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Hydrogeological assessment and temperature heterogeneity of the Karadala geothermal groundwater field on the left bank of the Ili River

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Abstract. The Karadala groundwater field in southeastern Kazakhstan is an important source of fresh confined groundwater and a potential low-temperature geothermal resource. This study aimed to characterize its hydrogeological setting and temperature heterogeneity within a defined study area on the left bank of the Ili River using archival records from 1968-1971 and hydrogeological survey materials from 2022-2024. A dataset comprising 15 wells located within the study-area polygon was analysed using descriptive statistics, Pearson and Spearman correlation analyses, and ordinary least-squares regression to assess the relationship between reported well depth and groundwater temperature. Well depths ranged from 420 to 663.5 m, while groundwater temperatures ranged from 22.0 to 42.4°C. A moderate positive relationship was observed between depth and temperature (Pearson's $r = 0.554$, $p = 0.032$; Spearman's $\rho = 0.666$, $p = 0.007$; $R^2 = 0.307$), together with pronounced temperature differences among wells of similar depths. The results indicate that well depth explains only part of the observed temperature variability and that the potential effects of localized groundwater flow, aquifer mixing, screened intervals, and tectonic controls require further investigation through standardized monitoring, static temperature logging, hydrochemical analysis, and environmental-tracer techniques.

Keywords: *Karadala, Ili artesian basin, Zharkent basin, Upper Cretaceous aquifer, thermal groundwater, temperature anomaly, monitoring.*

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1. Introduction

Groundwater is a major source of domestic and agricultural water supply in southeastern Kazakhstan, particularly in arid regions and irrigated farming areas [1, 2]. Thermal groundwater resources of the Ili and Zharkent basins are also used for water supply, recreation, and balneological purposes and have potential for direct geothermal applications [2, 3]. The eastern part of the Ili artesian basin, commonly referred to as the Zharkent Basin, contains substantial reserves of low-mineralized thermal groundwater and is locally characterized by elevated geothermal gradients [2].

The Karadala groundwater field is an important hydrogeological unit in the southeastern part of the Ili artesian basin. It extends approximately 100 km eastward from the town of Shonzhy (Chundzha) and comprises Quaternary, Neogene, Cretaceous, and Jurassic aquifer systems [4, 5]. The Middle–Upper Pliocene and Upper Cretaceous aquifers are of the greatest practical importance. Exploration of the field began in the late 1960s, followed by detailed drilling and aquifer testing in 1970-1971 [4, 6].

Despite several decades of groundwater abstraction, the origin, recharge mechanisms, and renewal conditions of the Karadala thermal groundwater system remain poorly understood [2, 4, 5]. In particular, limited direct information is available on groundwater age, residence time, the proportion of modern recharge, and the flow pathways connecting mountain recharge areas with production wells. These uncertainties are important because groundwater resources characterized by slow recharge may experience long-term piezometric-head decline if abstraction exceeds natural replenishment.

The Zharkent Basin is an intermontane sedimentary basin bounded by the Ketmen Range to the south and by the Kalkan and Katutau ranges and the Dzungarian Alatau to the north and northeast. Eastward, it continues into the Yili Basin in China. The basin comprises a Paleozoic basement composed predominantly of volcanic rocks overlain by Mesozoic and Cenozoic basin-fill deposits [2]. Recent regional interpretations suggest that the basin developed under extensional and strike-slip tectonic conditions and was subsequently modified by strike-slip and oblique faulting. These tectonic processes may have influenced sediment thickness, regional heat flow, and groundwater circulation [2].

Regional geothermal gradients are generally approximately 40°C/km and locally reach about 55°C/km within the Shonzhy–Dobyn geothermal anomaly [3]. Kan [6] provided one of the earliest descriptions of the spatial and temporal

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variability of groundwater temperature in the Ili Depression. Subsequent studies of the Karadala area linked the recharge and thermal characteristics of the Upper Cretaceous aquifer to deep groundwater circulation and potentially to structurally controlled groundwater flow and discharge [2, 8].

Groundwater from the Upper Cretaceous aquifer has reported temperatures of approximately 20-60°C at depths of several hundred metres, while its total dissolved solids concentration is generally below 1 g/L [2, 4, 8]. These characteristics are favourable for direct low-temperature geothermal applications. However, a reliable assessment of the geothermal resource requires information on formation temperatures, sustainable yields, hydrochemical compatibility, and the long-term hydraulic response of the aquifer [2, 9-12]. Studies of other low- and medium-temperature geothermal systems demonstrate the importance of integrating geological structure, hydrochemistry, isotope composition, geothermometry, water-rock interactions, and regional groundwater-flow analysis [9-12].

