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ASSESSMENT OF GROUNDWATER QUALITY AND POLLUTION RISKS NEAR A HYDROCARBON POWER PLANT

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Abstract

This study assesses the groundwater quality at the CET HIDROCARBURI ARAD site using a Global Pollution Index (I^*_{GP}) methodology that integrates multiple water quality indicators concerning legal thresholds. Water samples from three monitoring wells were collected annually over 11 years (2010-2020) and analyzed for pH, total suspended solids, fixed residue at 105°C, and chemical oxygen demand. The findings reveal that 93.94% of the samples exceeded acceptable limits based on 2008 regulatory references, with pollution levels surpassing ecological thresholds, particularly in Control Well No. 3, indicating persistent ecological stress. Despite this, long-term trends suggest overall groundwater stability, with 78.79% of historical data (2008-2017) falling within permissible ranges. Statistical analysis highlighted variations in pH and COD, suggesting localized impacts from nearby facilities such as a reagent store. The study recommends implementing a sustainable, site-specific water management plan supported by real-time monitoring and targeted assessments of emerging contaminants to enhance environmental protection and risk mitigation.

Key words: *groundwater quality, global pollution index, hydrocarbon power plant, environmental risk, statistical analysis.*

INTRODUCTION

Water is a fundamental resource essential for human development and ecological stability. It plays a critical role in agriculture, industry, and domestic use; however, only a tiny fraction of the Earth's water is readily accessible and of acceptable quality.
One critical concern is the degradation of groundwater due to industrial activities. Modern industrialization and population growth have amplified pollutant loads in surface and subsurface waters, surpassing nature's regenerative limits. This imbalance threatens aquatic ecosystems and poses risks to human health (Ahmed et al., 2022; Bashir et al., 2020).
Water quality, therefore, is not only an immediate environmental issue but a strategic national priority. It intersects local, regional, and global geospheres, which is key in maintaining Earth's ecological balance (Ullah et al., 2024). Protecting water resources requires the integration of comprehensive environmental policies into urban planning, especially in densely populated areas where contamination risks are highest (Guan et al., 2024).
Groundwater, a vital resource for drinking and irrigation, is increasingly vulnerable to pollution from surface-level industrial and technological activities (Ahmed et al., 2022; Al-Awah et al., 2023; Jayaswal et al., 2018; Zaharia, 2012; Zaharia et al., 2009). Such activities often discharge hazardous substances that pose immediate and long-term threats to environmental and public health (Biswas et al., 2014; Jalali et al., 2024; Krenkel, 2012; Sutadian et al., 2016; Ullah et al., 2024; Zainudin et al., 2024).
Among industrial sources, district heating plants present a significant risk to groundwater safety. Ageing infrastructure, corroded pipes, and fuel storage failures can lead to the release of heavy metals, hydrocarbons, salts, and industrial chemicals into soils and aquifers (Xiao et al., 2020; Liu et al., 2019). Understanding the migration of these contaminants through hydrogeological modeling enables early risk

identification, remediation planning, and legal compliance.

Pollutants associated with heating plants vary by fuel type and may include heavy metals (Bashir et al., 2020; Deshmukh et al., 2021; Hu & Shan, 2020a), nutrients like phosphates and nitrates (Isiuku & Enyoh, 2020), salts (Al-Aboodi et al., 2018), hydrocarbons (Jiang et al., 2022), and even radioactive substances in the case of nuclear facilities (Aly et al., 2020). Their monitoring is essential to maintaining water safety (Mokarram et al., 2023).

Pollution indices are widely used, cost-effective tools for evaluating water quality and informing environmental policy, especially in resource-limited settings (Berhanu et al., 2024; de Rosemond et al., 2009; Ravindiran et al., 2024; Thirumoorthy et al., 2024; Zaharia, 2012; Kumar et al., 2024). When combined with hydrogeological data, these indices offer a practical framework for understanding and managing contamination risks near industrial sites.

In line with EU regulations, including Directive 2000/60/EC and Directive 2006/118/EC, continuous groundwater monitoring is required to prevent and detect anthropogenic pollution, particularly where groundwater is a primary drinking water source. Romanian legislation reinforces these directives through national acts such as Water Law no. 107/1996 and Government Decision no. 188/2002, although explicit pollutant thresholds are sometimes lacking.

At CET H Arad, groundwater monitoring follows these legal frameworks, with four key indicators - pH, total suspended solids, fixed residue at 105°C, and COD-Cr - specified in the water management permit. These values are benchmarked against a 2008 reference sample (Analysis Bulletin, 14.11.2008). Any exceedance triggers immediate response to limit environmental harm.

