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Formation conditions, resource potential, and utilization prospects of cretaceous thermal groundwater in the Zharkent artesian basin

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Abstract. This study examines the formation conditions and resource potential of the Cretaceous thermal aquifer system of the Zharkent Artesian Basin, located in the eastern part of the Ili intermontane basin within the Panfilov District of the Zhetysu Region, Kazakhstan. The study is based on drilling and testing data from 18 deep wells completed between 1957 and 2016, supplemented by industrial hydrogeological reports and published results from previous investigations. The methods included structural-geological analysis, hydrodynamic delineation of the groundwater recharge area, and a groundwater-balance approach in which subsurface inflow was calculated using Darcy's law. The Upper Cretaceous aquifer occurs at depths of 1680-3702 m and, within the most prospective right-bank sector of the basin, at 2670-3702 m. The water-bearing sequence is 54-130 m thick. Wellhead water temperatures range from 74 to 103°C, free-flow discharge rates from 22 to 75 L/s, and excess wellhead pressures from 1.4 to 53.5 kgf/cm^2. The groundwater has low mineralization of 0.26-0.90 g/dm^3, is alkaline, and is predominantly of the Na–Cl–HCO_3 hydrochemical type, with elevated fluoride and dissolved silica concentrations. The recharge balance of the Cretaceous aquifer comprises four principal components: infiltration of surface runoff, 2.05 m^3/s (43.6%); infiltration of atmospheric precipitation, 0.107 m^3/s (2.3%); subsurface inflow from fractured Paleozoic rocks, 0.534 m^3/s (11.3%); and inflow along tectonic fault zones, 0.635 m^3/s (13.5%). Total recharge within the territory of Kazakhstan is estimated at 3.326 m^3/s. When transboundary groundwater inflow from the territory of China, estimated at 1.377 m^3/s, is included, total recharge reaches 4.703 m^3/s, equivalent to 406.3×10^3 m^3/day. The approved exploitable groundwater reserves of the Zharkunak geothermal field, amounting to 12960 m^3/day under categories B+C_1, represent only about 3.2% of the estimated natural groundwater resources. This ratio indicates substantial remaining potential for further development of the basin. The thermal-energy potential of the approved reserves is estimated at 3524.1 GJ/day, corresponding to an average thermal capacity of 40.8 MW, an annual thermal-energy output of 357.6×10^3 MWh, and an equivalent replacement of 43.9×10^3 tonnes of standard fuel per year. Potential pathways for cascading utilization of the geothermal resource are proposed, and two prospective development projects for the Zharkent Basin are considered.

Keywords: *geothermal groundwater, Cretaceous aquifer system, Zharkunak geothermal field, groundwater recharge, transboundary groundwater inflow, hydrogeothermics, geothermal energy, binary-cycle power generation, cascade utilization.*

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1. Introduction

Geothermal groundwater represents a renewable energy resource capable of supplying a continuous thermal load at comparatively moderate capital cost. The resource is also suitable for balneological applications, aquaculture, and greenhouse heating [1-3]. Under Kazakhstan's Strategy for Achieving Carbon Neutrality by 2060 [4]. development of hydrogeothermal resources has acquired increasing relevance as a distinct component of national energy policy. Applied aspects of geothermal-resource development in the Zharkent Basin have been addressed in previous studies [5, 6].

The Zharkent Basin, which forms the eastern part of the Ili intermontane basin, is regarded as one of the most prospective geological structures in Kazakhstan for high-temperature fresh groundwater. The first deep well that encountered thermal groundwater in the area, Well 1-G, was drilled in 1957 by the South Kazakhstan Oil Exploration Expedition as a structural exploration well. Testing of the Cretaceous aquifer system yielded approximately 4000 m^3/day (46 L/s) of groundwater at a wellhead temperature of 96°C and an excess pressure of 36 atm. Deep drilling subsequently demonstrated that the Zharkent depression had limited prospects for oil and gas development. Well testing nevertheless revealed high-temperature, high-yield aquifers associated with sedimentary units ranging in age from Permian to Cretaceous. Systematic investigation of the region's thermal groundwater began in 1960, initially at KazIMS and, from 1966 onward, at the Institute of Hydrogeology and Hydrophysics of the Academy of

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Sciences of the Kazakh SSR. The results were documented in archival reports, thermal-groundwater maps, monographs, and scientific publications [8-14].