The Karadala hydrogeological succession forms a multilayered artesian system. Across much of the field, a Miocene clay aquitard separates the Middle–Upper Pliocene sandy and gravelly deposits from the Upper Cretaceous sands and sandstones [4, 8]. Nevertheless, archival drilling records suggest that hydraulic windows may occur near the mountain front, potentially allowing hydraulic connections between these aquifer units [4]. Reported discharge rates from the Pliocene aquifer range from 6.9 to 40 L/s at drawdowns of 4.6-10 m. Wells completed in the Upper Cretaceous aquifer have reported discharge rates of 14.6-191 L/s at drawdowns of 12.8-71.5 m. Piezometric heads range from approximately 14.7 to 111 m above ground level, while total dissolved solids concentrations generally range from 0.2 to 0.8 g/L [4, 5]. A recent hydrogeological reassessment supplemented the archival information with field observations and well documentation collected during 2022-2024 [5].

The most recent evidence concerning the possible origin of recharge is provided by regional hydrochemical and stable-isotope studies [2, 3, 13]. Groundwater in the Upper Cretaceous aquifer is characterized by depleted $\delta^{18}O$ and $\delta^{2}H$ values, which may indicate high-elevation recharge derived primarily from precipitation and snowmelt, with a possible contribution from glacial meltwater [2]. Potential recharge pathways include infiltration along the mountain front and subsurface flow through fractured bedrock in the surrounding mountain ranges [2]. A recent hydrogeochemical investigation of Cretaceous geothermal groundwater in the Zharkunak zone further characterized the regional hydrochemical signature of the thermal groundwater system in the eastern Ili Depression [3].

Although these regional findings provide a preliminary conceptual model for the Karadala field, they cannot replace site-specific measurements. Stable isotopes, particularly $\delta^{18}O$ and $\delta^{2}H$, can help identify groundwater recharge sources and mixing processes [13-15], whereas tritium (^{3}H) and radiocarbon (^{14}C) can constrain different groundwater-age ranges [14, 15]. When applied together, these environmental tracers can help distinguish modern and older groundwater components and determine whether current abstraction induces recharge into the deep aquifer system. However, the absence of detectable tritium alone does not demonstrate that groundwater is fossil, because the result may also reflect analytical detection limits, radioactive decay, sampling procedures, or mixing with older groundwater [14, 15].

Consequently, site-specific measurements of $\delta^{18}O$, $\delta^{2}H$, ^{3}H, and ^{14}C in the Karadala groundwater field should be combined with standardized hydraulic monitoring, hydrochemical analyses, static temperature logging, and groundwater-flow modelling [2, 9-12, 14, 15]. Such an integrated approach would improve understanding of recharge pathways and groundwater residence-time distributions and provide a more reliable basis for assessing the sustainability of long-term groundwater abstraction and geothermal utilization.

This study aims to characterize the hydrogeological framework and groundwater-temperature heterogeneity of the left-bank part of the Karadala groundwater field using archival exploration records and hydrogeological survey data collected during 2022-2024. The specific objectives are to:

– systematize the available aquifer and well parameters;

– analyse the relationship between reported total well depth and groundwater temperature for 15 wells located within the defined study area;

– evaluate the limitations affecting the comparability of historical and recent groundwater observations;

– identify priorities for standardized monitoring and further hydrogeological and geothermal investigation.

2. Materials and methods

2.1. Study area

The Karadala groundwater field is located in the eastern part of the Ili artesian basin. It extends approximately 100 km eastward from the village of Shonzhy (Chundzha) towards the national border with China. In the north-south direction, the study area extends approximately 20 km northward from the foothills of the Ketmen Range [4, 5] (Figure 1).

Regionally, the study area belongs to the Zharkent Basin, which is bounded by the Ketmen Range to the south and by the Kalkan and Katutau ranges and the Dzungarian Alatau to the north and northeast. Eastward, the depression continues into China as the Yili Basin [32]. The landscape is characterized by a gently undulating piedmont plain that slopes northward towards the Ili River valley. Permanent surface watercourses are limited, and groundwater recharge is inferred to be associated mainly with runoff from the northern slope of the Ketmen Range and the infiltration of precipitation and snowmelt [2, 4]. During 2019-2023, the annual mean air temperature recorded at nearby meteorological stations ranged from 10.64 to 11.84°C. Annual precipitation at the Zharkent meteorological station ranged from 156.1 to 206.7 mm during the same period [5].

The geological succession comprises Paleozoic, Mesozoic, and Cenozoic formations. The mountainous margins and basement of the depression consist predominantly of Paleozoic volcanic and sedimentary rocks. The sedimentary cover comprises Jurassic, Upper Cretaceous, Miocene, Middle–Upper Pliocene, and Quaternary deposits [2, 4] (Figure 2).

The Upper Cretaceous succession consists mainly of quartz sands of variable grain size, sandstones, clays, and mudstones. The Middle–Upper Pliocene deposits of the Ili Formation comprise sands, gravel–pebble sediments, and clay interbeds. The principal hydrogeological characteristics of these aquifer systems, including their lithology, thickness, well discharge, drawdown, and groundwater mineralization, are summarized in Table 1. A regionally extensive Miocene clay aquitard separates the Pliocene and Upper Cretaceous aquifer systems across much of the study area.

