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GROUNDWATER QUALITY ASSESSMENT IN DOMESTIC WELLS OF HODĂI-BOIAN, CEANU MARE COMMUNE, ROMANIA

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ABSTRACT. This study provides a comprehensive chemical assessment of groundwater quality from 37 domestic wells in the rural village of Hodăi-Boian, Ceanu Mare commune, Romania, with emphasis on contamination risks arising from anthropogenic activities. Key water quality parameters—nitrites(NO_2^-), nitrates(NO_3^-), ammonium(NH_4^+), pH, turbidity, and electrical conductivity(EC)—were determined according to standardized analytical protocols and compared against Romanian and European regulatory thresholds. Exceedances of the maximum admissible concentration for NO_2^- were detected in seven wells, indicating recent contamination events likely linked to the proximity of animal shelters and latrines. NO_3^- and NH_4^+ concentrations remained below legal limits, although elevated NH_4^+ levels signal persistent microbiological activity. The findings revealed pronounced mineralization and frequent surpassing of conductivity limits, while pH values below 7.0 in selected wells suggested active organic fermentation processes. Water temperature ranged from 11–13 °C, confirming the shallow aquifer character. Correlative analysis demonstrated strong associations between well proximity to pollution sources, livestock density, and water quality deterioration. The results underscore the necessity of regular water quality monitoring, rigorous enforcement of protective distances, and technical improvements to well construction. Strengthening

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public health education and upgrading sanitation infrastructure are imperative to mitigate health risks and safeguard the safety of groundwater resources in vulnerable rural environments.

Keywords: *groundwater, water quality*, *physico-chemical parameters, domestic wells, rural area.*

INTRODUCTION

Worldwide, many communities, especially in rural areas, rely on wells as their primary source of drinking water and irrigation. Access to safe and clean drinking water and sanitation is a fundamental human right, essential for the full realization of life and all other human rights [1].

Freshwater resources are facing growing scarcity due to factors such as population growth, urban expansion, and climate change, all of which intensify water stress in many parts of the world [2].

However, poor water quality from wells can be linked to public health problems, leading to water-related epidemics such as cholera [3]. One way to improve water quality is by using water filters [4], but cost often represents a significant impediment.

Groundwater can be accessed via deep boreholes or shallow wells, with the latter being more common in low-income communities due to their lower construction costs and typical private ownership [5]. Water is extracted from shallow wells using a container and rope, and in some cases, manually operated or improvised pulleys, hand pumps, or electric pumps are employed.

The quality of drinking water is undeniably crucial for society, particularly for maintaining a high standard of public health. It is well known that many wells are situated near potential sources of contamination, such as solid waste landfills, which can lead to disease outbreaks.

Moreover, groundwater can dissolve minerals, resulting in undesirable characteristics such as hardness and contamination with toxicants and microorganisms. The use of untreated groundwater has been linked to waterborne diseases such as gastroenteritis, cholera, hepatitis, typhoid fever, and giardiasis, which are caused by bacteria, viruses, and protozoa [6].

The proximity of pollution sources—such as wastewater treatment plants, landfills, or agricultural fields—also affects the concentration of emerging pollutants in the soil. Their presence in agricultural ecosystems adversely affects soil and environmental health, ultimately impacting both ecological and human well-being [7].

The chemistry of water is a key factor in determining its suitability for various uses. Therefore, chemical analysis is crucial for assessing water quality and identifying potential pollutant pathways. Common chemical contaminants found in well water include nitrates (NO_3^-), nitrites ($NO2^-$), ammonium (NH_4^+), chlorides (Cl^-), sulfates (SO_4^{2-}), and heavy metals [8, 9].

Monitoring NO_3^-/NO_2^- levels is essential to ensure that water meets health and safety standards, such as those set by the World Health Organization (WHO) [10]. High NO_3^- levels in water are dangerous for human health, particularly for infants, causing methemoglobinemia or "blue baby syndrome," which reduces the blood's ability to carry oxygen [11].

Moreover, high NO_3^-/NO_2^- concentrations can lead to eutrophication when groundwater enters surface waters, promoting excessive algal growth and reducing oxygen levels in aquatic ecosystems [12]. Chronic exposure to $NO_3^-/NO_2^-$is also associated with certain cancers and thyroid problems in adults [13].

Heavy metals are important as well, as they significantly affect the suitability of water for both irrigation and drinking purposes [14]. For example, one study evaluated the quality of surface water near Baia Mare by determining the concentrations of several heavy metals and comparing contamination levels and overall water quality using the Heavy Metal Evaluation Index (HEI) for 2021 and 2022.

The findings revealed that the HEI value showed a deterioration in water quality in 2022 compared to 2021, which resulted in human exposure to higher health risks of intoxication with the studied metals.

In Romania, several studies have investigated the use of water from wells. S. Burca et al. [15] reported on the quality of shallow wells from Feleacu village, Cluj County, and Sândominic commune, Harghita County [16].

These papers monitored the physico-chemical parameters of shallow wells to assess their suitability for drinking water. Most samples showed moderate to high mineralization, and some were found to be contaminated by organic substances and NO_3^- ions. C. Roba et al. [17] studied the chemistry of groundwater and its suitability for drinking and irrigation purposes in several urban and rural areas from Cluj, Sălaj, Satu Mare, and Alba counties. They reported that a total of 40% of the private wells were suitable for drinking, while 60% were not recommended for high-quantity or long-term consumption.

Moreover, the calculated ingested dose suggested that regular consumption of water from certain private wells poses a significant health risk due to elevated levels of NO_3^- and NO_2^-.

Similarly, Hoaghia et al. [18] performed a detailed health risk assessment for groundwater consumers in the Mediaș area (Sibiu County), showing frequent exceedances of maximum admissible values for NO_3^- and NO_2^- and highlighting the associated non-carcinogenic health risks, particularly for children.

