

ASSESSMENT OF GROUNDWATER QUALITY IN THE DAK NONG AREA, LAM DONG PROVINCE (VIETNAM)

Purpose. This study aims to assess the current status of groundwater exploitation, identify primary pollution sources, and analyze temporal changes in groundwater quality in Dak Nong Province, thereby providing a scientific basis for the sustainable management and protection of this essential resource.

Methodology. The research combines field surveys, groundwater sampling, and laboratory analysis of key physico-chemical and microbiological parameters from 2019 to 2023. Data were processed using descriptive statistics, hydro-chemical diagrams, multivariate statistical analysis, and GIS integration to evaluate spatial and temporal variations in groundwater quality.

Findings. The results show that overall groundwater quality in Dak Nong is generally good and within national and WHO standards. However, specific parameters (Fe, Mn, NH_4^+ , NO_3^- , Coliform, and E. coli) exceeded thresholds in several locations, especially near landfills and cemeteries. Seasonal fluctuations and increasing concentrations of NO_3^- and NH_4^+ were observed in some areas, while microbiological pollution was widespread in shallow aquifers. Landfills and cemeteries were identified as the primary sources of pollution.

Originality. Unlike previous studies that mainly used indirect or model-based approaches, this research provides a comprehensive, up-to-date evaluation based on direct field measurements, supported by multivariate and GIS-based analyses. This allows for accurate identification of both pollution sources and groundwater quality trends across aquifers.

Practical value. The findings contribute scientific evidence to support groundwater management and planning in Dak Nong province. The study provides input for risk mapping, prioritization of “hotspot” areas, and policy recommendations, helping local authorities design effective strategies to reduce contamination, manage aquifer exploitation, and ensure water security under the pressures of climate change and socio-economic development.

Keywords: *Dak Nong, groundwater quality, exploitation status, groundwater*

Introduction. Clean water is a basic necessity in people’s daily lives [1]. Currently, the primary sources of water for human activities are two: surface water from rivers, streams, ponds, and lakes, and underground water sources [2]. In areas that often experience drought and water shortages, groundwater sources are crucial to daily activities [3]. Groundwater is one of the most vital natural resources for sustaining human life, supporting agricultural production, and driving industrial development [4, 5].

Globally, about 3 billion people depend on groundwater as their primary drinking water source. In Vietnam, particularly in the Central Highlands, groundwater is essential because surface water resources are unevenly distributed and seasonal. In Dak Nong province, groundwater serves as a key source for domestic use, irrigation, and industrial activities, making its sustainable management crucial for both environmental and socio-economic stability [6]. However, groundwater resources are increasingly under pressure from over-exploitation and contamination [7]. Declining water quality is a growing concern worldwide, driven by untreated do-

mestic wastewater, industrial effluents, agricultural runoff containing pesticides and fertilizers, and pollution from mining activities [8]. In addition, climate change and land-use changes are exacerbating these issues by altering recharge rates and increasing pollutant mobility [9]. Vietnam faces similar challenges, with several provinces reporting deterioration in groundwater quality, elevated concentrations of heavy metals, nitrates, and other contaminants, posing risks to public health and ecosystem integrity [10].

In the Dak Nong area, rapid socio-economic development, urban expansion, and intensive agriculture have led to a rising demand for groundwater extraction. Many boreholes and wells are drilled without systematic planning or licensing, and monitoring systems remain limited. Mining activities, particularly bauxite exploitation, pose additional risks of contamination from industrial waste. Despite these pressures, there is a lack of comprehensive studies that evaluate the current status of groundwater exploitation, identify key pollution sources, and analyze changes in groundwater quality over time in the province [6].

Previous research on groundwater quality assessment has employed a variety of approaches, including

fuzzy synthetic evaluation [11], groundwater sampling and analysis [12], estimation of the water quality index [13], GIS analysis [14], multivariate spatial analysis [15], statistical analysis [16], set pair analysis method [17], remote sensing [18], etc. Although the fuzzy synthetic evaluation method handles ambiguous and uncertain data well, allowing comprehensive assessment by flexibly combining water quality indicators and minimizing subjectivity in classification, it is complicated to establish fuzzy rules and weights, requiring high expertise, which can lead to subjective results if the rules are not clearly defined [11]. Complex data can be summarized into simple, easy-to-understand, and spatially comparable indices, but water-quality index methods may miss detailed information about some pollutants; depending on parameter and weight choices, they can introduce bias [13]. Despite its advantages of clear spatial display, integration of multi-source data to identify polluted areas, and fast and effective mapping and prediction, the GIS method can be limited by data resolution and struggles with real-time data [14]. The combination of GIS and remote sensing technology is used indirectly to assess groundwater quality by using surface indicators, such as soil moisture, geological deformation (via InSAR), and storage, combined with GIS for spatial analysis. However, it does not directly measure chemical parameters such as pH, heavy metals, or microbial contamination; instead, it primarily supports trend monitoring and source identification [18]. In addition, multivariate spatial analysis can handle multiple variables simultaneously, identifying pollution sources and spatial relationships; useful for big data and comprehensive assessment, but relatively complex, requiring large datasets and specialized software, and statistical assumptions can lead to errors if the data are not suitable [15]. Unlike the above method, the statistical analysis approach is more straightforward, lower-cost, and easier to integrate with other tools. However, this method can ignore spatial factors and requires extensive, high-quality data [16]. Although considered simple, flexible, and easy to calculate compared to other ambiguous methods, the Set Pair Analysis method has fewer practical applications than other methods due to its difficulty in handling complex data [17]. Overcoming some of the shortcomings of some of the above methods, such as providing direct, accurate, and real-time data from the field, helping to accurately identify specific pollutants that other methods, such as fuzzy, may miss due to abstraction or dependence on secondary data, the field investigation method can be used effectively to assess groundwater quality. Despite the disadvantages of cost and time, the outstanding advantages of reliability and local applicability make it most suitable for practical research, especially when combined with supporting methods such as GIS or statistics for data analysis. In addition, other methods are often more complex or less intuitive, while sampling and analysis ensure verifiable results and support sustainable management [12].