Table 1. Summary of the principal aquifer systems based on archival and reassessment data [4, 5]

Aquifer unit	Water-bearing lithology	Thickness, m	Discharge and drawdown	Total dissolved solids, g/L
Middle–Upper Pliocene aquifer system	Sands and gravel-pebble deposits	112-223; permeable inter-layers 1-70	6.9-40 L/s at S =4.6-10 m	0.2-0.7
Upper Cretaceous aquifer	Variably grained sands and sandstones	81-175	14.6–191 L/s at S = 12.8–71.5 m	0.2-0.8

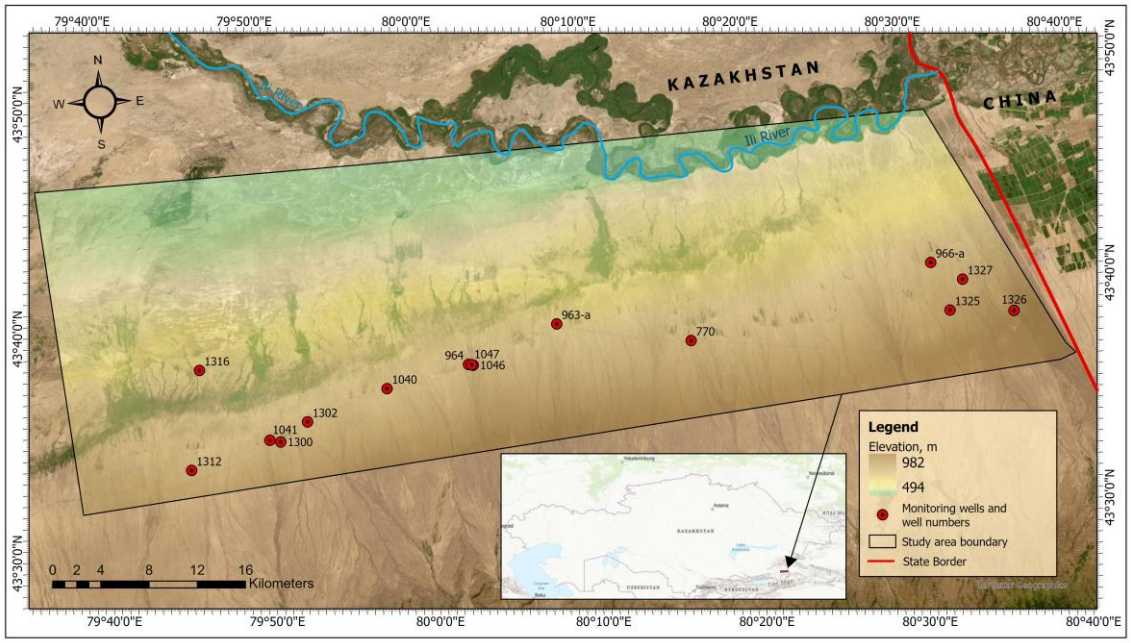


Figure 1. Location of the Karadala groundwater field

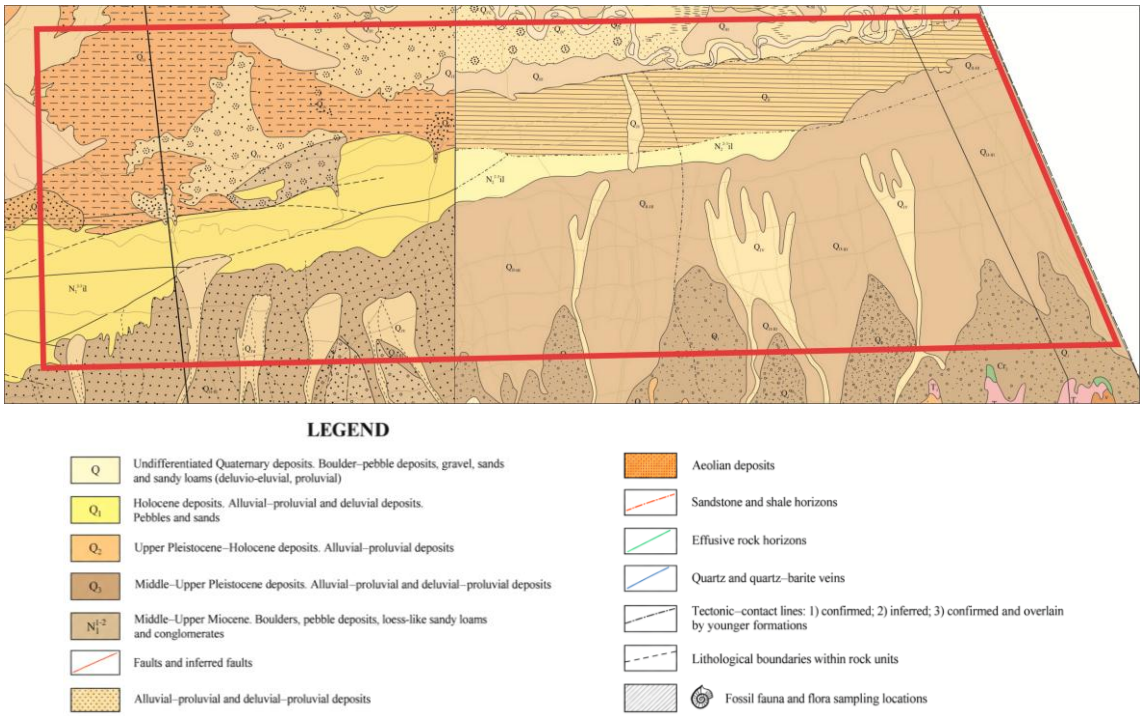


Figure 2. Fragment of the geological map at a scale of 1:200000 (the boundary of the study area of the Karadala groundwater field)

2.2. Data sources and well selection

This study used three principal sources of information:

– archival documentation of groundwater exploration conducted in 1968–1971, including drilling records, geophysical well logs, aquifer tests, groundwater-level observations, and temperature measurements [4];

– (2) the hydrogeological reassessment report for map sheets K-44-II and K-44-III (Figure 3), based on field investigations conducted in 2022–2024 [8];

– (3) published regional studies of the hydrogeology and geothermal conditions of the Zharkent Basin [2, 3].

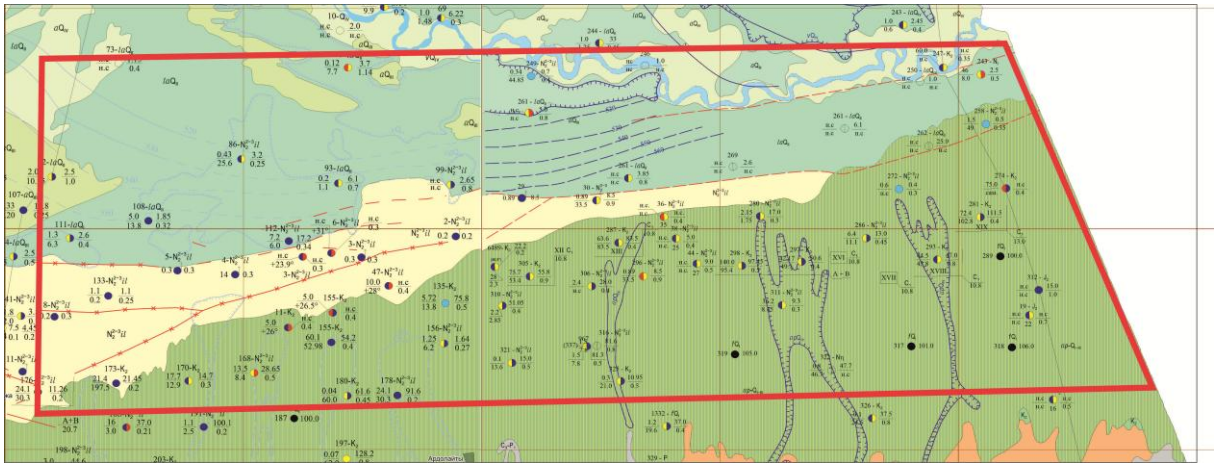


Figure 3. Hydrogeological map fragment of the Karadala groundwater field based on the 202202024 reassessment (scale 1:200000)