Targeted exploration of thermal groundwater within the Zharkent Artesian Basin began in 1980. Between 1980 and 1991, the Soyuzburgaz Production Association drilled 11 deep exploration wells specifically targeting geothermal groundwater [15]. In 2006, a pilot exploration project included inspection of all wells drilled for thermal groundwater during the 1980s and preparation of a technical and economic feasibility assessment for their utilization.

The Zharkunak geothermal field was established as a subsurface-resource development site through two principal stages of exploration. During 2007-2008, exploration-production Well 1-RT was drilled at the Darbazakum site. The well intersected the Upper Cretaceous aquifer at depths of 2776.8-2790.0 and 2791.6-2809.0 m. Fresh thermal groundwater was obtained under free-flow conditions at 24.2 L/s, with a discharge temperature of 98°C and an excess hydraulic head of 250 m at the wellhead. During exploration conducted at the Zharkunak site in 2015-2016, Well 5539 was drilled to a depth of 2850 m and exhibited an excess hydraulic head of 235 m. The Upper Cretaceous aquifer produced fresh thermal groundwater at 50.5 L/s, with a wellhead temperature of 103°C and total mineralization of 0.71 g/dm^3.

The exploitable groundwater reserves of the Zharkunak geothermal field were estimated using the hydrodynamic method for a production scheme consisting of five spatially distributed wells. The design withdrawal rate was 150 L/s, equivalent to 12960 m^3/day, over an operational period of 10000 days. The calculated reserves were submitted to the State Commission on Mineral Reserves of the Republic of Kazakhstan (GKZ RK) for approval under reserve categories B+C$_1$ [15].

The objective of this study is to determine the formation conditions of groundwater within the Cretaceous thermal aquifer system of the Zharkent Artesian Basin, quantify its recharge through a groundwater-balance assessment, and use these estimates to evaluate the basin's resource potential and identify priority directions for geothermal-resource utilization.

2. Materials and methods

2.1. Study area

The Zharkunak geothermal field is located in the Panfilov District of the Zhetysu Region, Kazakhstan. Geographically, it occupies the eastern part of the Ili intermontane basin. The study area is bounded by the Dzungarian Alatau Range to the north, the Ketmen Range to the south, and the Kalkan and Katutau Mountains to the west. Its eastern boundary coincides with the state border between Kazakhstan and China (Figure 1).

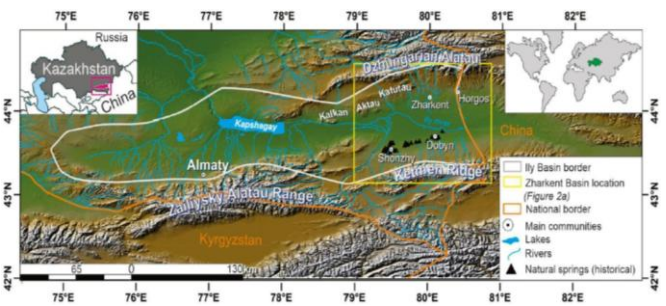


Figure 1. Overview map of the study area

2.2. Data Sources

The study is based on drilling records, geophysical well-logging data, and experimental well-testing results from 18 deep wells (1-G–7-G, 1-T–11-T, 1-TP, 2-TP, 1-RT, and 5539) drilled between 1957 and 2016. The dataset also includes technical reports prepared by the Lobninskaya Geological Exploration Expedition and materials from investigations conducted during 2006-2016; detailed hydrogeological observations of infiltration losses from surface watercourses; hydrochemical sampling data; results of experimental groundwater discharge tests; and published data from previous investigations [4, 8-14, 16].

The principal primary source was the report on exploration activities conducted at the Zharkunak site by Production Company «Geoterm» LLP during 2015-2016. This report integrates original drilling and well-testing data from Well No. 5539 with results and archival materials from previous investigations of the Zharkent Artesian Basin [15].