Given these considerations, this study adopts a field survey-based approach, combined with laboratory water-quality analysis, as its primary methodology. Field surveys allow for direct, location-specific measurement of physical and chemical parameters, ensuring data accuracy and reliability. This approach also enables the

collection of contextual information on local land use, waste-disposal practices, and potential pollution sources, which is critical for interpreting water-quality results. Although field surveys can be resource-intensive and may cover smaller areas compared to remote sensing methods, they provide a robust foundation for assessing real-world conditions, especially in areas like Dak Nong, where high-resolution, up-to-date spatial datasets are limited.

The objectives of this study are therefore threefold:

1) to assess the current exploitation status of groundwater in the Dak Nong area, including extraction volumes, usage patterns, and management practices;

2) to identify and evaluate primary waste sources impacting groundwater quality, such as domestic, agricultural, and industrial discharges;

3) to analyze changes in groundwater quality over time and propose recommendations for sustainable groundwater management. The findings aim to provide a scientific basis for local authorities to design and implement targeted measures to protect groundwater resources and ensure long-term water security for the province.

Study area. The Dak Nong area of Lam Dong province is located in the southwestern part of the Central Highlands, Vietnam, with a total natural area of approximately 6,515 km². Geographical coordinates limit it: from 11°45' to 12°50' North latitude, from 107°12' to 108°07' East longitude (Fig. 1).

Geographically, it borders Lam Dong and Dak Lak provinces to the east, Cambodia to the west and south with a 141 km-long borderline, and Binh Phuoc province to the south. The terrain is predominantly basaltic plateaus interspersed with low hills, with an average elevation of 500–700 m, offering high potential for agriculture on fertile red basalt soils. The river and stream network is relatively dense, with the Srepok River system serving as the central hydrological axis, along with numerous reservoirs and hydropower plants.

The climate is characterized by a tropical monsoon highland type, with two distinct seasons: the rainy season (May to October) and the dry season (November to April). The annual average temperature ranges between 22–23 °C with a low thermal amplitude; average annual rainfall is 2.2–2.5 m, concentrated mainly in the rainy season. These climatic conditions favor agricultural de-

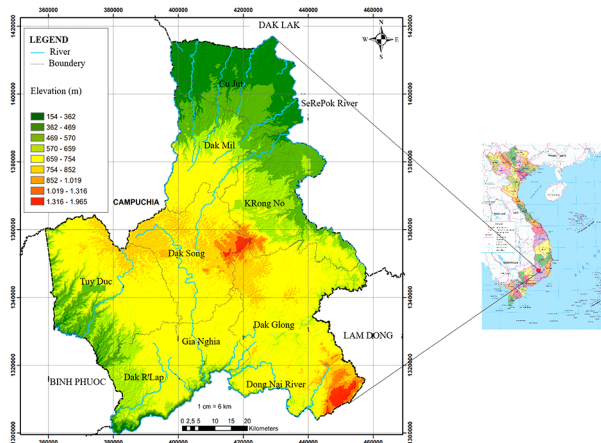


Fig. 1. Administrative map of the Dak Nong area, Lam Dong province

velopment but also pose risks of soil erosion and flash floods during the wet season.

According to 2021 statistics, the province has a population of about 622 thousand people, comprising various ethnic groups. The Kinh are the majority, alongside indigenous groups and migrants such as M'ngong, Ede, Tay, Nung, and Dao. The economy is primarily based on agriculture and forestry, mineral exploitation (including bauxite and construction materials), and hydropower development. However, resource exploitation activities, combined with the impacts of climate change, have exerted increasing pressure on the environment, particularly groundwater resources, which are the primary focus of this study.

Data and methodology. *Data.* The study was conducted based on the collection, inheritance, and synthesis of monitoring and investigation data from the Central Region Water Resources Planning & Investigation Federation, monitoring results (2019–2023), and related projects.