The quantitative analysis included 15 wells located on the left bank of the Ili River. This area represents the part of the Karadala groundwater field selected for the present study. All 15 wells had available well identifiers, coordinates, reported total depths, and groundwater-temperature values. Their locations were checked against the boundary provided in the Study area Karadala KMZ file, and all wells were located within the study-area polygon. Archival data were used to describe the hydrogeological structure, historical groundwater conditions, and earlier temperature observations. The statistical analysis was conducted only for the selected dataset of 15 wells. This separation reduced the risk of combining historical and recent measurements obtained using different methods and under different operating conditions.

2.3. Field measurements and spatial data

According to the 2022-2024 reassessment report, the regional field investigation was conducted at a scale of 1:200000 and included hydrogeological routes, inspection of flowing and non-flowing wells, groundwater observations, water sampling, and office-based data processing [5]. Field locations were determined using Garmin GPS receivers. Topographic maps and satellite and aerial images were also used to plan the field routes and interpret hydrogeological conditions.

Water temperature was measured using a TS-7-M1 liquid thermometer with a reported accuracy of 0.1°C. During measurement, the sensing part of the thermometer was submerged in water for approximately 2-3 minutes [5]. For flowing artesian wells, the recorded value represents the water temperature measured at the discharge point rather than an equilibrium formation temperature at depth.