In our previous paper [19], we conducted a rigorous multidisciplinary evaluation of shallow groundwater vulnerability and rural well water quality in Hodăi-Boian, Ceanu Mare commune. Despite NO_3^- and NH_4^+ levels being within legal limits, all tested wells exceeded the legal threshold for NO_2^- and showed microbiological contamination, including E. coli, posing serious health risks.

The present study aimed to analyze the chemical quality of water from wells used for domestic and agricultural consumption in the commune of Ceanu Mare, with a particular focus on the locality of Hodăi-Boian as an area with potentially higher risks regarding the safety of well water.

For this purpose, 37 wells were selected, distributed throughout the commune, considering the type of water use and the proximity to pollution sources such as stables, latrines, and intensively used agricultural areas.

Other parameters considered in this study included the number of inhabitants and large animals for each well, average daily and monthly water consumption, and water level and depth in the well.

The collected water samples were chemically characterized for NO_2^-, NO_3^-, NH_4^+, pH, turbidity, and electrical conductivity (EC), and were compared with allowable values for drinking water.

RESULTS AND DISCUSSION

Characterization of the Studied Households

To enable a rigorous assessment of the chemical risk associated with the use of water from wells in Hodăi–Boian, a descriptive analysis was conducted of the main usage parameters and the local hydrogeological context.

This section synthesizes data regarding the number of inhabitants served by each well, the number of large animals, water consumption, the water level and depth in the well, as well as distances to potential sources of contamination.

The analysis of these variables allows for the identification of key determinants that may directly influence the chemical quality of the water and provides the foundation for interpreting the laboratory results presented later.

Table 1 summarizes the key data concerning water use from 37 wells, highlighting essential parameters for evaluating both contamination risk and the sustainability of the local water resource.

The variables analyzed include the number of inhabitants served, the number of large animals, daily and monthly water consumption, the water level and depth in the well, as well as distances to potential sources of contamination such as stables and latrines.

For the thorough assessment of chemical risks associated with the use of well water in Hodăi–Boian, a descriptive analysis was undertaken of the main operational parameters and the hydrogeological context.

Considered aspects included the number of inhabitants served, the number of large animals, water consumption, the water level and depth in the well, as well as distances from potential sources of contamination.

These variables represent key determinants of the chemical quality of the water and support the interpretation of the laboratory results presented subsequently.

The number of inhabitants served by each well ranges from 1 to 6 (with an average of 2–4 persons), reflecting the specific characteristics of rural households.

The number of large animals varies between 1 and 9, with maximum values recorded at wells 4, 18, and 30, where livestock farming is more developed. This aspect is directly relevant from a chemical perspective, as the presence of a large number of animals favors the accumulation of organic matter and nutrients (nitrogen (N), phosphorus (P)), compounds that can rapidly reach the water source, especially when the distance to stables or latrines is small.

Figure 1 highlights these variations, indicating areas with an increased potential for chemical contamination. It is noteworthy that in many households, the number of animals equals or even exceeds the number of inhabitants, which further increases the pressure on the quality of the water source.

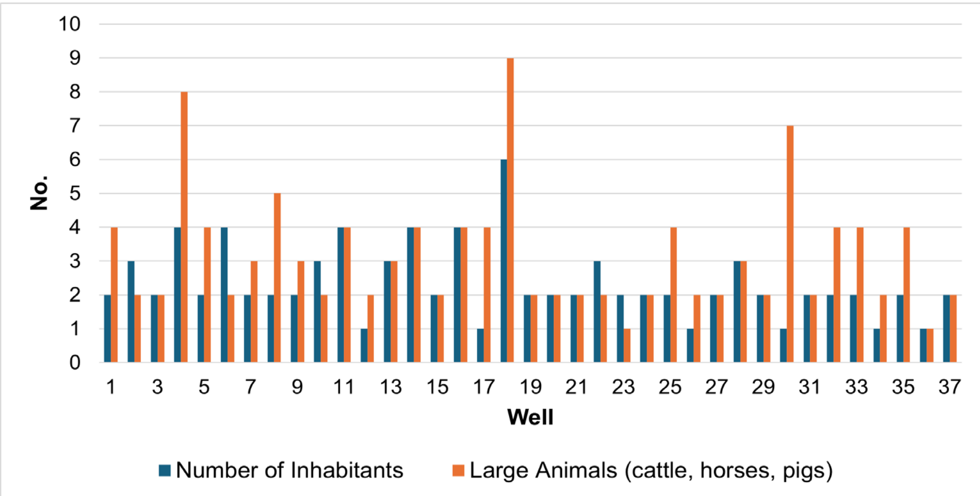

Figure 1. Number of inhabitants and large animals (cattle, horses, and pigs) associated with each well

From a chemical perspective, the simultaneous presence of a large number of animals and short distances to pollution sources represents a major risk factor for the accumulation of NO_2^-, NO_3^-, and NH_4^+ in well water, as well as for the occurrence of high levels of coliform bacteria and other indicators of organic pollution. These effects are often correlated with increased values of electrical conductivity and the total N content in water.

Daily water consumption is relatively constant for most wells (10–60 L), depending on household and livestock needs. Monthly values show significant fluctuations, with maximum levels recorded in households with a higher number of inhabitants and animals (Figure 2).

This pattern can directly influence the chemical dynamics of the water source, accelerating dilution and renewal processes, but also the temporary mobilization of contaminants present in the soil or within the well structure.

In certain hydrogeological contexts, these dynamics favor the transfer of NO_3^-, PO_4^{3-}, or heavy metals into the water mass, increasing risks to human health, especially in households with multiple sources of pollution [20].