To evaluate groundwater quality from 2010 to 2020, this study applied the Global Pollution Index (I_{GP}^{*}), integrating multiple parameters into a single, comprehensive score. Measurements at three monitoring wells revealed spatiotemporal variations in pollution levels linked to plant operations and well proximity, particularly in downstream locations.

These findings support the development of a robust, site-specific water management strategy and provide a replicable methodology for similar industrial environments. By coupling long-term data with integrated assessment tools, this research advances interdisciplinary knowledge at the intersection of environmental monitoring, regulatory policy, and industrial ecology.

MATERIALS AND METHODS

The municipality of Arad is situated in western Romania, bridging the southern Crisana and northern Banat regions within the expansive Tisza River plain. Geographically, it lies in the alluvial Arad Plain - part of the Western Plain - at 46°11′N latitude and 21°19′E longitude. The city spans 252.85 km² and is located at an altitude of 107 meters above sea level, alongside the Mureș River near the Deva-Lipova corridor. CET H Arad is located in the eastern central area of the municipality, approximately 1 km from the Arad railway station. Positioned on both sides of the Mureșel Canal - a branch of the Mureș River and a discharge route for treated wastewater – the plant occupies 3.62 hectares. It is not part of any protected area.

Commissioned in 1897 as Arad's first electricity source, the plant began with steam-driven generators and transitioned through various fuels: coal dust (1897-1953), fuel oil (1953-1963), a fuel oil-natural gas mix (1963 onward), and exclusively natural gas since 2009. It has long served the region’s thermal and industrial energy needs via combined heat and power systems.

No other major external pollution sources are identified in the study area. However, a sewage reservoir located roughly 15 meters from Control Well No. 1, belonging to a neighboring facility, may pose a potential risk. Similarly, a reagent store near Control Well No. 3 handles substances used for chemical water treatment, representing another possible contamination source.

Historically, CET H Arad operated four large combustion facilities, totaling over 50 MW of thermal output, regulated under EU industrial emission directives. These included two steam generators, a TA1 turbogenerator, and two hot water boilers, with a combined 362 MWt thermal and 12 MWe electric capacity. Electricity production ceased in 2008, and the facility is currently undergoing modernization, with older units scheduled for decommissioning.

Two medium combustion units remain in operation, providing 99 MWt of thermal energy. Groundwater quality at the site is monitored through three boreholes designated as control wells. Positioned in relation to the plant, Well No. 1 lies upstream, while Wells No. 2 and No. 3 are located downstream (Figure 1 and Table 1).

Figure 1. Geographic location of the study area: City of Arad, Romania, Europe. The map highlights the regional context and includes a satellite image of the CET Hidrocarburi power plant site (https://earth.google.com/web/search/europa+românia/)

Table 1. STEREO 70 coordinated of the sampling sites (https://www.cetharad.ro/mediu/)

Authorized sampling point	STEREO 70 Coordinates	
	Coordinate X	Coordinate Y
Control well No. 1	217188.26	526720.76
Control well No. 2	217343.56	526687.81
Control well No. 3	217182.34	526835.62

Methodology

Groundwater samples were analyzed for four key parameters: pH, Total Suspended Solids (TSS), Fixed Residue at 105°C, and Chemical Oxygen Demand (COD-Cr). Sampling was conducted annually over an 11-year period (2010–2020), following national standards and regulatory frameworks, including the Water Law no. 107/1996, Government Decision no. 188/2002, and the Ministry of Environment's Monitoring Plan (Romanian Parliament, 1996; Romanian Government, 2002; MMGA, 2006).

A minimum of four duplicate samples were collected and analyzed each year, in accordance with officially approved methods outlined in Romanian legislation (MMGA, 2006). The measured values were compared against multiple reference points:

- Authorized baseline values from CET H Arad's 2008 test report.
- Historical groundwater quality levels (2008-2017).
- National standards for drinking water (STAS 1342/91; Romanian Standards Institute, 1991).
- Legal thresholds for wastewater discharged into the aquatic environment.

Sampling was limited to the three existing control wells on-site, as mandated by the operational permits, which stipulate annual testing per well. The results, including the calculated Global Pollution Index ((I^*_{GP}), were graphically represented for each sampling location to visualize trends and deviations.

Reference data, including authorized and historical limits, are detailed in Table 2, while national drinking water standards used for comparative analysis are presented in Table 3.

To evaluate groundwater pollution, the study employed the methodology developed by Zaharia (Zaharia, 2012; Zaharia & Murarasu, 2009), which is particularly well-suited for regulatory assessments focused on legal compliance. This approach offers a practical and straightforward means of aggregating multiple pollutant measurements into a single standardized index. Its simplicity, combined with its ability to track trends and facilitate comparisons, makes it an effective tool for communicating findings to policymakers, regulators, and other stakeholders.