The reported total well depth was used as the depth variable because the exact depth of temperature measurement and the centre of the screened interval were not consistently available. Consequently, total well depth was not interpreted as the precise depth from which the measured water entered the well.

2.4. Data harmonization and quality control

Well identifiers were standardized across the available sources. Coordinates recorded in degrees, minutes, and seconds were converted to decimal degrees. Decimal commas were replaced by decimal points, and the units of depth, temperature, and discharge were standardized as metres, degrees Celsius, and litres per second, respectively.

The coordinates of the 15 wells were plotted and checked against the study-area boundary. Records with unresolved identifiers or conflicting information were not merged. Historical and recent temperature observations were considered directly comparable only when the well identity, reported depth, measurement conditions, and measurement method could be established. No correction for mean annual ground-surface temperature was applied, and the measured water temperatures were not converted to equilibrium bottom-hole temperatures. The archival records include point measurements at the outlets of flowing wells (Figure 4) as well as temperature measurements obtained at different depths in selected deep wells [4]. Therefore, the complete collection of historical and recent temperature records was treated as a methodologically heterogeneous dataset.



Figure 4. Flowing thermal wells (t = 42.4°C)

Spatial interpolation was not performed because the dataset contained only 15 wells and their spatial distribution was uneven. Temperature differences were therefore interpreted only for the observed well locations.

2.5. Statistical analysis

Descriptive statistics were calculated for reported total well depth and groundwater temperature, including the minimum, maximum, mean, median, and sample standard deviation.

The relationship between groundwater temperature (T) and reported total well depth (D) was evaluated using Pearson's correlation coefficient (r) and Spearman's rank correlation coefficient (ρ). Pearson's coefficient was used to evaluate the linear relationship, whereas Spearman's coefficient was used to assess the monotonic relationship and reduce sensitivity to non-normality and individual extreme values.

$$T = a + bD\,, \tag{1}$$

where T is groundwater temperature, °C; D is reported total well depth, m; a is the regression intercept, °C; b is the regression slope, °C/m.

3. Results and discussion

3.1. Hydraulic properties and groundwater quality

Groundwater in both principal aquifer systems generally occurs under confined conditions. Historical piezometric heads ranged from approximately 14.7 to 111 m above ground level, although flowing conditions were reported less frequently for wells completed in the Middle–Upper Pliocene deposits [4].

Historical transmissivity values for the Pliocene aquifer system ranged from 403 to 521.3 m²/day, while hydraulic diffusivity ranged from 2.07×10^5 to 6.49×10^5 m²/day. For the Upper Cretaceous aquifer, transmissivity ranged from 503 to 877.3 m²/day, and hydraulic diffusivity ranged from 3.35×10^5 to 3.41×10^6 m²/day [8]. These values were obtained from historical aquifer tests and may not represent current hydraulic conditions. Updated pumping and recovery tests are required to evaluate the present response of the aquifers.

Groundwater in both aquifer systems is predominantly fresh. Historical records classify the Pliocene groundwater as sulfate-bicarbonate sodium-calcium water and the Upper Cretaceous groundwater as bicarbonate-sulfate sodium-calcium water. Reported total dissolved solids concentrations generally range from 0.2 to 0.8 g/L and do not exceed 1.0 g/L in the available records [4, 8]. This finding is consistent with regional studies describing the Upper Cretaceous groundwater of the Zharkent Basin as low-salinity water [2].

3.2. Well depth and groundwater temperature

The quantitative dataset comprised 15 wells located within the selected left-bank part of the Karadala groundwater field (Table 2). Reported total well depths ranged from 420.0 to 663.5 m, with a mean of 510.5 m and a sample standard deviation of 79.3 m. Groundwater temperatures ranged from 22.0 to 42.4°C, with a mean of 30.3°C, a median of 28.0°C, and a sample standard deviation of 7.0°C. All 15 measurements exceeded 20°C, the temperature threshold used in the reassessment report to identify thermal groundwater. Four wells had temperatures of at least 34°C.

Table 2. Depth, groundwater temperature, and coordinates of the 15 wells in the left-bank Karadala study area [5]

No.	Well	Depth, m	Temperature,°C	Latitude	Longitude
1	1312	424	24.0	43.562331	79.753697
2	1316	420	24.5	43.636222	79.767572
3	1041	420	25.0	43.581361	79.835644
4	1300	449	26.6	43.579581	79.846631
5	1302	493	28.6	43.593333	79.875261
6	1040	515	34.5	43.614514	79.958722
7	964	570	42.4	43.628819	80.043689
8	1046	570	42.4	43.628039	80.048403
9	1047	573	42.3	43.628478	80.046917
10	963-a	570	27.5	43.654842	80.136617
11	770	463	31.0	43.636222	80.273267
12	1325	479	22.0	43.646275	80.540481
13	1326	428	25.0	43.642797	80.605981
14	966-a	663.5	30.5	43.682556	80.523953
15	1327	620	28.0	43.668542	80.555392

Pearson's correlation indicated a statistically significant moderate positive linear relationship between reported well depth and groundwater temperature ($r = 0.554$, $p = 0.032$). Spearman's correlation showed a stronger positive monotonic relationship ($\rho = 0.666$, $p = 0.007$).