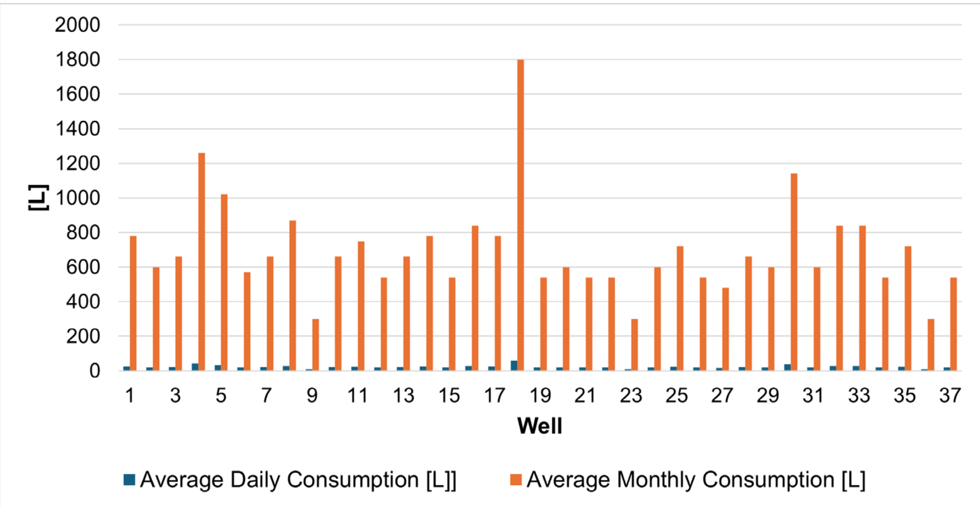

Figure 2. Average daily and monthly water consumption per well

Figure 3 illustrates the variability of water level and the depth of the water column in the analyzed wells. The water level in the wells ranges from 3 to 8 meters, while the depth of the usable water column varies between 1.2 and 3 meters.

Wells with low water levels are more vulnerable to chemical contamination due to their limited dilution capacity and increased sensitivity to external factors such as heavy rainfall or nearby livestock activities.

Under these conditions, there is a high risk of exceeding the permissible concentrations for NO_3^-, phosphates (PO_4^{3-}), and other soluble substances, with a negative impact on water potability [20].

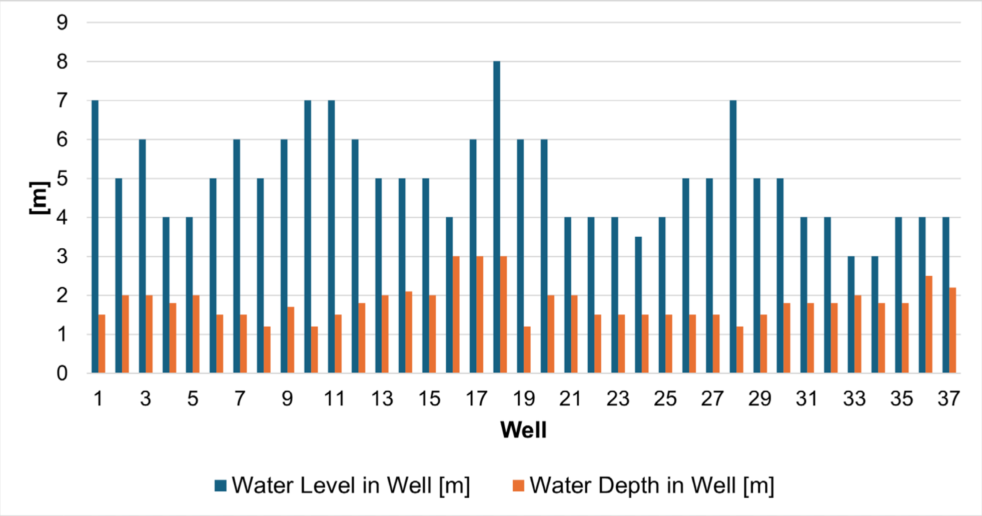

Figure 3. Water level and depth of the water column in each well (m)

Figure 4 highlights the distribution of distances between wells and potential sources of pollution (stables and latrines), showing that the measured distances range from 6 to 22 meters.

A significant proportion of wells are located less than 15 meters from these sources, which facilitates the rapid infiltration of N compounds, bacteria, residues of veterinary pharmaceuticals, and other contaminants resulting from inadequate management of animal waste.

This indicates an increased susceptibility to contamination with highly mobile substances such as NO_2^-, NO_3^-, and NH_4^+. The risk of transfer of these pollutants increases exponentially at shorter distances and is further influenced by factors such as soil structure, land slope, and groundwater level. In addition, the use of pesticides and herbicides in households can amplify contamination through infiltration or surface runoff, representing an additional threat to well water quality [20, 21].

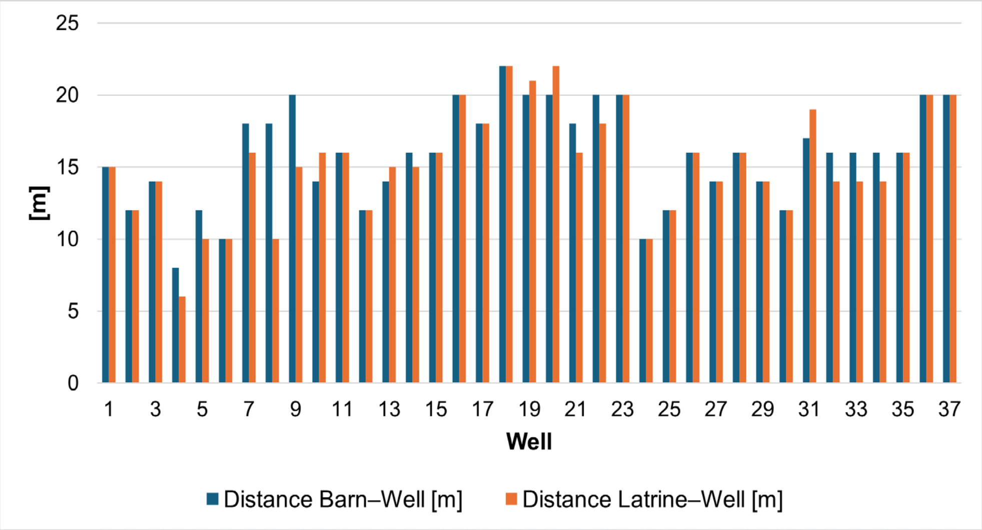

Figure 4. Distance from well to barn and latrine (m)

Chemical Analysis of Water from the Investigated Wells

To assess the potability status and chemical contamination risks associated with the consumption of water from wells in Hodăi–Boian, seven essential chemical and physico-chemical parameters were analyzed: concentrations of NO_2^-, NO_3^-, NH_4^+, pH, turbidity, electrical conductivity, and water temperature.