Spatial – geological – hydrological background data. Spatial data includes administrative boundaries at all levels (province, district, commune), main river and stream networks (Serepok, Dong Nai, and tributaries), reservoir and weir systems, along with terrain elevation layers (DEM, 30 m resolution) to serve the analysis of factors such as terrain, slope, flow, and basin division. Geological and hydrogeological data were collected based on geological maps and aquifer zoning maps, including the central units: Holocene bulk materials (qh), Pleistocene basalt eruptions (β_{qp}), Pliocene–Pleistocene basalt eruptions ($\beta(n_2 - qp)$), lower–middle Jurassic fissure sediments (j_{1-2}), and very poor or water-free units such as the Deo Bao Loc formation (J_{3dbl}), Don Duong formation (K_{2dd}) and intrusive magmatic rocks (Dinh Quan, Deo Ca, Ca Na). This information was compiled and standardized from multiple reports, projects, and related specialized documents, serving as the basis for analysis, assessment, and the establishment of maps of groundwater distribution and fluctuations in the province.

Meteorology and hydrology data. Meteorological and hydrological data are derived from monitoring data for the period 2019–2023 at the Dak Mil and Dak Nong stations, including air temperature, rainfall, humidity, evaporation, wind speed, and sunshine hours. This information is used to correct for seasonal factors (rain vs. dry) and to standardize seasonal groundwater quality indicators. At the same time, statistics on the irrigation and hydropower systems, including the number of lakes and dams by scale, are compiled to assess the level of surface flow regulation and its impact on groundwater recharge capacity.

Data on the current status of groundwater exploitation. Information on the current status of groundwater exploitation is compiled from the Department of Natural Resources and Environment's database and from previous investigation projects. The data includes a list of drilled and dug wells, geographical coordinates, exploited aquifers, well depth, static and dynamic water levels, design flow, and actual exploitation flow. In addition, pumping and testing logs (if any) are also inherited to serve the assessment of the exploitation capacity and performance of the works. This information plays a vital

role in determining the level of exploitation, assessing fluctuations in groundwater levels, and building a database to support the management and planning of sustainable groundwater resource exploitation.

Data on groundwater quality. Groundwater quality was assessed using monitoring and investigation data from previous periods, including basic physical-chemical parameters, major ions, nutrient indicators, and trace metals. In addition, the study also used new sampling data to supplement and update the status of groundwater quality in the study area. The monitoring results were compared with the thresholds and limits specified in the National Technical Regulation QCVN 09:2023/BTNMT on groundwater, issued by the Ministry of Natural Resources and Environment, to ensure the assessment is consistent with current groundwater quality standards in Vietnam. In addition, the World Health Organization (WHO, 2022) recommended standards were used for supplementary assessment, especially to determine indicators with a direct impact on human health when using groundwater. Simultaneous application of domestic and international standards enhances comprehensiveness and accuracy in assessing groundwater quality while supporting more effective management, exploitation, and protection of water resources.

Land used data. The land-use/land-cover data include major land types, such as agricultural land, residential areas, industrial areas, and forest land. In addition to these standard land classes, potential hotspots of environmental impacts are specifically identified, including landfills, cemeteries, agricultural processing facilities, industrial clusters, bauxite mining and processing areas, petrol stations, and livestock farms. This detailed classification helps accurately identify potential sources of environmental and land resource impacts in the study area. In addition, district-level socio-economic statistics are also integrated to support a comprehensive analysis of influencing factors, including population density, industrial development scale, agricultural structure, and other socio-economic activities. Combining land-use data with socio-economic information provides a basis for assessing the impact of mining and production activities on the natural environment, thereby enabling more effective land management and environmental protection solutions.

Methodology. Data collection. The study was carried out in a six-step process. First, the research team collected data on natural conditions, climate, soil, current land use, population, and production activities related to groundwater exploitation and use in Dak Nong. At the same time, existing documents from state management agencies on the location, flow, and exploitation purposes of wells were compiled, along with data on domestic, agricultural, and industrial waste sources that could potentially affect groundwater quality.

Sampling design and layout of measurement points. The next step is a field survey to verify the collected information, determine the exact location of the exploitation wells and monitoring wells, and make a preliminary assessment of the hydrological and geological characteristics, surrounding environmental conditions, and the potential level of pollution. On that basis, sampling points are selected to represent areas with different char-

acteristics in terms of population distribution, exploitation levels, and impacts from production and living activities. The sampling design is carried out according to the principle of stratification by water storage units and land use level. The selected monitoring points represent the aquifers qh , β_{qp} , $\beta(n_2 - qp)$, j_{1-2} , while giving priority to areas with high population density, intensive agricultural areas, and areas near potential waste sources. To reflect seasonal variations in recharge, samples were collected at least twice a year, corresponding to the dry season (November–April) and the rainy season (May–October). The types of sampling structures included household wells, public wells, and production wells, while wells with potential cross-contamination (open or uncased) were excluded. Field protocols were strictly followed, requiring at least three full-volume flushes of the water column or until field parameters (pH, EC, DO, temperature) were stable within $\pm 5\%$ before sampling.