The fitted ordinary least-squares regression equation was:

$$T = 5.368 + 0.04881D, \quad (2)$$

where T is groundwater temperature, °C; D is reported total well depth, m.

The coefficient of determination was $R^2 = 0.307$, indicating that differences in reported well depth accounted for approximately 31% of the observed temperature variance (Figure 5).

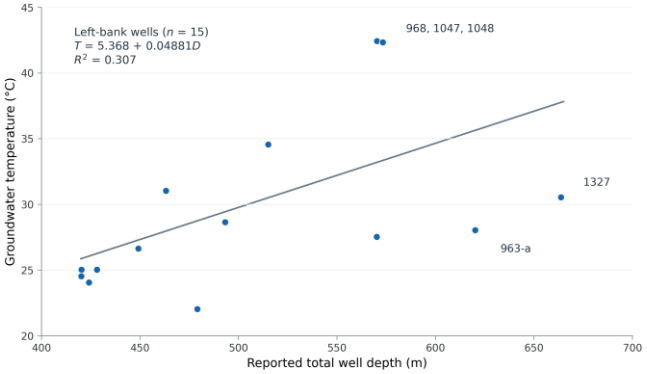


Figure 5. Relationship between groundwater temperature and reported total depth for 15 wells in the left-bank Karadala study area

Substantial temperature differences were observed among wells of similar depth. Wells 964, 1046, and 1047 recorded temperatures of 42.3-42.4°C at depths of 570-573 m, whereas well 963-a had a temperature of 27.5°C at a reported depth of 570 m. Well 1040 recorded 34.5°C at a depth of 515 m. These differences indicate that reported total well depth alone does not explain the observed temperature variability. Other possible controls include differences in screened intervals, groundwater-flow conditions, well construction, measurement conditions, and local hydrogeological or structural features.

3.3. Findings of the 2022-2024 reassessment

Historical exploration of the Karadala groundwater field included the drilling of approximately 60 wells, of which about 40 penetrated Cretaceous deposits and around 20 penetrated Middle-Upper Pliocene deposits. Many of these wells remain in existence, and some continue to discharge under artesian conditions. The 2022-2024 reassessment documented only a part of these historical and privately drilled wells.

According to the reassessment report, some private wells completed in the Cretaceous deposits have casing or filter-string diameters of 133-219 mm. However, their records frequently lack information on groundwater temperature, specific capacity, groundwater chemistry, screened intervals, and aquifer-testing procedures [8].

Reported discharge rates for several private wells range from 7.5 to 23 L/s at drawdowns of 12-21 m. These values cannot be directly compared with historical well yields because the testing duration, pumping conditions, measurement procedures, and recovery observations were not consistently documented. The reassessment also identified uncontrolled artesian discharge and insufficient monitoring of actual groundwater abstraction at some locations. These observations demonstrate the need for a standardized well inventory and regular monitoring. However, the available information alone is insufficient to demonstrate regional groundwater depletion. Such an assessment would require consistent time series of piezometric heads, well discharge, groundwater abstraction, and well-condition data.

3.4. Discussion

The moderate positive correlation between groundwater temperature and reported well depth is consistent with a general tendency for temperature to increase with depth. However, the coefficient of determination ($R^2 = 0.307$) indicates that differences in well depth are statistically associated with only approximately 31% of the observed temperature variance. The marked temperature contrast among wells at similar depths further demonstrates that depth alone cannot explain the observed temperature distribution.

The analysed dataset includes wells 770, 964, 1040, 1046, and 1047, which were assigned in the archival interpretation to an area of elevated groundwater temperature and possible concealed groundwater discharge along tectonic fault zones [4]. At the regional scale, recent studies identify the tectonic segmentation of the Zharkent Basin as a potentially important control on geothermal-system heterogeneity [3].

The agreement between the observed temperature anomalies and the earlier conceptual interpretation makes a structural-hydrodynamic explanation plausible. However, it does not demonstrate the presence of a particular fault beneath each warm well. The locations of some intrabasinal faults remain interpretative because the structures are concealed beneath Quaternary deposits and constrained by a sparse network of deep wells [3].

Wells 964, 1046, and 1047 are also located close to one another. Their similar temperatures may therefore represent a single local thermal feature rather than three spatially independent anomalies. Other possible explanations for the observed temperature differences include variations in screened intervals, vertical borehole flow, mixing between aquifers, differences in artesian discharge, well construction, and wellhead measurement conditions.

The regression slope obtained from different wells must not be interpreted as an in-well geothermal gradient. Reliable estimation of the geothermal gradient requires temperature measurements at several depths within the same well under stable thermal conditions.