These analyses enable the identification of potential pollution sources, the degree of mineralization, as well as public health risks, providing a comprehensive overview of local water quality.

The concentrations of NO_2^- (Figure 5) reveal exceedances of the safety limit for drinking water (0.5 mg/L) in seven wells (4, 5, 8, 18, 30, 35, and 31). This finding is indicative of recent pollution with organic matter of animal or human origin, likely correlated with the proximity of pollution sources (latrines, barns) or improper waste management within households.

From a chemical perspective, NO_2^- is a sensitive indicator of acute contamination and poses a serious risk to the health of young children and infants, due to its methemoglobin-forming potential [20].

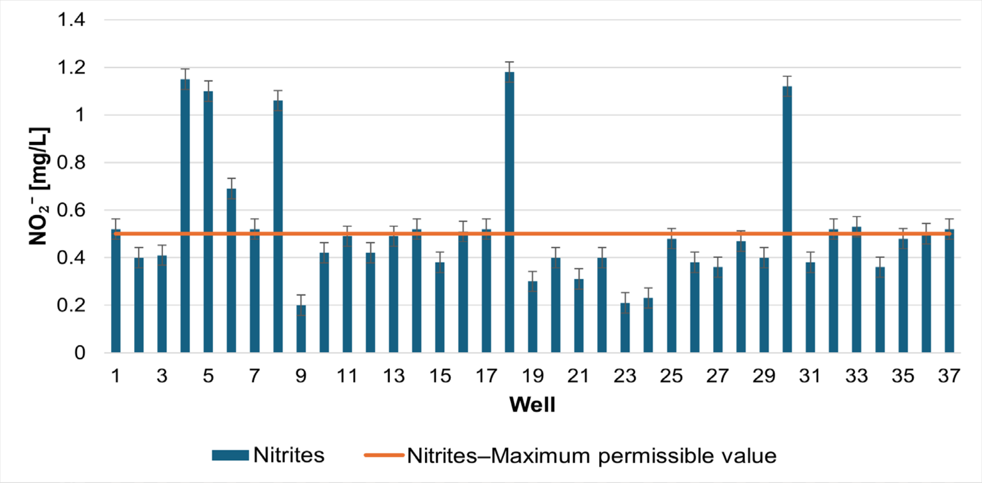

Figure 5. NO_2^- concentration in water from the investigated wells compared to the maximum admissible value

Figure 6 shows a relatively heterogeneous distribution of NO_3^- concentrations, with values approaching the maximum admissible limit in wells 4, 5, 18, 35, 36, and 37.

This pattern reflects a constant input of NO_3^- from diffuse sources, such as the use of chemical fertilizers or infiltration from animal waste.

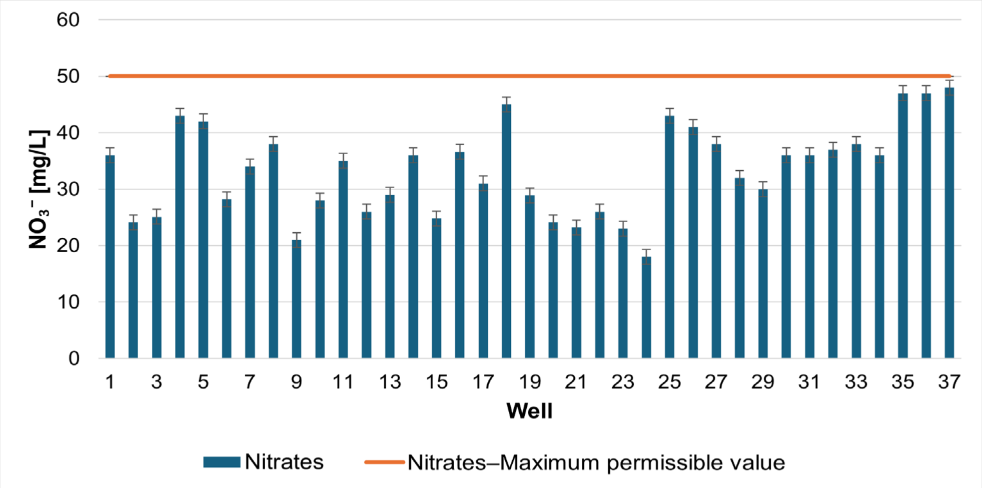

Figure 6. NO_3^- concentration in the water of the investigated wells compared to the maximum admissible value

NO_3^- are stable compounds with high persistence in groundwater, which underlines the importance of regular monitoring and the implementation of preventive measures to reduce the risk of chronic exposure.

All measured NH_4^+ values (Figure 7) remain below the potability threshold; however, the presence of relatively elevated concentrations (close to 0.4 mg/L in wells 4, 5, 8, 18, and 30) indicates recent low-level N input (e.g., manure or latrines) or local anoxic conditions. In oxic environments, NH_4^+ should be converted to NO_3^- [22, 23].

Unlike NO_3^-, NH_4^+ is less stable and reflects more recent pollution, often correlated with household or livestock activities near the wells.