The first step involves calculating a quality index (EQ_i) for each parameter using the following formula:

$$EQ_i = \frac{C_i,measured}{MACi} \quad (1)$$

where:

- EQ_i is the quality index for parameter I;
- C_i is the measured concentration of parameter I;
- MAC_i is the maximum allowable concentration according to applicable standards.

Following the calculation of the quality index (EQ_i), each parameter was assigned an Evaluation Score (ES_i) based on the scale provided in Table 4.

Table 2. Reference levels for groundwater at CET H ARAD
(Water Management Authorization, 2018*Aut. G. Water; Integrated Environmental Authorization
*AIM CET H Arad, 2018; Dumescu, 2018)

Sampling point	Legal reference level *Test control_ Year 2008 cf. *Aut. G. Water CET H and *AIM				Historical reference level CET H cf.			
Location CET H Arad	Quality indicators (i) Maximum Allowable Values (MACi)				Location CET H Arad			
Authorized zone	pH	TSS	Fix residue at 105°C	COD-Cr	pH	TSS	Fix residue at 105°C	COD-Cr
	[pH units]	[mg/l]	[mg/l]	[mg/l]	[pH units]	[mg/l]	[mg/l]	[mg/l]
Control well No. 1	7.00	3.00	401.0	8.40	7.00-7.50	17.40-19.00	303.00-411.60	5.70-8.40
Control well No. 2	7.50	2.10	503.00	5.60	7.00-7.50	8.20-14.00	264.00-417.20	2.40-5.80
Control well No. 3	7.00	1.60	458.20	4.90	7.00-7.50	9.40-13.00	192.00-421.60	4.90-5.50

Table 3. The admissible values according to STAS 1342/91 - drinking water
("Romanian Standards Institute, STAS 1342-91, Drink Water" 1991) for the quality indicators considered in the study

STAS 1342-91-DRINKING WATER Quality indicators (i)							
Allowed values (A)				Exceptionally allowed values (EA)			
pH	TSS	Fix residue at 105°C	COD-Cr	pH	TSS	Fix residue at 105°C	COD-Cr
[pH units]	[mg/l]	[mg/l]	[mg/l]	[pH units]	[mg/l]	[mg/l]	[mg/l]
6.50 -7.40	-	100.00-800.00	3.00	max. 8.50	-	30.00-1200.00	5.00

Both the Specific Quality Index and corresponding Evaluation Score were computed for each monitored parameter in the groundwater samples. These calculations referenced four benchmarks:

- Legal thresholds defined in the water management and integrated environmental authorizations;
- Historical groundwater data from CET H Arad (2008-2017);
- National drinking water standards (STAS 1342/91);
- Regulatory limits for wastewater discharge into aquatic environments.

Subsequently, the groundwater pollution status at each sampling location was evaluated using

the Global Pollution Index (I_{GP}^{*}), integrating all reference cases.
The overall Global Pollution Index for each sample was calculated using the following equation (Zaharia, 2012; Zaharia & Murarasu, 2009):

$$I_{GP}^{*} = (100 * n)/(ES_1 * ES_n + \sum_{i=1}^{n-1} ES_i * ES_{i+1}) \qquad (2)$$

where:
- I_{GP}^{*} is the Global Pollution Index,
- n is the number of parameters,
- ES refers to the assigned Evaluation Score for each parameter.

The final pollution classification for each sampling point was determined using the interpretation scale provided in Table 5.

Table 4. Correlation scale between Quality Index (EQi), Evaluation Score (ESi), and environmental impact on the pollution level for the sampling points monitored on the CET H Arad sit (Zaharia, 2012)

Quality Index (EQ_i)	Evaluation Score (ES_i)	Environmental Impact
$EQ_i = 0$	10	Water bodies are unaffected by industrial activity.
$0.00 < EQ_i \leq 0.20$	9	Industrial influence is present but not quantifiable.
$0.20 < EQ_i \leq 0.70$	8	Impact detected, but below first alert threshold. Alert level: Possible consequences.
$0.70 < EQ_i \leq 1.00$	7	Impact within second-level permissible limits. Intervention level: Potential outcomes expected.
$1.00 < EQ_i \leq 2.00$	6	Pollution exceeds the first legal limit. Effect: Noticeably strong impact.
$2.00 < EQ_i \leq 4.00$	5	Pollution surpasses the second limit. Effect: Environmentally detrimental.
$4.00 < EQ_i \leq 8.00$	4	Third limit exceeded. Effect: Clear negative consequences.
$8.00 < EQ_i \leq 12.00$	3	Severe degradation – Level 1. Impact: Fatal effects over average exposure duration.
$12.00 < EQ_i \leq 20.0$	2	Severe degradation – Level 2. Impact: Rapid onset of fatal effects.
$EQ_i > 20.00$	1	Environment rendered unsuitable for life.