Historical potentiometric contours indicate that groundwater in the Upper Cretaceous aquifer generally flows from south to north. The hydraulic gradient was estimated to range from 0.0136 to 0.0571 in the piedmont zone and from 0.0016 to 0.0125 within the groundwater-field area [4].

The principal recharge mechanism was historically interpreted as infiltration of runoff from the northern slope of the Ketmen Range through outcrops of permeable rocks and possible hydraulic windows in the Miocene clay sequence [4]. Additional recharge may occur through fractured zones of the Paleozoic basement. Regional isotope and hydrochemical data support a conceptual model involving both mountain-front and mountain-block recharge to the Upper Cretaceous reservoir [3]. However, these regional findings have not yet been verified using isotope measurements from the 15 wells analysed in the present study.

Within this conceptual model, relatively cool groundwater may occur closer to areas of active recharge. Groundwater may gradually warm as the aquifer deepens and water moves through the regional flow system towards discharge areas. Local upward flow of deeper groundwater could produce positive temperature anomalies. Nevertheless, distinguishing conductive heat transport from advective heat transport requires static temperature logging, borehole-flow measurements, hydrochemical and isotope analyses, and integration of these results with a validated geological and structural model.

A major limitation of this study is the methodological heterogeneity of the available data. Historical temperature records include measurements at the outlets of flowing artesian wells, point measurements at selected depths, and continuous temperature logs [4]. The 2022-2024 reassessment primarily documented the current condition and use of selected wells, but standardized technical records were unavailable for some sites [8].

Consequently, differences between historical and recent observations cannot automatically be interpreted as temporal changes in the groundwater system. For example, an apparent decrease in well discharge may result from declining hydraulic head, clogging, corrosion, screen design, pumping conditions, changes in well construction, or differences in aquifer-testing procedures.

Discrepancies among records for individual wells require particular attention. Until the original field logs can be examined, conflicting values should be retained as separate database records containing information on the source, observation date, measurement method, operating conditions, and verification status. Conflicting measurements should not be averaged. This approach would help distinguish genuine hydrogeological changes from digitization, transcription, and well-identification errors.

The results identify priority areas for future monitoring but do not provide sufficient evidence of groundwater depletion or temporal temperature change. A standardized monitoring programme should include repeated measurements of static piezometric levels, artesian discharge, groundwater abstraction, water temperature, hydrochemical composition, and well condition.

Static temperature logging and borehole-flow measurements should initially focus on the cluster of warm wells 964, 1046, and 1047 and on nearby well 963-a, which has a substantially lower temperature at a similar reported depth. Site-specific measurements of $\delta^{18}O$, $\delta^{2}H$, ^{3}H, and ^{14}C would further help evaluate recharge sources, groundwater mixing, and residence time. These observations are required before the sustainability of long-term groundwater abstraction and geothermal use can be reliably assessed.

4. Conclusions

The Karadala groundwater field is a multilayered artesian system in which the Middle-Upper Pliocene and Upper Cretaceous aquifers are of primary importance for groundwater abstraction. Across most of the field, these aquifers are separated by a regionally extensive Miocene clay aquitard, although hydraulic windows may occur in the piedmont zone.

Historical well discharge rates range from 6.9 to 40 L/s for the Middle–Upper Pliocene aquifer and from 14.6 to 191 L/s for the Upper Cretaceous aquifer. Groundwater is predominantly fresh, with reported total dissolved solids concentrations not exceeding 1.0 g/L. Historical records also indicate strongly confined conditions, with piezometric heads locally reaching more than 100 m above ground level.

The dataset of 15 wells in the left-bank study area shows a statistically significant moderate positive relationship between reported total well depth and groundwater tempera-

ture. Pearson's correlation coefficient is $r = 0.554$ ($p = 0.032$), while Spearman's rank correlation coefficient is $\rho = 0.666$ ($p = 0.007$). The regression coefficient of determination is $R^2 = 0.307$, indicating that differences in well depth are associated with approximately 31% of the observed temperature variance.

Wells 964, 1046, and 1047 record temperatures of 42.3-42.4°C at depths of 570-573 m, whereas well 963-a records 27.5°C at a similar depth. This contrast indicates localized temperature heterogeneity that cannot be explained by well depth alone. Upward groundwater flow along concealed tectonic structures is a plausible working hypothesis, but it requires independent geological, geophysical, and borehole verification.

The 2022-2024 reassessment identified incomplete technical records and insufficient groundwater monitoring at several locations. The available data are insufficient to quantify groundwater-resource depletion, establish temporal changes in groundwater temperature, or reliably estimate the field's current geothermal potential.

Priority actions should include verification of well identities and construction details, development of a unified groundwater database, and restoration of a representative monitoring network. Monitoring should combine measurements of piezometric head, artesian discharge, groundwater abstraction, temperature, and groundwater chemistry. Static temperature logging, standardized aquifer testing, and site-specific isotope studies are also required to evaluate recharge sources, groundwater residence time, and sustainable abstraction.