Field measurement, sample collection, and preservation. During the sampling phase, groundwater samples were collected at the exploitation wells in accordance with current technical procedures (TCVN 5999:1995; TCVN 6663-11:2011). Field parameters, including pH, EC, TDS, temperature, DO, and ORP, were measured directly using multi-parameter devices calibrated daily; water levels were determined from field benchmarks. The samples were collected in HDPE plastic bottles (acid-washed for metals), glass jars (for COD and NH_3), and sterile jars (for microorganisms). After collection, the samples were stored and transported at $4 \pm 2^\circ\text{C}$, metal samples were acidified with HNO_3 , and the analysis was conducted according to APHA. To ensure quality (QA/QC), the field added a transport blank, duplicate sample ($\geq 10\%$), and spike sample to check recovery.

Laboratory analysis. Water samples were analyzed in a laboratory that meets ISO/IEC 17025 standards, in compliance with APHA standards (2017, 23rd/24th edition) and current Vietnamese regulations. Basic parameters include pH, hardness, TDS, Fe, Mn, Cl^- , SO_4^{2-} , NO_3^- , NH_4^+ , COD, and Coliform, reflecting the physicochemical and microbiological characteristics of groundwater. The primary ions determined include NO_3^- (Gran titration), Cl^- , SO_4^{2-} , NO_3^- (ion chromatography), Ca^{2+} , Mg^{2+} , Na^+ , K^+ (ICP-OES/ICP-MS or AAS). Nutrient groups and additional parameters such as NH_4^+ (phenate), PO_4^{3-} (ascorbic acid), Fe and Mn (ICP-OES), hardness and alkalinity (titration) were also analyzed in parallel. Total dissolved solids (TDS) were calculated from EC or determined by the filtration-drying method. Microbiological parameters (Coliforms, E. coli) were analyzed by membrane filtration. Quality control was strictly implemented through calibration coefficient of determination $R^2 \geq 0.995$, recovery 80–120 %, repeatability RPD $\leq 20\%$, and charge balance error (CBE) $|\text{CBE}| \leq 5\text{--}10\%$, ensuring data reliability and comparability.

Data processing and standardization. The analysis results were then processed using descriptive statistics, comparisons, and correlation analysis to assess regional differences. They were integrated into a GIS system to show the spatial distribution of water quality indicators. Data were checked for outliers using the IQR method and analyzed for distribution using the Shapiro–Wilk test. Values below the detection limit (DL) were calcu-

lated to reduce bias. The results were standardized by season and aquifer, and meteorological variables were interpolated to synchronize with the sampling time. Before hydrochemical analysis, the data were checked for neutralization and ion balance to ensure integrity. Monitoring data from different time points were also aggregated to identify trends in groundwater quality.

Hydrochemical analysis and determination of saturation index. After the data were normalized, the hydrochemical characteristics of groundwater were analyzed through Piper, Durov, and Stiff diagrams to determine the facies and clarify the dominance of major ions. On that basis, water evolution mechanisms such as ion exchange, dissolution-precipitation of carbonates and sulfates were inferred. At the same time, the saturation index (SI) for major minerals such as calcite, dolomite, and gypsum was calculated using PHREEQC or WATEQ4F to evaluate the corrosion-scaling tendency under the hydrochemical conditions of the aquifers.

Identifying impact sources and separating components. To analyze the sources of impact on groundwater quality, multivariate statistical methods were applied. Spearman correlation matrix was used to identify the relationship between variables, then principal component analysis (PCA, Varimax rotation) and hierarchical cluster analysis (HCA, Ward linkage method with Euclidean distance) were deployed to separate groups of variables, thereby identifying potential sources (natural background, agriculture, domestic/industrial wastewater, basalt weathering). In addition, the results were spatially correlated using GIS by overlaying the GWQI index and pollution indicators with land-use classes, distance classes to the discharge source (buffer 500–2,000 m), and mining work density (kernel density), thereby clarifying the relationship between discharge-source distribution and groundwater quality.

Trend and seasonal analysis. To assess seasonal variation in water quality, the parameters were compared between the wet and dry seasons using the Mann–Whitney U or the Wilcoxon signed-rank test for pairwise data. For multi-year series, the trend over time was tested using the Mann–Kendall test combined with Sen's slope. When the data had a clear seasonal pattern, the Seasonal-Kendall method was applied to separate the seasonal effects and identify long-term trends.

Water quality assessment. Finally, the assessment step involves comparing the analysis results with current groundwater quality standards. On that basis, the study assesses the current status of groundwater quality, identifies the primary sources of impact, and analyzes the fluctuation trends during the study period, thereby providing a scientific basis for the management, exploitation, and protection of groundwater resources in Dak Nong. To quantify the quality, the study uses the groundwater quality index (GWQI – weighted arithmetic) with the formula

$$W_i = \frac{k}{S_i}; \quad Q_i = \left(\frac{C_i}{S_i} \right) \times 100; \quad GWQI = \frac{\sum W_i Q_i}{W_i}$$

where W_i is weight of the i^{th} parameter; S_i is standard permissible value of the i^{th} parameter; C_i is observed concentration of the i^{th} parameter; k is proportionality constant ensuring that the sum of weights equals 1.