Table 5. Correlation of Global Pollution Index, I_{GP}^{*}, with effects in the water body (Zaharia, 2012)

Values I_{GP}^{*}	Consequences in the body of water
1	Water body unaffected by human activity.
$1 \leq I^*_{GP} < 2$	Minor anthropogenic influence; human activity is within acceptable environmental bounds.
$2 \leq I^*_{GP} < 3$	Noticeable stress on aquatic life is caused by human activity.
$3 \leq I^*_{GP} < 4$	Significant disruption of biological processes due to pollution.
$4 \leq I^*_{GP} < 6$	Serious ecological damage; aquatic life is endangered.
$I^*_{GP} > 6$	degraded body of water unfit for all living forms

To evaluate whether the monitored parameters varied significantly across the control wells, the F-test (ANOVA: Single Factor) was applied. This statistical approach was essential in determining whether differences in parameter values could be attributed to the wells' positions relative to the potential pollution source.
The analysis involved hypothesis testing as a structured method to assess statistical significance using the variables detailed in Table 6. The null and alternative hypotheses were defined as follows:
- H_0 (Null Hypothesis): The parameter values across the wells do not significantly differ; any observed variations are random, indicating that the well's location does not influence the results.
- H_1 (Alternative Hypothesis): The parameter values differ significantly, suggesting that variations are influenced by the sampling well's proximity to the potential source of contamination.

This framework provided the basis for interpreting spatial trends and assessing localized impacts on groundwater quality.

Table 6. Variables considered in the statistical analysis of groundwater quality at CET H Arad

Independent variable	Dependent variable	Constant elements
Control well No. 1	pH, COD-Cr, Total Suspended Solids (TSS), Fixed Residue	Well position relative to the pollution source
Control well No. 2		Temperature periodicity
Control well No. 3		Precipitation regime periodicity

RESULTS AND DISCUSSIONS

Evaluation of the power plant activity on the quality of groundwater based on global pollution index

To assess the impact of CET H Arad's operations on groundwater quality, multiple evaluation scenarios were considered. Maximum permissible values for the monitored parameters - pH, TSS, fixed residue at 105°C, and COD-Cr - were derived from the site's Water Management Authorization and Integrated Environmental Authorization.

After calculating the Global Pollution Index, the results were illustrated in Figure 1. These indicate a general deterioration of groundwater quality, with pollution levels causing discomfort to aquatic life - except in 2016, when I^{*}_{GP}, values remained within allowable limits (Figure 2).

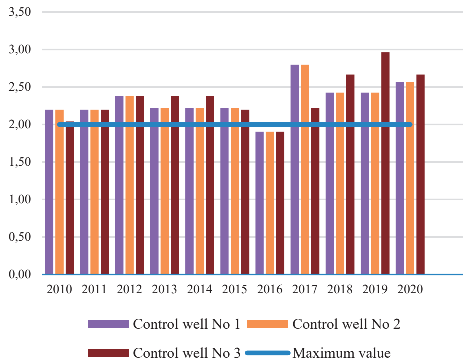

Figure 2. Results of groundwater quality assessment based on the referential values from the Water Management Authorization and Integrated Environmental Authorization for CET H Arad

A second scenario involved benchmarking results against the site's historical baseline values. As illustrated in Figure 3, groundwater quality generally remained within acceptable historical limits. However, notable exceptions were observed:

- Control Well No. 1 in 2017 and 2020;
- Control Well No. 2 in 2018, 2019, and 2020;
- Control Well No. 3 in 2019 and 2020.

In these cases, the I^{*}_{GP}, values exceeded thresholds, signaling environmental stress and potential ecological discomfort.

While many values did not surpass regulatory limits, a concerning upward trend in I^{*}_{GP}, values over the last three years suggest emerging risks. This trend warrants closer investigation into potential operational changes or external factors influencing groundwater quality during that period.

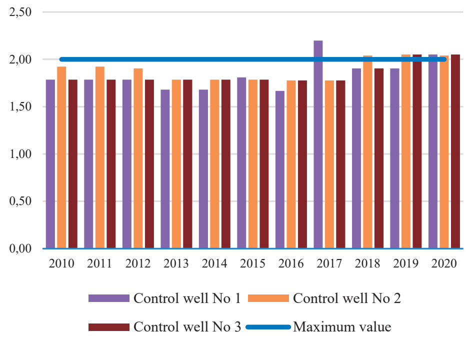

Figure 3. Groundwater quality results based on historical annual mean values (2008-2017) for CET H Arad

The analysis also included a comparison of groundwater quality results against standardized drinking water values: the Accepted (A) limits shown in Figure 4, and the Exceptionally Accepted (AE) limits presented in Figure 5.

These reference values were sourced from national standards for drinking water quality (Romanian Standards Institute, STAS 1342-91, 1991).

