocarbons, groundwater remediation

1. Introduction

The 'old gasworks' in Bydgoszcz, located on Jagiellońska Street along the Brda River, stands as one of Poland's oldest and longest-operating gas facilities. Commencing operations on 1 October 1860, it continued to produce municipal gas until 1973 [1–3]. The gas was manufactured through the dry distillation of hard coal at temperatures ranging from 900 to 1 100°C, employing specially constructed coke ovens [4–6]. This process yielded coke (70–80%), coke oven gas (12–18%) and by-products such as post-gas water (3–5%), post-gas tar (2.5–4.5%), benzol (0.8–1.4%) and ammonia (0.2–0.4%) from coal [1, 4, 5, 7–10]. The post-gas water comprised a mixture of ammonia, ammonium salts, pyridine, phenols, and other compounds [11]. Conversely, post-gas tar is a blend consisting primarily of aromatic hydrocarbons, phenols, pyridine, and quinoline bases [5, 12]. These by-products stand as the most significant source of pollution in the areas where these plants were situated. The town gas produced within these facilities served both municipal and industrial purposes in Bydgoszcz.

However, its production was associated with a high level of nuisance, particularly for the ground and water environment. Pollutants from operational plants primarily entered the environment due to equipment failures, leaks, and improper storage of wastewater and technological waste [1, 3]. During this period, technological waste was typically stored on the gas plant site in specially prepared pits and environmentally toxic solid waste was often utilized for land levelling [13, 14].

Nevertheless, one of the major contributors to soil and water contamination at the 'old gasworks' site resulted from poorly executed construction works linked to the dismantling of installations and the decommissioning of sewage and waste storage tanks [1, 2, 13, 15]. The primary contaminants identified in the vicinity of such installations include organic compounds, particularly aromatic hydrocarbons such as PAHs (polycyclic aromatic hydrocarbons) and BTEX hydrocarbons (benzene, toluene, ethylbenzene, xylenes), phenol, and mineral oil.

Contaminants persisting in the soil and in inadequately decommissioned sewage and industrial waste ponds remain active sources of groundwater environment degradation [1, 3, 13]. These contaminants, moving in the direction of groundwater flow toward the Brda River, continue to pose a significant threat to groundwater and surface water quality.

2. Location of the 'old gasworks'

The site where the facility for the production of city gas through dry coal distillation was situated is located in Bydgoszcz on Jagiellońska Street, directly adjacent to the Brda River (Fig. 1) [3, 15]. Currently, the remnants of the original industrial installation have been appropriately secured and are of a heritage nature. The existing industrial buildings have undergone renovation and are now utilized as workshops and offices. The surrounding area has been repurposed for the construction of new internal roads, footpaths, and green spaces.

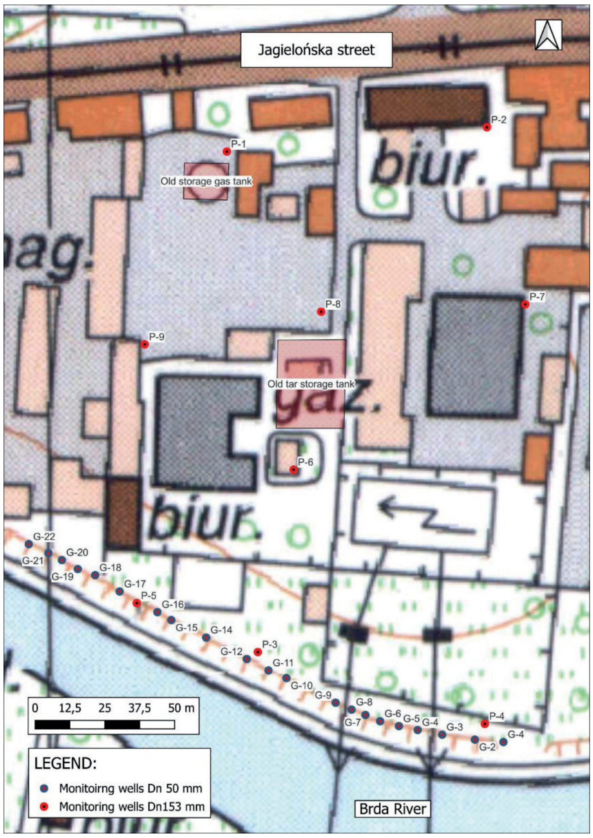


Fig. 1. Map indicating the locations of the monitoring wells used for groundwater sampling [3]