2.3. Research methods

The study employed a set of established hydrogeological methods:

1. Structural-geological analysis. Stratigraphic subdivisions identified from deep-well sections were compiled and systematized. A tectonic zonation scheme of the basin was developed, and the block structure of the basement and the role of fault systems in controlling groundwater circulation were assessed.

2. Hydrodynamic analysis. A schematic map of the recharge area of the Cretaceous aquifer was constructed. The analysis accounted for the degree of aquifer confinement by low-permeability strata at its base and top, as well as hydraulic contacts between the water-bearing formations, overlying aquifers, and the saturated fractured zone of Paleozoic rocks. Hydrogeological windows were delineated, and potentiometric contours were constructed to characterize the regional hydraulic-head distribution.

3. Groundwater-balance assessment of recharge**.** Recharge to the Cretaceous aquifer was calculated as the sum of four independently estimated components: infiltration losses from surface runoff within the recharge area; infiltration of atmospheric precipitation; groundwater inflow from the fractured zone of Paleozoic rocks across areas of direct contact with Cretaceous deposits; and groundwater inflow along tectonic fault zones. This component-based approach follows established groundwater-balance practice where direct hydrological observations are limited [17, 18].

Recharge from atmospheric precipitation was calculated as:

$$Q_{oc} = h \cdot F \cdot \alpha / T \,, \quad (1)$$

where h is the long-term mean annual amount of runoff-generating precipitation, m; F is the total area of hydrogeological windows, m^2; α is the dimensionless infiltration coefficient; T is number of seconds per year (31.5×10^6 s).

Groundwater inflow along tectonic fault zones and transboundary subsurface inflow were estimated using Darcy's law in discretized form:

$$Q = k \cdot I \cdot m \cdot B \cdot n \,, \quad (2)$$

where k is hydraulic conductivity, m/day; I is the dimensionless hydraulic gradient; m is aquifer thickness, m; B is the width of the water-transmitting section of the flow zone, m; and n is the number of hydraulically similar zones.

4. Hydrochemical analysis. Water-chemistry data were processed with concentrations expressed in mg/dm^3 and milliequivalent percentages (% meq). Ionic compositions were represented using the Kurlov formula, groundwater types were classified according to their dominant ionic composition, and compliance with the requirements of ST RK 452-2002 [19] for mineral medicinal and medicinal-table waters was assessed.

5. Thermal-energy potential assessment. The thermal-energy potential was estimated from the standard heat-balance relationship;

$$W = Q \cdot \rho \cdot c \cdot \Delta T \,. \quad (3)$$

where Q is the thermal-water discharge, ρ is water density, c is specific heat capacity, and ΔT is the temperature decrease between the production temperature and the designated discharge temperature.

The resulting thermal-energy values were converted to gigacalories, gigajoules, megawatt-hours, and tons of standard fuel equivalent. Resource-utilization pathways and their seasonal allocation were adopted from the Program for Development of Kazakhstan's Geothermal Resources as Renewable Energy Sources prepared by Satbayev University [20].

3. Results and discussion

3.1. Geological and structural setting

According to the hydrogeological regionalization of Kazakhstan [21]. the eastern part of the Ili Basin, corresponding to the Zharkent Basin, constitutes the Zharkent Artesian Basin. The sedimentary cover consists of Mesozoic and Cenozoic deposits ranging from Triassic to Quaternary age. The present study focuses on the Cretaceous thermal aquifer system; the geological description is thus concentrated primarily on the Cretaceous succession.

Cretaceous deposits crop out locally within the Aktau, Malaisary, and Kalkan mountain ranges along the southern margin of the Zharkent Basin. The Upper Cretaceous light-gray sandy sequence is widespread throughout the basin and has been penetrated by numerous deep wells, including Wells 1-T, 2-T, and 3-T in the Usek area; Wells 1-TP and 2-TP in the Priili area; Well 1-RT in the Darbazakum area; and Well 5539 at Zharkunak. The sequence consists predominantly of course- to medium-grained, quartz-rich sandstones that are generally weakly cemented. The thickness of the Upper Cretaceous succession is relatively uniform across the basin, ranging from 54 m in Well 8-T to 130 m in Well 2-TP (Table 1) [15].