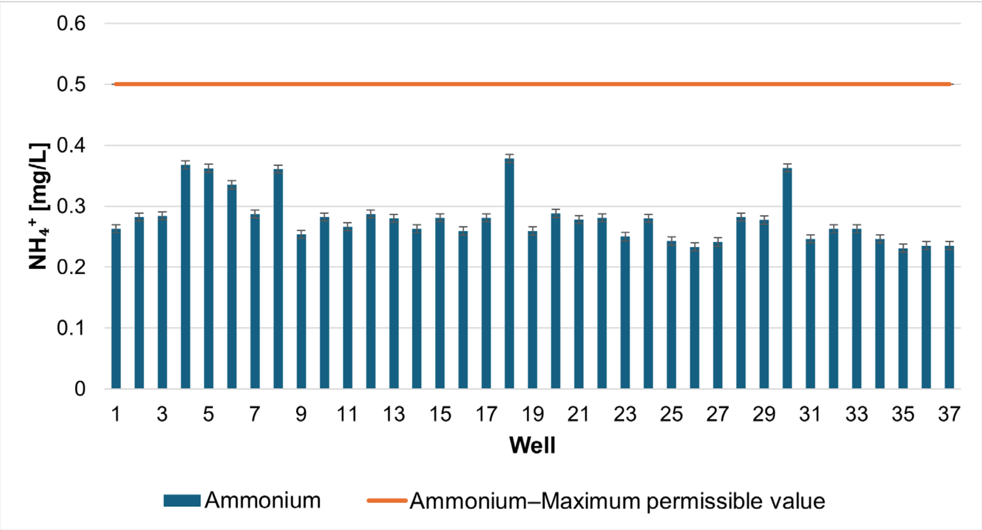

Figure 7. NH_4^+ concentration in well water compared to the maximum admissible value

The pH values (Figure 8) generally fall within the optimal range for drinking water (6.5–9.5), except for a few wells that display slightly acidic pH values (6.8–7.0), suggesting possible fermentation processes or increased microbiological activity. Slightly alkaline pH values, observed in most wells (>8), may reflect the mineral nature of the geological substrate, but also a high degree of mineralization and the presence of inorganic compounds (bicarbonate(HCO_3^-), carbonate(CO_3^{2-}), sodium (Na^+)).

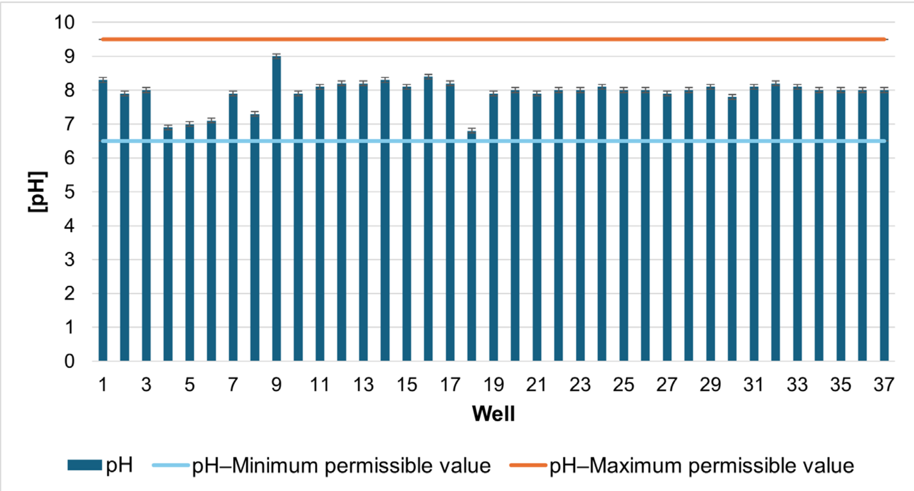

Figure 8. pH values of well water compared to the permissible limits

In Figure 9, turbidity remains below the maximum admissible limit for drinking water (5 NTU); however, values ranging between 2.1 and 4.5 NTU suggest the persistent presence of suspended solids, colloidal particles, or undecomposed organic matter [24, 25]. This phenomenon may result from insufficient filtration, contamination with plant material, or infiltration of rainwater into the well structure—factors that can potentially impact the clarity and microbiological safety of the water.

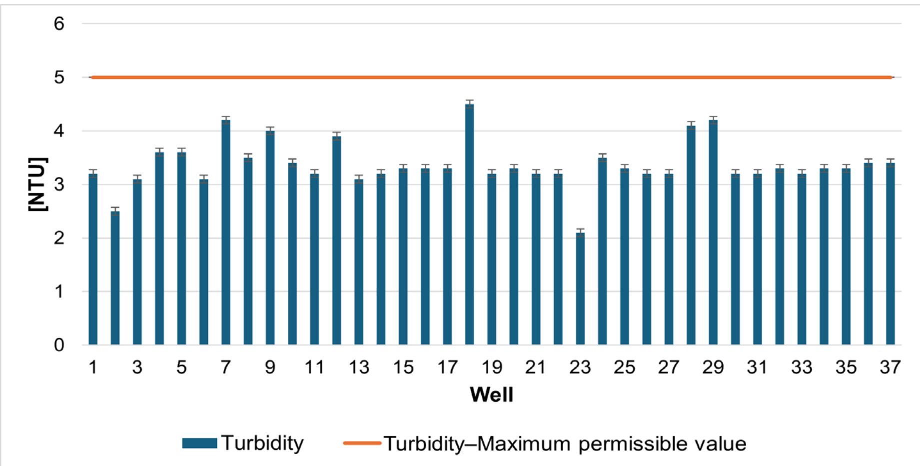

Figure 9. Turbidity of well water compared to the maximum admissible value

No transmitted light optical microscopy images of the most turbid samples (7, 18, and 29) were obtained in this study. The identification of dispersoid nature was based on indirect field evidence, context interpretation, and supporting literature regarding rural well water contamination (e.g., soil particles, organic matter, microorganisms).