The GWQI results are classified into: very good (<50), good (50–100), poor (100–200), poor (200–300), and unsuitable (> 300). In addition, to evaluate irrigation usability, the SAR, %Na, RSC, PI, KR, MH, and indices are calculated and illustrated on USSL and Wilcox charts to provide a more comprehensive view of the quality and suitability of water resources for agriculture.

Results and discussion. Current status of groundwater exploitation and use. Groundwater resources in the Dak Nong area play an essential role in the life and socio-economic development of the locality, especially amid an insufficient surface water supply due to harsh, fluctuating climate conditions. The whole province has 4,873 boreholes/wells exploiting groundwater, with a total exploitation flow of 19,208.4 m³/day. Cu Jut district has the highest number of exploitation works and flow, with 770 works and 6,056.9 m³/day, accounting for 31.5 % of the total exploitation flow. Gia Nghia city has the fewest exploitation works, with 272 works and a flow of 544.5 m³/day. There are 163 large exploitation projects ($Q \geq 10$ m³/day) with a total flow of 13,809.3 m³/day, focusing on serving production, business, services, and daily life. Most of the exploitation is mainly in the Pliocene – Pleistocene β Basalt aquifer (n-qp), accounting for 55.23 % of the total flow, followed by the lower – middle Jurassic aquifer (j1-2), accounting for 44.47 %. The Holocene aquifer (qh) accounts for a minimal flow rate of 0.3 %. Regarding the purpose of use, groundwater exploitation is mainly for daily life (57.86 %), followed by production and livestock (39.57 %), and to a lesser extent for irrigation of industrial crops, especially coffee (2.57 %).

Fluctuations in groundwater quality and pollution levels. Groundwater quality is assessed based on water sample analysis results from 2019 to 2023. Table 1 summarizes the sample rate exceeding some key indicators in 2023. The results show that most of the monitoring indicators such as pH, total dissolved solids (TDS), hardness, chemical indicators (NH₄⁺, NO₂⁻, NO₃⁻, Cl⁻, F⁻, SO₄²⁻, As, Cd, Pb, Cr, Cu, Zn, Hg) are within the allowable limits of Vietnam Standard QCVN 09:2023/ BTNMT, showing that groundwater in Dak Nong basically maintains quite good quality. However, groundwater quality in the Dak Nong area has clear fluctuations between aquifers.

Fig. 2 clearly visualizes the status of groundwater quality in Dak Nong, highlighting microbiological contamination as the most significant concern. The data drawn from Table 1 demonstrates a pronounced disparity between microbiological and chemical/metallic con-

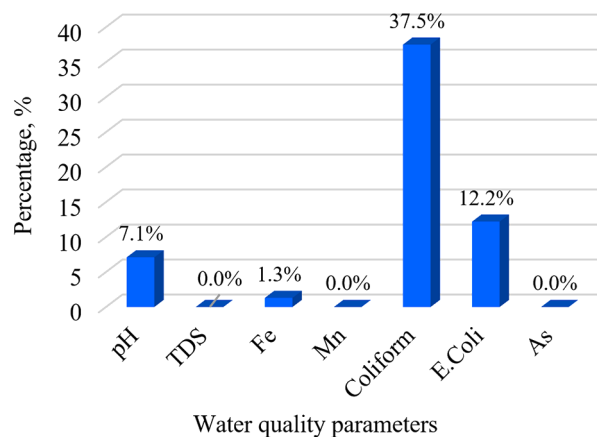


Fig. 2. The sample rate (%) exceeded some key indicators in 2023

tamination. Coliform has the highest exceedance rate at 37.5 %, followed by E. Coli at 12.2 %. This high frequency confirms extensive anthropogenic pollution from untreated household waste and poor sanitation practices. In contrast, most metallic indicators, including Mn and As, show an exceedance rate of 0 %, and Iron (Fe) is very low at 1.3 %. This confirms that, while overall water quality remains relatively good, the most pressing issue for management is controlling microbiological contamination.

In the Holocene layer (qh), the water is mainly of the light type, bicarbonate-sodium chloride and calcium bicarbonate. Still, up to 33.3 % of samples have pH exceeding the standard, 25 % exceed the Fe standard, and 100 % exceed the Coliform standard, with some places 800 times higher. Severe microbiological pollution is concentrated in the communes of Duc Xuyen, Dak Nang, and Truc Son, and in the center of Dak Mam town (Krong No district). Although the concentrations of Fe and Mn have decreased in recent years, they still exceed the threshold at times. As it has not exceeded the standard, but Coliform and E. Coli are very high, mainly due to the water source being directly drawn from untreated household wells and the pumping equipment not being cleaned periodically.