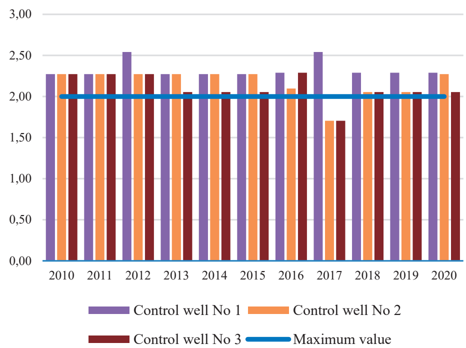

Figure 4. Results obtained according to STAS 1342-91 - Drinking water - Permissible values (A)

Although this comparison does not imply that groundwater from the CET H Arad site is intended or suitable for human consumption, it serves as a meaningful benchmark for evaluating the aquifer's environmental condition. This approach strengthens the broader purpose of the study, which is to understand, monitor, and manage groundwater quality in proximity to hydrocarbon power plant operations.

Assessing the site's groundwater status was a central objective of this investigation. It provides critical insights into the environmental impact of CET H Arad's activity and supports the formulation of preventive strategies to mitigate pollution and maintain groundwater quality.

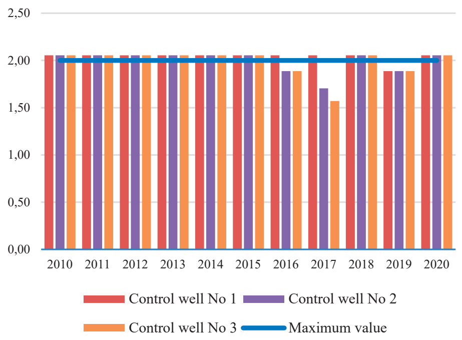

Figure 5. Results obtained in accordance with STAS 1342-91 drinking water - Exceptionally permissible values (EA)

When compared to the accepted drinking water standards (A), the I^*_{GP} values generally indicate discomfort to life forms throughout the study period, except for Control Wells 1 and 3 in 2017, where values fell within acceptable limits (Figure 4). Similarly, when assessed against the exceptionally accepted values (AE), discomfort was still observed in most years, except for Control Well No. 1 in 2019, and Control Wells No. 2 and 3 in 2016, 2017, and 2019, which showed groundwater quality within acceptable bounds (Figure 5).

Despite these occasional acceptable readings, groundwater from the CET H Arad site is not suitable for drinking, as contaminants from hydrocarbon-related processes pose potential health risks if leaked into the aquifer.

Further analysis was performed using Romanian regulatory standards for wastewater discharged into aquatic environments ("Romanian Government, Decision No. 188/2002"). When comparing I^*_{GP} values against these permissible limits, groundwater quality was again generally poor, with discomfort levels indicated across most years. Exceptions were noted in:

- Control Well No. 1 in 2019,
- Control Well No. 2 in 2016 and 2019,
- Control Well No. 3 in 2016, 2017, and 2019 (Figure 6).

These findings reinforce the need for continued monitoring and risk management at the site, especially considering localized pollution trends.

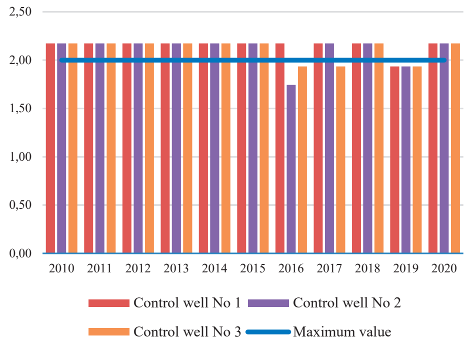

Figure 6. Groundwater quality assessment results compared to the permissible values for technological wastewater discharged into the aquatic environment, as specified by *Government Decision No. 188/2002* (HG 188/2002)

Across the 2010-2020 study period, various referential benchmarks were used to calculate the Global Pollution Index (I^*_{GP}) for groundwater at the CET H Arad site. The results consistently indicate a state of environmental discomfort for life forms in most cases, except for comparisons to historical site-specific values from 2008-2017. When evaluated against this Historical Level, 78.79% of the samples remained within permissible limits.

In contrast:

- Using the Water Management Authorization and Integrated Environmental Authorization thresholds, 93.94% of values exceeded acceptable levels, with only 6.06% falling within legal limits.
- The same proportion (93.94%) was observed when compared to standardized drinking water values (A).
- For exceptionally accepted values (AE) for drinking water, 78.79% of samples were categorized as causing discomfort, while 21.21% were within limits.

- A similar distribution was found when comparing I^*_{GP} results against the permissible values for technological wastewater discharge, mirroring the percentages associated with AE.