Author contributions

Conceptualization: RSA, SAK, YSA; Data curation: RSA; Formal analysis: RSA, SAK; Funding acquisition: RSA, YSA; Investigation: RSA, YSA; Methodology: RSA, SAK, YSA; Project administration: YSA; Resources: RSA, YSA; Software: RSA; Supervision: YSA; Validation: YSA, RSA; Visualization: SAK; Writing – original draft: RSA, SAK, YSA; Writing – review & editing: RSA, SAK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Іле өзенінің сол жағалауындағы Қарадала геотермалдық жерасты сулары кен орнының температуралық гетерогенділігін гидрогеологиялық бағалау

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Аңдатпа. Қазақстанның оңтүстік-шығысында орналасқан Қарадала жерасты сулары кен орны тұщы арынды жерасты суларының маңызды көзі және төмен температуралы геотермалдық энергияның әлеуетті ресурсы болып табылады. Зерттеудің мақсаты 1968-1971 жылдардағы мұрағаттық мәліметтер мен 2022-2024 жылдардағы гидрогеологиялық зерттеу деректері негізінде Іле өзенінің сол жағалауындағы белгіленген зерттеу аумағының гидрогеологиялық жағдайы мен температуралық әркелкілігін сипаттау болды. Зерттеу аумағында 15 ұңғымадан тұратын деректер жиынтығына сипаттамалық статистика, Пирсон және Спирмен корреляциялық талдаулары және ең кіші квадраттар әдісіне негізделген сызықтық регрессия көмегімен талданды. Талдау дереккөздерде көрсетілген ұңғыма тереңдігі мен жерасты суларының температурасы арасындағы байланысты бағалау мақсатында жүргізілді. Ұңғымалардың тереңдігі 420-663.5 м, ал жерасты суларының температурасы 22.0-42.4°C аралығында өзгерді. Тереңдік пен температура арасында статистикалық мәнді орташа оң байланыс анықталды: Пирсон коэффициенті ($r = 0.554$), ($p = 0.032$); Спирмен коэффициенті ($\rho = 0.666$, $p = 0.007$; $R^2 = 0.307$). Сонымен қатар, тереңдігі ұқсас ұңғымалар арасында айқын температуралық айырмашылықтар байқалды. Нәтижелер ұңғыма тереңдігі байқалған температуралық өзгергіштіктің тек бір бөлігін ғана түсіндіретінін көрсетті. Жерасты суларының жергілікті қозғалысының, әртүрлі сулы кешендер суларының араласуының, сүзгі орнатылған аралықтардың және тектоникалық құрылымдардың ықтимал әсерін стандартталған мониторинг, статикалық температуралық каротаж, гидрохимиялық талдау және экологиялық трассерлер әдістері арқылы қосымша зерттеу қажет.

Негізгі сөздер: *Қарадала, Іле артезиан алабы, Жаркент алабы, жоғарғы бор сулы кешені, термалды жерасты сулары, температуралық аномалия, мониторинг.*

Гидрогеологическая оценка и температурная неоднородность Карадалинского месторождения геотермальных подземных вод на левом берегу реки Или

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Аннотация. Карадалинское месторождение подземных вод, расположенное на юго-востоке Казахстана, является важным источником пресных напорных подземных вод и потенциальным ресурсом низкопотенциальной геотермальной энергии. Целью настоящего исследования являлась характеристика гидрогеологических условий и температурной неоднородности выбранного участка месторождения на левом берегу реки Или на основе архивных материалов 1968-1971 гг. и данных гидрогеологического обследования 2022-2024 гг. Выборка, включающая 15 скважин в пределах полигона исследуемой территории, была проанализирована с использованием описательной статистики, коэффициентов корреляции Пирсона и Спирмена и линейной регрессии методом наименьших квадратов для оценки связи между указанной в источниках глубиной скважин и температурой подземных вод. Глубина скважин изменялась от 420 до 663.5 м, а температура подземных вод – от 22.0 до 42.4°C. Между глубиной и температурой выявлена статистически значимая умеренная положительная связь (коэффициент Пирсона ($r = 0.554$, $p = 0.032$; коэффициент Спирмена ($\rho = 0.666$, $p = 0.007$; $R^2 = 0.307$)), при этом между скважинами сопоставимой глубины наблюдались существенные температурные различия. Полученные результаты показывают, что глубина скважины объясняет лишь часть наблюдаемой температурной изменчивости. Возможное влияние локального движения подземных вод, смешения вод разных водоносных комплексов, интервалов установки фильтров и тектонических структур требует дальнейшего изучения с использованием стандартизированного мониторинга, статического температурного каротажа, гидрохимического анализа и методов экологических трассеров.

Ключевые слова: *Карадала, Илийский артезианский бассейн, Жаркентский бассейн, верхнемеловой водоносный комплекс, термальные подземные воды, температурная аномалия, мониторинг.*

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