Electrical conductivity, presented in Figure 10, frequently exceeds the maximum admissible value of 2500 µS/cm for drinking water, according to Directive (EU) 2020/2184 [26]. Such exceedances indicate either a naturally high mineralization of the water—caused by a geologic substrate rich in salts—or an inorganic input from anthropogenic sources such as animal waste or fertilizers.

From a chemical perspective, this parameter reflects the presence of dissolved ions (sodium(Na^+), potassium(K^+), calcium(Ca^{2+}), magnesium (Mg^{2+}), Cl^-, SO_4^{2-}, NO_3^-), which require special attention when evaluating potability, especially for vulnerable groups [27].

Total dissolved solids (TDS) and salinity were not directly measured in this study. However, the well-established correlation between electrical conductivity and these parameters was considered in the interpretation of the results.

Elevated conductivity values suggest a high level of mineralization (dissolved ions), often associated with mixtures rich in NO_3^-, Cl^-, and HCO_3^-, while correlation with the Cl^-/Br^- ratio may assist in identifying the source of salinity [28].

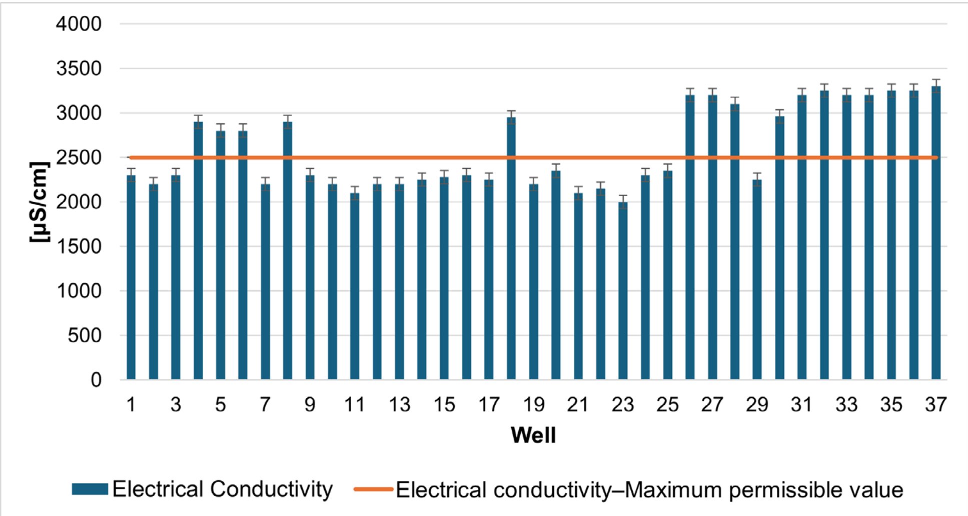

Figure 10. Electrical conductivity of well water compared to the maximum admissible value

The water temperature values (Figure 11) range between 11°C and 13°C, which is typical for shallow groundwater sources in a temperate-continental climate. While these parameters do not significantly influence the chemical quality of water, they can have an indirect impact on microbiological activity and the solubility of certain chemical compounds.

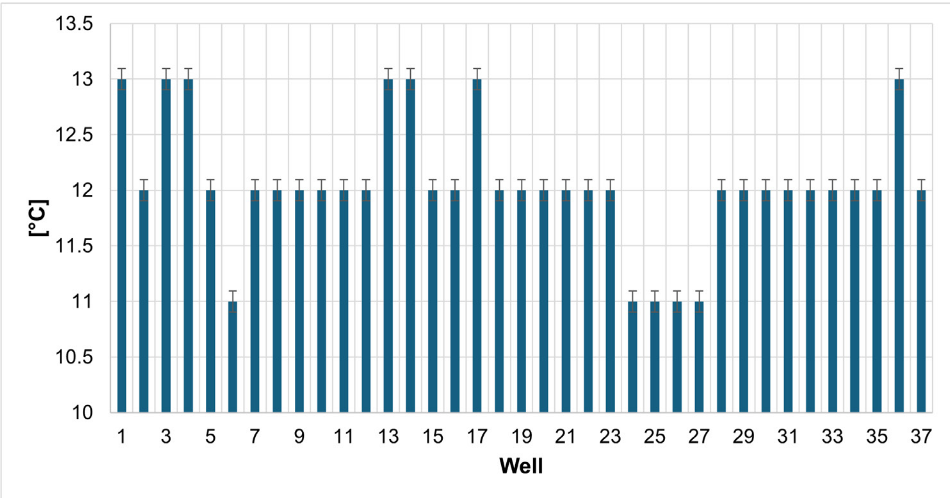

Figure 11. Water temperature in the analyzed wells

The results of the chemical analyses performed on water samples from wells in Hodăi–Boian highlight significant public health risks, mainly due to repeated exceedances of NO_2^- concentrations and high levels of NO_3^-, especially in wells located near potential pollution sources.

The water from wells in the Hodăi–Boian area shows moderate concentrations of NO_2^- (0.20–1.18 mg/L), with values below the maximum permissible limits set by current legislation. The results obtained are comparable to those reported for wells in Feleacu (0–1.61 mg/L) [15], but higher than those determined in wells from Mediaș (0.15–0.85 mg/L) [18], where values frequently approach regulatory thresholds, suggesting an increased risk of chronic NO_3^- exposure.

NO_3^- concentrations determined in Hodăi–Boian (18–48 mg/L) are lower than those reported in studies conducted in Sândominic (11–94 mg/L) [16] and Mediaș (11–130 mg/L) [18], indicating a possible reduction in recent organic pollution inputs.

NH_4^+ levels were within the permissible limits (<0.5 mg/L), ranging between 0.21 and 0.37 mg/L. These values are similar to those found in Sândominic (0–0.38 mg/L) [16], but higher than those in Feleacu (0–0.22 mg/L) [15], and significantly greater than those reported in Mediaș (0.01–0.01 mg/L) [18], suggesting local hydrogeological conditions that favor the retention of NH_4^+ compounds.