In the Pliocene – Pleistocene Basalt layer [β (n-qp)], the water has a light composition, mainly sodium bicarbonate and calcium–magnesium bicarbonate; most parameters such as TDS, hardness, NO₂⁻, NO₃⁻, Cl⁻, F⁻, SO₄²⁻, As, Cd, Cr, Cu, Zn, Mn, Hg, Fe are within the standard. However, some samples exceed pH, NH₄⁺, Pb, Phenol, Coliform, and E. Coli, especially Coliform, which exceeds in 37.5 % of samples, with the location near the Gia Nghia landfill showing the highest value, 800 times higher than the standard. NO₃⁻ concentration exceeds the threshold in Nghia Trung ward (Gia Nghia city), near Doi Phao cemetery; Mn and NH₄⁺ tend to increase at some monitoring points during 2022–2023.

For the lower-middle Jurassic layer (j₁₋₂), fresh water is of the sodium bicarbonate and sodium–magnesium bicarbonate types; in general, the parameters of pH, TDS, hardness, NH₄⁺, NO₂⁻, NO₃⁻, Cl⁻, F⁻, and SO₄²⁻ do not exceed the standards. Only Fe exceeded in one sample (4.8 %), and Coliform exceeded in 25 % of samples, mainly in Dak Mam town (Krong No); As slightly exceeded in one year at one monitoring point. Notably,

Table 1

Summary of sample rates exceeding some key indicators in 2023

Parameters	Number of samples	Number of samples exceeding the standard	Rate, %
pH	84	6	7.1
TDS	85	0	0
Fe	76	1	1.3
Mn	84	0	0
Coliform	80	30	37.5
E. Coli	49	6	12.2
As	95	0	0

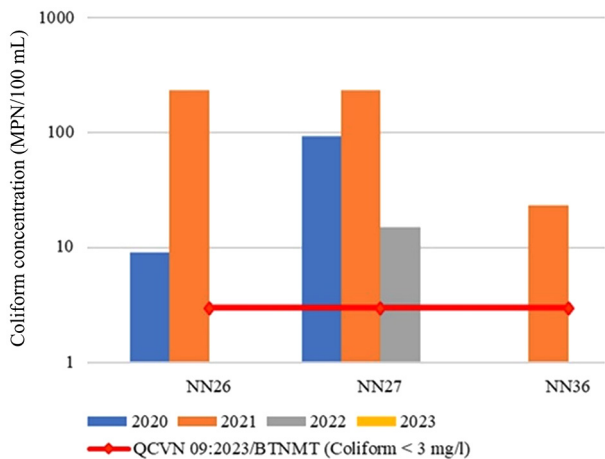


Fig. 3. Coliform concentration chart at groundwater monitoring points TCN_{j-2} in 2020–2023

Coliform levels were many times higher during 2020–2022, but by 2023 they had decreased and met the standard (Fig. 3).

Current status and distribution of impacting waste sources. The primary sources of waste affecting groundwater quality are landfills and cemeteries distributed in the province. The province has 14 landfills/burial sites, most of which lack a waterproof lining system and are poorly treated or untreated (except for Truong Son 1 Waste Treatment Plant – Cu Jut). This increases the risk of waste seeping into the groundwater, especially during the rainy season. In addition, the Dak Nong area has 142 cemeteries, with high density concentrated in Dak Mil, Dak R’lap, Cu Jut, and Dak G’long districts. These cemeteries often lack surrounding walls or wastewater collection systems. Large cemeteries (over 8,800 graves) concentrated in Cu Jut, Dak R’lap, Dak Mil, and Dak G’long districts are identified as having a high risk of pollution due to water seeping from burial areas into the aquifer. Furthermore, agricultural, livestock, urban, and industrial production activities have been abusing fertilizers and chemicals, and discharging untreated wastewater from industrial parks, factories, and small urban areas, increasing the risk of groundwater pollution.

This finding is strongly supported by the risk assessment maps for primary pollution sources (Figs. 4 and 5). The susceptibility mapping clearly delineates the high-risk zones surrounding landfills and cemeteries, characterized by geological and hydrological conditions favorable to contaminant infiltration. Specifically, the areas where Coliform and NO₃ exceedance were observed are spatially correlated with the zones classified as high or very high potential for pollution in Fig. 4 (Cemeteries) and Fig. 5 (Landfills). This spatial coincidence confirms that the observed localized contamination, particularly the extremely high Coliform levels near the Gia Nghia landfill and NO₃ near the Doi Phao cemetery, results from the lateral and vertical migration of leachate from these specific anthropogenic sources. This reinforces the conclusion that water quality degradation in the Bazan aquifer is primarily driven by point-source pollution resulting from inadequate waste management.

Challenges and solutions. The research results show that groundwater plays a vital role in life and production

in the Dak Nong area, which often suffers from drought and water shortages. However, this resource faces the risk of declining reserves and quality. From 2019 to 2023, although groundwater quality was generally quite good and within the permissible limits of the National Technical Regulation (QCVN 09:2023/BTNMT), some essential indicators showed signs of pollution and exceeded the limits at many locations and times. Groundwater levels in some areas, especially in Dak Mil and Cu Jut districts, have decreased significantly due to overexploitation for agricultural production.