These findings emphasize the groundwater body's vulnerability to industrial impact, highlighting the need for continuous monitoring and targeted mitigation strategies.

Evaluation Based on Statistical Analysis

In addition to index-based evaluation, the study incorporated statistical analysis of four key groundwater parameters - pH, COD-Cr, TSS, and fixed residue - monitored at the three control wells from 2010 to 2020. Given the nature of hydrocarbon power plant operations, impacts may arise from combustion byproducts, chemical treatments (acids or alkalis), or accidental spills.

A Fisher F-test (ANOVA: Single Factor) was used to determine whether variations in these parameters were statistically significant across the wells. The analysis was grounded in the previously defined null (H_0) and alternative (H_1) hypotheses regarding spatial variation due to the plant's location.

As an example, pH variation is shown in Figure 7. Between 2010 and 2015, pH levels in Control Well No. 2 (downstream) were consistently higher than those in Well No. 3 (also downstream). Interestingly, the pH values for Well No. 1 (upstream) closely resembled those of Well No. 2 during this period, suggesting minimal or no influence from plant operations on this parameter.

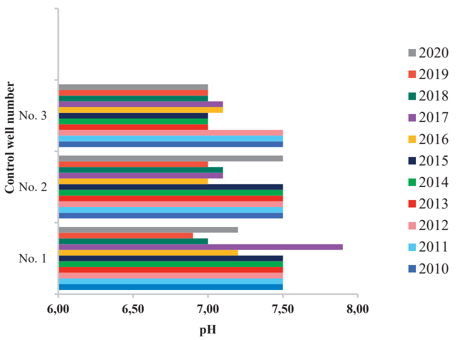

Figure 7. Variation in pH levels across the three control wells (Wells 1, 2, and 3) at CET H Arad during the 2010–2020 monitoring period

To visualize potential trends and deviations, the average pH values across the wells were plotted (Figure 8). This graph highlights long-term fluctuations and can be used to assess whether pH variations fall within standardized limits, potentially revealing early signs of deviation or pollution influence.

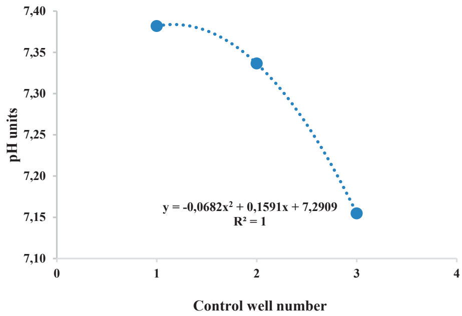

Figure 8. The function for calculating the pH variation in the three sampling points

A distinct pattern emerged when analyzing the variance in Chemical Oxygen Demand (COD-Cr) across the wells. Statistically significant differences were identified between Control Wells 1 and 2 and Wells 1 and 3, indicating that well location relative to the power plant (upstream vs. downstream) may influence COD-Cr concentrations.

This conclusion is further supported by the lack of significant variation between Wells 2 and 3, both situated downstream of the CET H Arad facility. These findings validate hypothesis H_1 (the location affects parameter variation), rejecting H_0 (no significant difference). Specifically:

- For Wells 1 and 2, $P = 0.045 < 0.05$ and $F = 4.57 > F_{(crit)} = 4.35$.
- For Wells 1 and 3, the variation is even more pronounced, with $P = 0.013$ and $F = 7.51 > F_{(crit)} = 4.35$.

Average COD-Cr values exhibited a descending trend from Well 1 to Wells 2 and 3, indicating a reduction in oxidizable substances and oxygen demand. This may be explained by a sewage collection reservoir located approximately 15 meters from Well 1, which likely contributes to higher concentrations of organic compounds upstream. As groundwater flows downstream, these substances appear to dilute, improving aerobic conditions for aquatic life.

In recent years, Well 1 consistently recorded higher COD-Cr values, especially from 2016 onward, except for 2017. That year, Wells 2 and 3 showed a nearly 80% drop in COD-Cr levels compared to the previous year (Figure 9). This anomaly may correlate with significant rainfall and elevated Mureș River discharge in 2017, leading to increased groundwater recharge and dilution of pollutants in the aquifer. The trend of COD-Cr over time is best represented by a second-degree polynomial function, reflecting the non-linear pattern of concentration changes (Figure 10).