3. Characterization of geological and hydrogeological conditions

The geological structure within the vicinity of the 'old gasworks' in Bydgoszcz has been examined through several monitoring wells to a depth of 9.0 m below ground level [14, 16]. During these geological investigations, sandy and sandy rubble deposits were identified from the ground surface to a depth of 0.5–2.6 m. Immediately below these deposits are Quaternary sandy and clayey silts, ranging in thickness from 0.8 to 6.6 m. Further down, there are fine, medium, and coarse-grained sands containing gravel and pebbles with thicknesses varying from 0.7 to over 7.6 m. These formations rest on moraine cobbles or directly on Pliocene chert clays, drilled to depths between 6.2 and 8.7 m [13, 16].

Hydrogeological conditions in the 'old gasworks' area are characterized by the presence of a Quaternary aquifer, with the water table being free or slightly confined at depths ranging from 1.7 to 3.6 m. The aquifer primarily receives water from surface water and precipitation, with water runoff flowing in a southerly and south-westerly direction toward the Brda River. The filtration coefficient of the aquifer ranges from $3 \cdot 10^{-4}$ m/s to $8 \cdot 10^{-4}$ m/s [13–16].

4. Extent of groundwater investigations carried out at the 'old gasworks' site

Physicochemical analyses of groundwater samples taken from piezometers located in the 'old gasworks' area in Bydgoszcz were conducted in 2013, following the PN ISO 5667 standard. Water samples for the tests were collected after pumping three volumes from each observation well. This means that the samples were not collected from a specific depth [10].

To evaluate the extent of groundwater contamination with polycyclic aromatic hydrocarbons in the 'old gasworks' area, 25 groundwater samples were collected for physicochemical analyses. The locations of the monitoring wells are illustrated in Figure 1. Monitoring wells numbered P-1 to P-9 are evenly distributed across the gasworks site, while monitoring wells numbered G-1 to G-22 were strategically positioned in the test barrier along the Brda River to assess the pollutant load flowing from the site into surface water [3].

Water samples were collected following established procedures, employing a specialized pumping set from Grundfos, and placed into specially prepared glass containers. Subsequently cooled to 4°C, these samples were then transferred to the laboratory at the AGH University of Krakow for the determination of BTEX hydrocarbon and phenol concentrations

5. Test methodology for BTEX and phenol

Water samples for BTEX determination underwent extraction with pentane in separators on a KS 250 Basic shaker from IKA Labortechnik for 10 min. The prepared samples were then chromatographically analysed using a Model STAR 3400 CX gas chromatograph with a SATURN 2000 mass detector from Varian-HP-5MS 30m column, ID 0.250 mm, 0.25 µm film [3, 15].

Similarly, water samples designated for phenol determination were extracted with carbon tetrachloride in separators on a KS 250 Basic shaker from IKA Labortechnik for 10 minutes. Subsequently, the prepared samples were chromatographically analysed using the same Model STAR 3400 CX gas chromatograph.

The results of the groundwater sample analyses collected from monitoring wells in the 'old gasworks' area in Bydgoszcz for BTEX and phenol hydrocarbons are presented in Tables 1 and 2. The quality of groundwater in the studied monitoring wells was assessed based on the Regulation of the Minister of Maritime Economy and Inland Navigation dated 11 October 2019, which outlines the criteria and methods for assessing the status of groundwater bodies (Dz.U. 2019 item 2148). For the monitoring wells, due to the presence of BTEX and phenol compounds, the groundwater was classified as V groundwater quality class [11]. For BTEX, Class V of groundwater quality means that the concentration of pollutants is higher than 0.1 mg/l, and for phenol, it's higher than 0.05 mg/l.