The main challenges facing water resources in Dak Nong today include overexploitation of groundwater due to high demand for domestic use and irrigation of industrial crops, especially coffee, leading to decreased water levels and depletion of water resources during the dry season. In addition, water pollution from waste areas such as landfills and cemeteries is also a serious problem, with groundwater pollution levels far exceeding the allowable

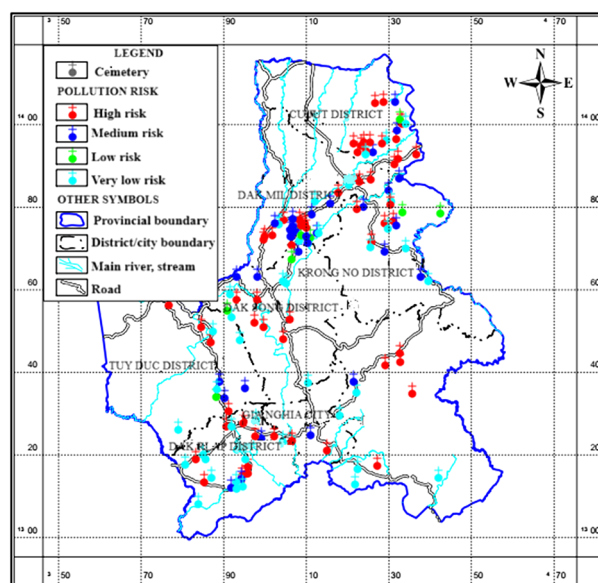


Fig. 4. Map of the classification of pollution potential of cemeteries

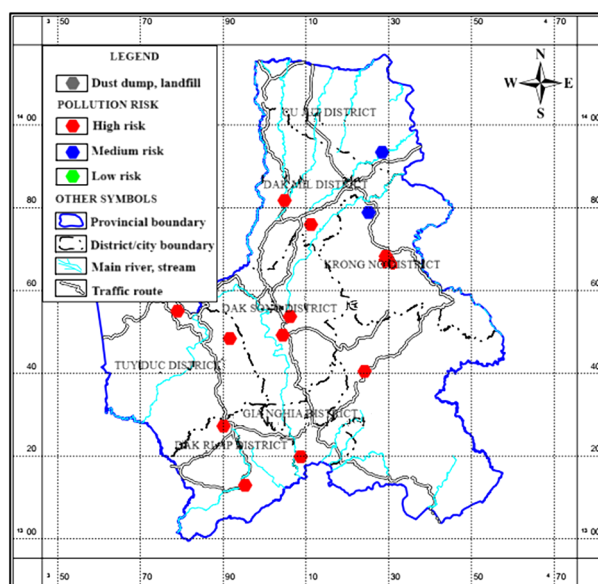


Fig. 5. Map of landfill pollution potential classification

limit. For example, the groundwater near Gia Nghia landfill has a Coliform content 800 times higher. In addition, the management of groundwater exploitation systems lacks precise planning and licensing, and water supply works are poorly inspected and maintained due to limited funding and human resources, making groundwater exploitation difficult to control and causing significant long-term negative impacts on water resources.

With the above current situation, solutions to protect and sustainably manage groundwater in Dak Nong need to be implemented synchronously from the exploitation households to the provincial level. In this study, the author proposed a comprehensive solution package, implemented from the household, community, to district and provincial levels, to protect and sustainably manage groundwater in Dak Nong. At the household and community levels, priority should be given to simple and effective measures such as periodic disinfection (shock-chlorination) and flushing, maintenance, and cleaning of the pump/pipe system; covering and protecting well mouths, establishing a minimum sanitary protection zone of 20 m around the well; encouraging the installation of small-scale pre-treatment (aeration → sedimentation → filtration → disinfection) for directly exploited water sources to quickly reduce microbiological pollution at “hot spots” (Duc Xuyen, Dak Nang, Truc Son, Dak Mam) and especially locations close to Gia Nghia landfill or Nghia Trung area. Regarding waste source control, priority should be given to upgrading landfills/dumpsites into sanitary landfills with waterproofing layers, leachate collection & treatment systems, closing and rehabilitating high-risk landfills; reviewing, planning, and resolutely handling cemeteries with high density or located on highly permeable geological layers (ensuring safe distances from exploitation wells, fences, and wastewater collection systems of cemeteries).

At the scale of resource exploitation, it is necessary to restructure licensing and quotas for each aquifer (priority should be given to reducing exploitation in areas with declining water levels such as Dak Mil and Cu Jut), updating registration books/licenses, controlling and penalizing illegal exploitation wells, and at the same time encouraging the shift of part of agricultural irrigation needs to surface water sources or rainwater storage solutions, applying water-saving irrigation (drip, mulching) to reduce pressure on aquifers. Regarding monitoring and data management, it is necessary to strengthen the seasonal and aquifer monitoring network (at least two periods/year, rainy/dry), integrate the GWQI index and multivariate analysis (PCA/HCA, GIS) to detect abnormalities early, build a central database, and a “hotspot” risk map updated annually as a management decision-making tool.