The pH values ranged from 6.8 to 9.0, with most samples exhibiting a slightly alkaline character (pH >8). However, some samples with pH below 7.0 were also identified, where the presence of dissolved carbon dioxide and organic fermentation processes may promote the mobilization of potentially toxic compounds (e.g., metals). The range determined is comparable to that reported in Feleacu (6.5–8.43) [15] but differs somewhat from the characteristic values of wells in Sândominic, where pH often falls below 7.0.

Electrical conductivity in water from Hodăi–Boian wells exhibited high values (2000–3300 µS/cm), with the threshold of 2500 µS/cm being exceeded in approximately half of the wells. This suggests pronounced natural mineralization, possibly amplified by inorganic inputs of anthropogenic origin, which may also indicate an increased microbiological risk. In comparison wells, electrical conductivity values were significantly lower, ranging between 671–1792 µS/cm [15] and 573–1532 µS/cm [16].

The elevated values of electrical conductivity and turbidity confirm both pronounced mineralization and the input of solid particles and dissolved substances, reflecting a direct influence of anthropogenic factors and local waste management practices.

The data analyzed reveal a clear correlation between animal density, distances to pollution sources, and the potential for chemical contamination of well water. Regular monitoring of key chemical indicators (NO_2^-, NO_3^-, NH_4^+ and where applicable, pesticides) is essential to prevent risks associated with the consumption of water from vulnerable sources. It is also recommended to strictly observe the minimum distance between wells and pollution sources, by current legislation and best rural management practices.

Overall, the data obtained underscore the necessity of continuous monitoring of these water sources, the implementation of sanitary protection measures, and the adoption of sustainable resource management practices to reduce contamination risks and ensure safe drinking water access for the local community.

Study Limitations

While this study provides a comprehensive chemical assessment of groundwater quality in domestic wells in Hodăi-Boian, certain limitations should be acknowledged. The analysis did not include microbiological parameters or specific toxic contaminants such as pesticides and heavy metals, which are important for a complete risk evaluation. Sampling was limited to a single period and does not capture seasonal fluctuations in water quality. Additionally, total dissolved solids (TDS) and salinity were estimated indirectly from electrical conductivity, and the nature of suspended particles in turbid samples was inferred from field evidence rather than direct microscopic analysis. Finally, to ensure privacy, precise geographical coordinates were omitted, which may limit the spatial resolution of exposure assessment.

Despite these limitations, the study provides valuable insights into groundwater quality in a vulnerable rural environment and offers a solid basis for future research.

Recommended Monitoring Strategy

To improve the quality of well water for rural inhabitants, it is strongly recommended to implement a systematic groundwater monitoring strategy at the community level. This should include regular testing of key physico-chemical and microbiological parameters (such as NO_3^-, NO_2^-, NH_4^+, pH, turbidity, electrical conductivity (EC), and bacterial indicators) at least twice per year, ideally in both dry and wet seasons.

Monitoring should be coordinated by local public health authorities in collaboration with water management experts and should involve clear protocols for sampling, data recording, and rapid communication of results to well owners.

Additionally, educational campaigns should be organized to raise awareness among local residents about potential contamination sources and the importance of maintaining sanitary protection zones around wells.

Where water quality problems are identified, targeted interventions—such as improving well construction, relocating animal shelters or latrines, and promoting water treatment solutions—should be promptly recommended and supported.

CONCLUSIONS

The chemical analysis of water from the 37 wells in the village of Hodăi-Boian revealed exceedances of the maximum admissible concentration for NO_2^- (0.5 mg/L) in seven cases, indicating possible recent organic or livestock-related pollution.

NO_3^- concentrations (18.0–48.0 mg/L) remained below the 50 mg/L threshold but reached values close to this limit in three wells, suggesting a constant input of nutrients from fertilizers or household infiltration.

NH_4^+ levels (0.23–0.37 mg/L), although below the 0.5 mg/L threshold, indicate microbiological activity and a potential risk of recent contamination.

Physico-chemical parameters (pH 6.8–9.0; turbidity 2.1–4.5 NTU; conductivity 2000–3300 µS/cm) reflect pronounced mineralization and the presence of fine suspended particles, with frequent exceedances of the recommended limits for drinking water, especially about conductivity.

The presence of pH values below 7.0 in three wells indicates organic fermentation processes, while temperatures of 11–13°C confirm the nature of shallow groundwater.

The results highlight a significant influence of anthropogenic activities on groundwater quality, posing potential risks for human consumption, especially in the case of unprotected or inadequately maintained sources.

EXPERIMENTAL SECTION

The village of Hodăi-Boian, located in the southeastern part of Cluj County (Ceanu Mare commune), lies within the low hilly area of the Transylvanian Plain (46°38′26.62″ N, 24°00′35.75″ E).

This rural settlement is characterized by a diverse agricultural landscape, traditional land use patterns, and temperate-continental climate—factors that shape both the local hydrographic network and groundwater resources.

The village's geographical position within the Transylvanian Plain determines not only soil composition and vegetation, but also directly influences the quality and availability of natural water sources of major scientific interest in the context of water supply and environmental monitoring in Central and Eastern European rural areas.

Characterization of the Studied Households

The aim of the present study was to provide a detailed assessment of the chemical quality of water from wells used for domestic and agricultural purposes within the territory of Ceanu Mare commune, with a particular focus on the village of Hodăi-Boian.

To highlight the influence of anthropogenic factors on water quality, the investigation focused on 37 households in Hodăi-Boian, each with its well (Figure 12). The sampling strategy was designed to ensure uniform coverage of the entire village area and to reflect the diversity of water use conditions.