Table 1. Concentration of BTEX and phenol in water samples analysed from 7 monitoring wells located in the area of the 'old gasworks' in Bydgoszcz [3, 11]

Substation	Monitoring wells (groundwater quality class)								
	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9
Benzene [µg/dm^3]	No sampling possible (borehole filled with soil)	<0.2 (V)	1986.2 (V)	No sampling possible (borehole filled with soil)	879.1 (V)	782.5 (V)	28.4 (V)	608.0 (V)	2.2 (V)
Toluene [µg/dm^3]		0.5 (V)	1173.5 (V)		547.6 (V)	491.7 (V)	31.7 (V)	320.1 (V)	1.7 (V)
Ethylbenzene [µg/dm^3]		<0.2 (V)	162.2 (V)		173.3 (V)	588.3 (V)	12.1 (V)	37.0 (V)	0.9 (V)
Xylene [µg/dm^3]		0.6 (V)	1086.7 (V)		716.7 (V)	509.4 (V)	33.7 (V)	228.3 (V)	1.8 (V)
Phenol [µg/dm^3]		<0.5 (V)	11.3 (V)		7.1 (V)	17.3 (V)	2.4 (V)	3.0 (V)	0.8 (V)

Table 2. Concentrations of BTEX and phenol in water samples collected for testing from monitoring wells situated in the test barrier along the Brda River in the area of the 'old gasworks' in Bydgoszcz [3, 11]

Substation	Monitoring wells (groundwater quality class)																
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G14	G15	G16	G17	G18
Benzene [μg/dm³]	28.2 (V)	4.7 (V)	56.5 (V)	43.5 (V)	31.6 (V)	12.2 (V)	312.6 (V)	2.7 (V)	1.3 (V)	82.6 (V)	1 237 (V)	2 864 (V)	3 281 (V)	1 044 (V)	657 (V)	963 (V)	837 (V)
Toluene [μg/dm³]	<0.2 (V)	1.4 (V)	1.6 (V)	4.6 (V)	1.1 (V)	2,6 (V)	1.5 (V)	0.6 (V)	0.8 (V)	6.7 (V)	648 (V)	1 365 (V)	1 818 (V)	821 (V)	472 (V)	549 (V)	511 (V)
Ethylbenzene [μg/dm³]	<0.2 (V)	0.3 (V)	9.7 (V)	5.3 (V)	1.4 (V)	0.5 (V)	17.4 (V)	<0.2 (V)	0.3 (V)	2.8 (V)	106 (V)	97.4 (V)	143 (V)	134 (V)	87.9 (V)	178 (V)	231 (V)
Xylene [μg/dm³]	0.5 (V)	1.9 (V)	2.2 (V)	6.8 (V)	1.2 (V)	0.8 (V)	22.4 (V)	0.5 (V)	0.5 (V)	11.7 (V)	443 (V)	1 011 (V)	1 126 (V)	866 (V)	433 (V)	469 (V)	548 (V)
Phenol [μg/dm³]	<0.5 (V)	<0.5 (V)	<0.5 (V)	0.9 (V)	<0.5 (V)	<0.5 (V)	0.6 (V)	<0.5 (V)	<0.5 (V)	1.1 (V)	4.7 (V)	4.8 (V)	6.1 (V)	5.4 (V)	2.8 (V)	3.6 (V)	5.3 (V)

6. Evaluation of study results

The laboratory test results of BTEX and phenol contaminant concentrations in groundwater, as presented in Tables 1 and 2, indicate significant contamination in the area of the 'old gasworks' in Bydgoszcz [10]. The spatial distribution of the individual contaminants in the groundwater stream shows considerable variation. Among the samples studied, elevated concentrations of hydrocarbons in groundwater were notably identified in monitoring wells P-3, P-5, P-6, and P-8, as well as in test monitoring wells G7 and G10 to G18.

The total BTEX concentrations in groundwater samples exhibited a wide range, from 1.1 μg/dm³ (P-2) to 6 368 μg/dm³ (G14). Notably high total BTEX values were also observed in water samples from monitoring wells P-5 and P-6 at 2 316.7 and 2 371.9 μg/dm³, respectively, and in monitoring wells G7 (353.9 μg/dm³), G11 (2 434 μg/dm³), G12 (5 337.4 μg/dm³), G15 (2 865 μg/dm³), G16 (1 649.9 μg/dm³), G17 (2 159 μg/dm³) and G18 (2 127 μg/dm³). Among the identified BTEX components, the highest concentrations were found for benzene, ranging from <0.2 μg/dm³ (P-2) to 3 281 μg/dm³ (G14), toluene (<0.2 μg/dm³ in monitoring well G1 to 1 173.5 μg/dm³ in monitoring well P-3), and xylene (0.5 μg/dm³ in monitoring well G1 to 1 086.7 μg/dm³ in monitoring well P-3). In contrast, phenol concentrations in the water samples were significantly lower than those of BTEX, ranging from <0.5 to 17.3 μg/dm³.