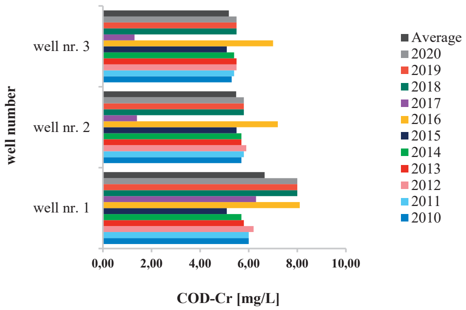

Figure 9. Variation in Chemical Oxygen Demand (COD-Cr) across the three control wells at CET H Arad during the 2010–2020 monitoring period

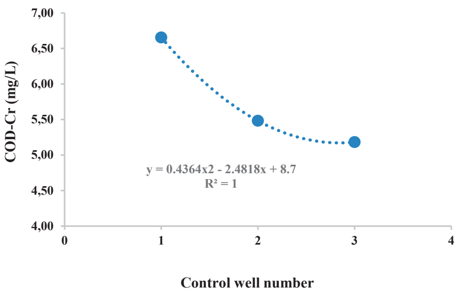

Figure 10. The function for calculating the COD-Cr variation in the three sampling points

A consistent pattern was observed across all control wells for Total Suspended Solids (TSS) (Figure 11). From 2010 to 2016, TSS concentrations remained relatively stable, averaging around 2 mg/L. However, a sharp increase was noted during 2017–2019, with average values rising by approximately eightfold. In 2020, TSS levels declined by about 30% compared to the peak period, suggesting a potential link with annual rainfall volume and temperature fluctuations.

Unlike other parameters, TSS exhibited a linear variation across the three wells (Figure 12), indicating a consistent spatial distribution pattern unaffected by well location.

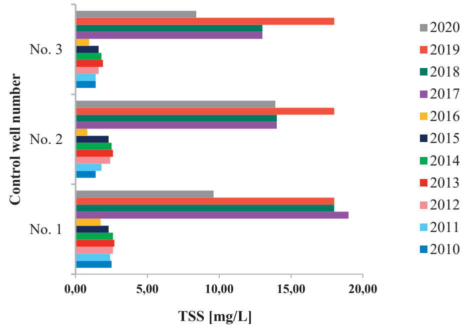

Figure 11. TSS variation in the three wells during the studied period

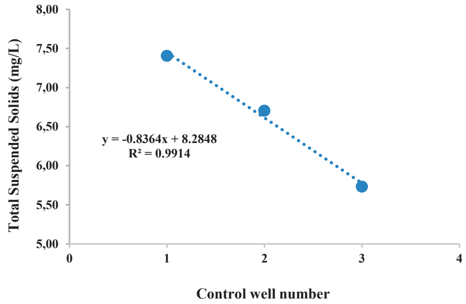

Figure 12. The function for calculating the TSS variation in the three sampling points

As expected, Fixed Residue followed a similar trend to TSS over the study period (Figure 13), given that suspended particles significantly contribute to the residual solids in water samples.

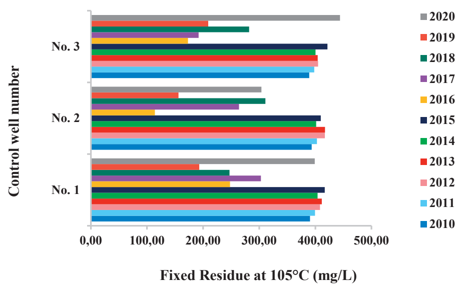

Figure 13. Fixed residue variation in the three wells during the studied period

The inter-well variation in Fixed Residue (Figure 14) showed a second-degree polynomial trend, comparable to the observed pattern in pH variations, highlighting non-linear distribution influenced by both suspended load and water chemistry dynamics.

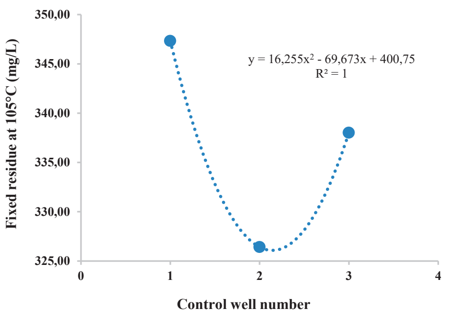

Figure 14. The function for calculating the fixed residue variation in the three sampling points

As shown in Table 7, the statistical comparison of pH values between control wells revealed no significant differences among most pairings. For Wells 1 and 2, the $P\text{-}value = 0.683 > 0.05$ and $F = 0.172 < F_{(crit)} = 4.351$, indicating that variations are likely due to random factors rather than spatial influences. A similar outcome was observed between Wells 2 and 3, where $P = 0.082 > 0.05$ and $F = 3.521 < F_{(crit)} = 4.351$. These results suggest that pH levels remained relatively stable across the sampling points and were not significantly influenced by the wells' positions in relation to the power plant.
The results summarized in Table 7 support the acceptance of the null hypothesis (H_0) in the comparisons of pH values between Wells 1 and 2, and Wells 2 and 3, where no statistically significant differences were found. These variations appear to result from arbitrary or random factors rather than systematic spatial influences.