Regarding technical measures for treatment/remediation at heavily polluted sites: deploy emergency isolation-disinfection measures, consider centralized treatment solutions for landfill leachate (collection → biological treatment/disinfection), and in chemical/metal contaminated cells, it is necessary to assess the landfill treatment capacity (pump-and-treat, permeable reactive barrier) based on the results of geological-hydrological investigations. At the institutional and operational levels, it is necessary to complete and promulgate a plan

for managing groundwater quality at the provincial level, assigning inter-sectoral responsibilities (environmental resources, agriculture, Health, localities), designing a program for periodic inspection and testing, and emergency response; along with that is a communication and training program for the community on well sanitation, operating small treatment systems, and an investment support mechanism (preferential loans, technical support) for projects upgrading landfills, centralized water supply systems, and rainwater collection infrastructure. Priority is given to implementation according to the roadmap:

1) urgent – treating Coliform/E.coli hotspots and cleaning household wells;

2) medium-term – upgrading landfills, planning cemeteries, strengthening monitoring networks;

3) long-term – managing exploitation by aquifer, developing enhanced water compensation plans, and completing the legal/economic framework to ensure harmonious and sustainable exploitation and protection.

Conclusion. The study was conducted to assess groundwater quality in the Dak Nong area comprehensively, determine the current status of exploitation and the level of impact from waste sources, and analyze variations in water quality over space and time. Data were collected through field surveys, taking representative groundwater samples at the principal aquifers (qh , $\beta(n-qp)$, j_{1-2}), in two rainy and dry seasons. Water quality indicators (physical chemistry, heavy metals, nutrients, microbiology) were analyzed according to APHA standards and compared with QCVN and WHO. The results showed that groundwater quality in Dak Nong is generally quite good, with most parameters within standards. However, microbiological pollution (Coliform, E. coli) is common in the Holocene layer (qh) and locally in the basalt layer $\beta(n-qp)$, especially serious in areas near Gia Nghia landfill, Nghia Trung cemetery, and some communes in Krong No.

Parameters Fe, Mn, NH_4^+ , and NO_3^- exceeded the standard at times, in which NO_3^- and NH_4^+ tended to increase at some points in the period 2022–2023. The lower-middle Jurassic layer (j_{1-2}) was generally less affected, but still had Coliform exceeding the standard in the period 2020–2022. The study provides the necessary scientific evidence for planning and managing groundwater resources in Dak Nong, particularly for developing risk maps, guiding sustainable exploitation of each aquifer, and issuing policies to control waste sources.

The results also serve as the basis for the province to implement community communication programs on water, sanitation, hygiene, and safe water use, while contributing to ensuring water security amid climate change and rising exploitation demand. In the future, if we deploy solutions in a synchronized manner, such as strengthening monitoring, managing aquifer exploitation, controlling landfills and cemeteries, and applying measures to treat household domestic water, groundwater quality can be fully protected and improved.

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Оцінка якості підземних вод у районі Дак Нонг, провінція Ламдонг (В'єтнам)

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Мета. Оцінка сучасного стану експлуатації підземних вод, визначення основних джерел забруднення й аналіз часових змін якості підземних вод у провінції Дак Нонг, що забезпечує наукове підґрунтя для сталого управління й захисту цього важливого ресурсу.

Методика. Дослідження поєднує польові обстеження, відбір проб підземних вод і лабораторний аналіз основних фізико-хімічних і мікробіологічних показників за період 2019–2023 рр. Обробка даних здійснювалася із використанням описової статистики, гідрохімічних діаграм, багатовимірного статистичного аналізу й інтеграції ГІС з метою оцінки просторово-часових змін якості підземних вод.

Результати. Отримані результати свідчать про те, що загалом якість підземних вод у провінції Дак Нонг є задовільною й відповідає національним нормативам і рекомендаціям ВООЗ. Водночас у низці пунктів зафіксовано перевищення гранично допустимих концентрацій окремих показників (Fe, Mn, NH₄⁺, NO₃⁻, коліформи та *E. coli*), особливо поблизу полігонів твердих відходів і кладовищ. У деяких районах спостерігаються сезонні коливання й тенденція до зростання концентрацій NO₃⁻ і NH₄⁺, тоді як мікробіологічне забруднення є поширеним у неглибоких водоносних горизонтах. Основними джерелами забруднення визначені полігони відходів і кладовища.

Наукова новизна. На відміну від попередніх досліджень, у яких переважно застосовувалися непрямі або модельні підходи, у цій роботі представлена комплексна й актуальна оцінка якості підземних вод на основі безпосередніх польових вимірювань, доповнених багатовимірним аналізом і ГІС. Це дозволяє точно ідентифікувати джерела забруднення та простежити тенденції зміни якості підземних вод у різних водоносних горизонтах.

Практична значимість. Результати дослідження формують наукову основу для управління та планування використання підземних вод у провінції Дак Нонг. Отримані дані можуть бути використані для картування ризиків, визначення пріоритетних «гарячих точок» і розроблення рекомендацій для органів влади щодо зменшення забруднення, раціонального управління експлуатацією водоносних горизонтів і забезпечення водної безпеки в умовах кліматичних змін і соціально-економічного розвитку.

Ключові слова: Дак Нонг, якість підземних вод, стан експлуатації, підземні води

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