7. Conclusions

The groundwater studies conducted in the 'old gasworks' area in Bydgoszcz revealed that the groundwater in each case was classified as Class V of groundwater purity according to the Regulation of the Minister of Maritime Economy and Inland Navigation of October 11, 2019, concerning the criteria and method for assessing the status of uniform parts of groundwater. The highest concentrations of BTEX compounds and phenol were observed in monitoring wells located near the Brda River in the central part of the former gasworks area. This is due to the movement of pollutants towards the river in accordance with the flow of groundwater.

An analysis of the results obtained for the BTEX aromatic hydrocarbon and phenol studies in collected groundwater samples indicates that the investigated area is heavily degraded and should undergo a remediation process in the near future, utilizing methods that allow for the effective cleansing of the soil-water environment.

From an analysis of the available literature [4, 8, 9], it is evident that various methods have been employed worldwide for the remediation of contaminated areas after 'old gasworks'. However, in cases where the dismantling of the technological installation and its accompanying buildings was possible, one of the more effective remediation methods was the use of both 'ex-situ' and 'in-situ' methods. In this process, heavily contaminated soil was first mechanically removed and transported for cleansing or disposal, and then a selected 'in-situ' method was employed for the 'in-place' remediation of the soil-water environment.

In the case of 'old gasworks' in Bydgoszcz, such a procedure is not applicable due to the fact that the surface area is still occupied by old but renovated buildings, which are under the supervision of the conservator of monuments. Moreover, numerous underground installations within the property prevent the use of the 'ex-situ' method. Under these circumstances, only the 'in-situ' method is feasible, allowing for on-site soil and groundwater remediation. For effective environmental remediation of hydrocarbons, it would be advisable to employ several integrated remediation methods.

Due to the very high concentrations of pollutants, it would be appropriate to initiate environmental remediation using a physical or chemical method and then continue the purification process using a biological method.

Acknowledgments: The paper was performed within the framework of AGH University of Krakow statutory research grant No. 16.16.190.779 Faculty of Drilling, Oil and Gas, Department of Petroleum Engineering.

References

[1] Bojakowska I., Irmiński W.: *Zanieczyszczenia związkami organicznymi gleb na terenie starych gazowni*. Przegląd Geologiczny, vol. 50, nr 8, 2002, pp. 691–697.

[2] Landmeyer J.E., Chapelle F.H., Petkewich M.D., Bradley P.M.: *Assessment of natural attenuation of aromatic hydrocarbons in groundwater near a former manufactured-gas plant, South Carolina, USA*. Environmental Earth Sciences, vol. 34(4), 1998, 279–292. https://doi.org/10.1007/s002540050279.

[3] Macuda J.: *Badania fizykochemiczne wód i gruntów na terenie pomorskiego Operatora Systemu Dystrybucyjnego Sp. z o.o. Oddział Dystrybucji Gazu w Bydgoszczy*. GEOFIX, Kraków 2013 [unpublished].

[4] Birak P.S., Miller C.T.: *Dense non-aqueous phase liquids at former manufactured gas plants: Challenges to modeling and remediation*. Journal of Contaminant Hydrology, vol. 105, 2009, pp. 81–98. https://doi.org/10.1016/j.jconhyd.2008.12.001.

[5] Taniewski M. (red.): *Technologia chemiczna – surowce*. Wydawnictwo Politechniki Śląskiej, Gliwice 2000.

[6] Thavamani P., Megharaj M., Krishnamurti G.S.R., McFarland R., Naidu R.: *Finger printing of mixed contaminants from former manufactured gas plant (MGP) site soils: Implications to bioremediation*. Environment International, vol. 37, 2011, pp. 184–189.

[7] Haeseler F., Blanchet D., Druelle V., Werner P., Vandecasteele J.P.: *Analytical characterization of contaminated soils from manufactured gas plants*. Environmental Science and Technology , vol. 33(6), 1999, pp. 825–830. https://doi.org/10.1016/j.envpol.2023.122658.