Table 7. The ANOVA F and P parameters resulted after the comparison of the measured groundwater quality parameters for the control wells

Comparison Between Wells	Parameter	F Value	F Critical	p Value	Significant Difference*
Well No. 1 vs Well No. 2	pH	0.172	4.351	0.683	No
	COD-Cr	4.571	4.351	0.045	Yes
	TSS	1.11	4.351	0.314	No
	Fixed Residue at 105°C	0.793	4.351	0.388	No
Well No. 1 vs Well No. 3	pH	4.358	4.351	0.05	Slight (borderline)
	COD-Cr	7.511	4.351	0.013	Yes
	TSS	2.136	4.351	0.181	No
	Fixed Residue at 105°C	3.14	4.351	0.103	No
Well No. 2 vs Well No. 3	pH	3.521	4.351	0.082	No
	COD-Cr	2.401	4.351	0.145	No
	TSS	1.893	4.351	0.203	No
	Fixed Residue at 105°C	0.922	4.351	0.356	No

This pattern extends to Total Suspended Solids (TSS) and Fixed Residue, where all inter-well comparisons, including Wells 2 and 3 for COD-Cr, showed no significant differences. As with pH, the lack of significance suggests that these parameters were largely unaffected by well positioning or hydrocarbon plant activity during the evaluated period.
However, in contrast, a slight but statistically significant difference in pH was detected between Wells 1 and 3 ($P = 0.0498 < 0.05$; $F = 4.358 > F_{(crit)} = 4.351$), implying potential localized influence. More pronounced effects were observed for COD-Cr:

- Between Wells 1 and 2: $P = 0.0451 < 0.05$; $F = 4.5708 > 4.351$.
- Between Wells 1 and 3: $P = 0.0126 < 0.05$; $F = 7.511 > 4.351$.

These findings partially reject H_0 and weakly support H_1, suggesting that well positioning relative to the power plant may influence groundwater chemistry - particularly for parameters like pH and COD-Cr.
On average (2010-2020):

- pH at Well 3 was approximately 3% lower than at Well 1.
- COD-Cr was 28% higher at Well 3, and 21% higher at Well 2, compared to Well 1.

This may reflect the effects of chemical reagent use and disposal near downstream wells, potentially linked to the hydrocarbon plant's daily operations. While the differences are not universally significant, the results warrant further investigation and highlight the need for a targeted environmental management strategy to monitor and mitigate potential impacts.

CONCLUSIONS

This study applied the Global Pollution Index (I^*_{GP}) to evaluate the groundwater quality at the CET H Arad hydrocarbon power plant site. Annual water quality data collected over an 11-year period (2010-2020) from three control wells formed the basis for assessing key environmental indicators.

The findings reveal that, in 93.94% of cases - when measured against legal thresholds outlined in the Water Management Authorization and Integrated Environmental Authorization - pollution levels were high enough to cause discomfort to aquatic life. This conclusion is based on comparisons with a 2008 baseline sample defined as legal reference.

Control Well No. 3, located downstream of the plant, emerged as the most impacted, consistently exhibiting I^*_{GP}values indicative of ecological stress. Nonetheless, the overall groundwater system appeared stable during the studied period. When compared to the site's historical quality baseline (2008-2017), 78.79% of the readings fell within permissible limits, suggesting no significant long-term degradation.

Statistical analysis further confirmed that Control Well No. 3 is most affected, especially in terms of pH and COD-Cr levels. These differences are likely linked to the well's proximity to potential pollutant sources, supporting the idea of localized environmental influence from plant activities.

Given the high proportion of samples exceeding authorized values and the aquifer's connection to the ROMU20 and ROMU22 groundwater bodies, which serve as sources for drinking water downstream, the potential risk to human health and ecosystems is significant. This underscores the urgent need for a sustainable and adaptive groundwater management plan.

Although the Global Pollution Index and statistical tools provide valuable insight, their effectiveness is limited by their reliance on historical or annual data, which may fail to capture temporal fluctuations or short-term pollution events. Thus, a more robust monitoring strategy is recommended, incorporating:

- Quarterly or monthly sampling to improve data resolution;
- Expanded monitoring networks with additional wells positioned at varying distances from the plant;
- Real-time data collection systems and assessment of emerging contaminants,
- Consideration of pedological and hydrogeological variability that may affect pollutant migration and sample integrity.

Further, it is advised to:

- Establish protective perimeters around existing wells to minimize external contamination;
- Investigate the chemical status of the deeper ROMU22 aquifer supplying the CET H Arad area;
- Develop protocols for new well placements, especially considering planned new plant infrastructure on the same site.

Ultimately, long-term protection of groundwater resources in industrial settings like CET H Arad depends on an integrated strategy - combining science-based monitoring, stricter regulatory enforcement, and proactive infrastructure planning.

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