For each household, data was collected regarding the intended use of water (domestic or agricultural), the number of inhabitants and farm animals (cattle, horses, pigs), as well as the average daily and monthly water consumption. In addition, relevant parameters for risk assessment were determined, including the water level and depth in the well, and the distance to animal shelters and latrines. The water level, depth of the wells, and distances to potential contamination sources (animal shelters, latrines) were measured in situ by the investigators using measuring tapes and field equipment. Information regarding water use and livestock numbers was collected through direct inquiry with well owners.

This integrated approach allowed for the identification of significant correlations between the chemical quality of water, potential sources of pollution, and the socio-economic characteristics of each household, thus providing a comprehensive picture of the risks and vulnerabilities associated with the use of local water sources in rural environments.

Chemical processes relevant in rural groundwater under the influence of agricultural and domestic contaminants

From a chemical perspective, groundwater in rural areas is subjected to complex processes involving the transformation of N compounds, SO_4^{2-}, heavy metals, and other substances originating from fertilizers, animal manure, latrines, as well as the use of pesticides or other plant protection products. Among them, the Ncycle involves reactions where organic compounds and NH_4^+ are gradually oxidized to NO_2^- and then to NO_3^-, under the action of nitrifying bacteria, as follows:

Ammonification and nitrification:

Organic matter → NH_4^+
$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O$ (Nitrosomonas bacteria)
$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$ (Nitrobacter bacteria)

Denitrification (under anaerobic conditions):

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2\uparrow$

These processes are significantly influenced by the water's pH and oxygen content. A slightly acidic or neutral pH and good aeration favor nitrification, while an alkaline environment or lack of oxygen favors the accumulation of NH_4^+ and reduction processes with possible release of nitrogenous gases into the atmosphere [29].

Regarding the pH, if the value is situated below 7 than it favors the solubilization of heavy metals and the occurrence of fermentation reactions. A pH value higher than 8 favors the accumulation of NH_4^+, which is no longer efficiently oxidized to NO_3^- [30].

Degradation processes of pesticides and organics: pesticides may undergo abiotic degradation (hydrolysis, photolysis) or biodegradation under the action of microorganisms [31], generating metabolites with variable toxicity following the reactions of hydrolysis of pesticides and enzymatic biodegradation, respectively:

$$R\text{-}Cl + H_2O \rightarrow R\text{-}OH + HCl$$
$$\text{Organic pesticide} + O_2 \rightarrow \text{Oxidized metabolites} + CO_2 + H_2O$$

These reactions are not specific to each compound but highlight the chemical complexity of contaminants in rural groundwater. Thus, groundwater contamination in wells is determined not only by the amount of infiltrated pollutants but also by the chemical specificity of the subsurface environment and the complex interactions between present compounds, pH, and bacterial activity, which can generate both mobilization and immobilization processes for substances with toxic potential.

Chemical Analysis of Water from the Investigated Wells

Water samples were collected in polyethylene containers, complying with the SR EN ISO 5667/2017 standard [32], transported to the laboratory in a refrigerated box, stored at 4°C, and analyzed within 24 hours from collection. Each sample was analyzed in triplicate, and the average of the values obtained was used to interpret the results. The chemical analysis of the samples aimed to identify the main risk factors for human health and agricultural water use at the local level.

The quality of the water samples collected from the domestic wells was determined by analyzing the following parameters: the concentration of NO_3^- and NO_2^-; turbidity; water conductivity; and the water pH.

The concentrations of NO_3^- and NO_2^- were determined spectrophotometrically using portable colorimeters (HANNA Instruments HI 96728 for NO_3^- and HI 96708 for NO_2^-; Hanna Instruments, USA). For NO_3^-, the cadmium reduction colorimetric method was applied (adapted according to EPA 353.2 [33] and ISO 7890-3:1988 [34]), with the reaction yielding an amber coloration measured at 525 nm. For NO_2^-, the ferrous sulfate colorimetric method was used (adapted from ISO 6777:1984 [35] and EPA 353.2 [33]), generating a greenish-brown tint read at 575 nm. Each measurement was performed using pre-dosed reagents and single-use optical cuvettes, following the manufacturer's instructions. The detection range was 0.0–30.0 mg/L for NO_3^- and 0–150 mg/L for NO_2^-.

NH_4^+ concentrations were determined in the field using a portable colorimeter (HANNA Instruments HI 93700, Hanna Instruments, USA) with salicylate-based reagents, according to the indophenol blue method (adapted from ISO 7150-1:1984 [36] and Standard Methods 4500-NH_3 [37]). The method relies on the reaction of NH_4^+ with salicylate and hypochlorite, forming a blue-green indophenol complex measured photometrically at 655 nm. Pre-dosed reagent packets and single-use optical cuvettes were used, as specified by the manufacturer. The detection range for NH_4^+-N was 0.00–0.80 mg/L.

The pH and electrical conductivity (EC) of water samples were measured using a portable multiparameter meter (HANNA Instruments HI 991301, Hanna Instruments, USA). pH was determined with a combined glass electrode, previously calibrated with standard buffer solutions (pH 4.01, 7.00, and 10.01) as per the manufacturer's protocol. Electrical conductivity was measured in µS/cm, with calibration performed using standard KCl solution. All measurements were conducted in situ, with the probe rinsed with distilled water between samples.

Turbidity was measured using a portable turbidimeter (HANNA Instruments HI 93703, Hanna Instruments, USA), based on the nephelometric method according to ISO 7027:1999 [38]. The instrument was calibrated with formazin standards, and turbidity was recorded in nephelometric turbidity units (NTU). Water samples were measured in optical glass cuvettes, with care to avoid air bubbles and sedimentation.

The results obtained were compared with the maximum allowable concentrations in drinking water, as specified by Directive (EU) 2020/2184 and Law 458/2002: 50 mg/L for NO_3^-, 0.5 mg/L for NO_2^-, and 0.5 mg/L for NH_4^+ [26,39].

In rural areas, where water supply is often provided by individual wells, a general threshold of 5 NTU is applied as the reference limit for potability, in accordance with national legislation and the requirements of European Directives [26–39].

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