[8] Hatheway A.W.: *Geoenvironmental protocol for site and waste characterization of former manufactured gas plants; worldwide remediation challenge in semi-volatile organic wastes*. Engineering Geology, vol. 64, 2002, pp. 317–338.

[9] Mulvey P.: *The nature of bonding to black carbon a re-evaluation of risk of MGPs, Gasworks Europe, Redevelopment, site management and contaminant issues of former MGP's and other tar oil polluted sites*. MGP 2008 Conference in Dresden, Germany, 2008, pp. 81–97.

[10] Norma PN-ISO 5667-11. 2017-10. *Jakość wody – Pobieranie próbek – Część 11: Wytyczne dotyczące pobierania próbek wód podziemnych*.

[11] *Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 11 października 2019 r. w sprawie kryteriów i sposobu oceny stanu jednolitych części wód podziemnych*. Dz.U. 2019, poz. 2148.

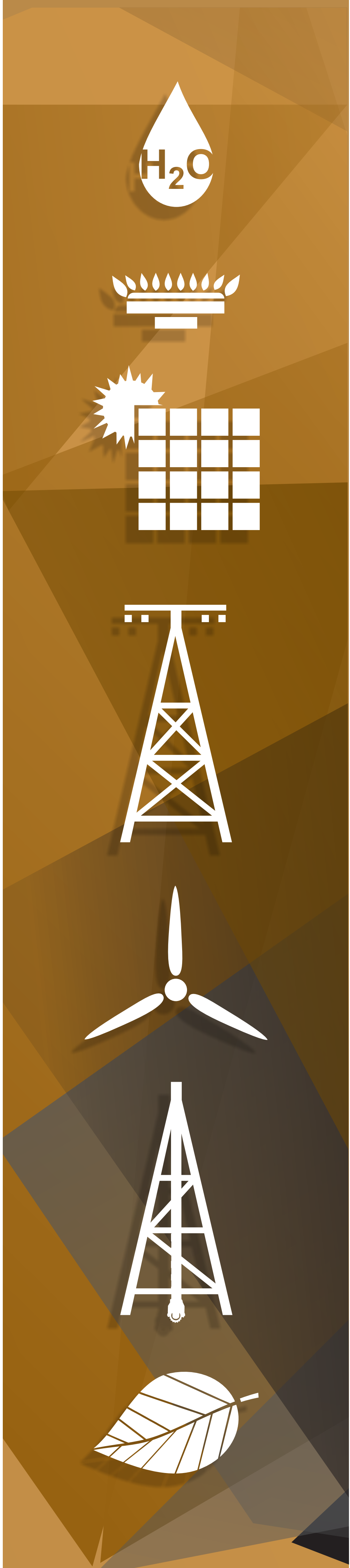
[12] Grabas K., Kołwzan B., Śliwka E., Karpenko E.: *Wpływ ramnolipidu, produkowanego przez pseudomonas ps-17, na biodegradację smoły pogazowej*, pp. 93–98. http://www.pzits.not.pl/docs/ksiazki/Ekotoks_2008/Grabas%2093-98.pdf [10.09.2023].

[13] Irmiński W.: *Pobór prób gruntu do badań laboratoryjnych i mikrobiologicznych na terenie Oddziału Dystrybucji Gazu w Bydgoszczy, ul. Jagiellońska 42*. PIG, Warszawa, czerwiec 2008.

[14] Irmiński W., Konieczyńska M.: *Dokumentacja hydrogeologiczna „Stara Gazownia", Bydgoszcz, ul. Jagiellońska 42*. PIG, Warszawa, styczeń 2005.

[15] Macuda J.: *Matematyczne modelowanie warunków oczyszczania środowiska gruntowo-wodnego dla wybranej metody jego remediacji przy uwzględnieniu istniejących warunków geologicznych, hydrogeologicznych i uzbrojenia terenu „starej gazowni" w Bydgoszczy*. PN-B EKO-KONCEPT, Kraków 2014 [unpublished].

[16] Dekonta Sp. z o.o.: *Dodatek do dokumentacji hydrogeologicznej w zakresie rozpoznania zasięgu i stopnia skażenia środowiska gruntowo-wodnego na terenie starej gazowni w Bydgoszczy*, *ul. Jagiellońska 42*. Kielce 2005.



H_2O