Table 1. Stratigraphic subdivision of well sections from wells drilled during geothermal groundwater exploration

No.	Geothermal exploration area	Well No.	Absolute wellhead elevation, m	Cretaceous System			
				Upper Cretaceous – K_2		Lower Cretaceous – K_1	
				Aquifer depth interval, m	Thickness, m	Aquifer depth interval, m	Thickness, m
1	Usek	1-T	530.6	2026-2114	88	2114-2286	172
		2-T	530.0	1680-1785	105	1785-1906	121
		3-T	529.9	2264-2349	85	2349-2455	20
2	Kirovskaya	4-T	–	2774-2889	115	2889-2948	59
3	Pre-Ili	1-TII	–	2828-2910	82	–	–
		2-TII	–	2670-2800	130	–	–
4	Molodezhnaya	6-T	722.4	3642-3702	60	–	–
		7-T	738.9	2794-2863	69	–	–
		8-T	722.4	3640-3694	54	–	–
		11-T	721.3	2764-2832	68	–	–
5	Darbazakum	1-PT	509.0	2737-2817	80	–	–
6	Zharkunak	5539	515.0	2700-2817	117	–	–

The Zharkent Basin has a predominantly east-west orientation, extending from the Kalkan-Boguty structural divide in the west to the Korgas River along the Kazakhstan-China state border in the east. Its northern boundary is formed by the Katutau anticlinorium and the Dzungarian Alatau, whereas the southern boundary follows the eastern spurs of the Trans-Ili Alatau, including the Boguty anticlinorium, the Kungey Alatau spurs, and the Ketmen anticlinorium (Figure 2). Based on basement structure, the Zharkent Depression comprises three second-order structural-tectonic elements: the northern marginal zone represented by the Aktau-Zhambylbastau anticlinal zone, the central part of the depression, and the southern marginal monocline represented by the Ketmen Monocline.

The basement of the Zharkent Depression exhibits a pronounced block-faulted structure, particularly in its northern part. The east-west-trending Aktau and Ketmen faults, which delimit and dissect the northern and southern margins of the depression, exerted a major control on basin initiation and subsequent structural development. During the Paleozoic, particularly the Permian, and throughout the Mesozoic, these faults, together with other fault systems, influenced regional sedimentation. As discussed below, the block structure of the basement and the dense fault network represent major geological controls on the formation and recharge of groundwater resources within the Cretaceous thermal aquifer system.

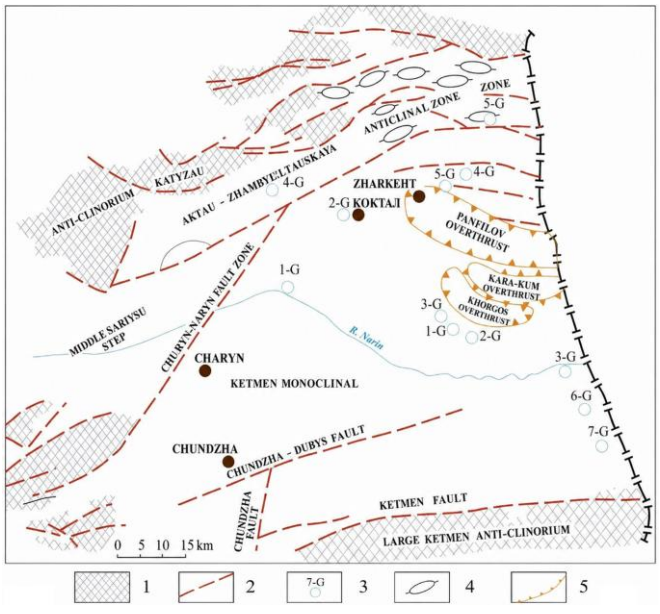


Figure 2. Tectonic zonation scheme of the Zharkent Depression (compiled by V.A. Zavaley from materials of V.F. Shlygina, L.M. Mordison, and others). 1 – outcrops of Paleozoic rocks; 2 – tectonic faults; 3 – exploration wells; 4 – local geological structures; 5 – boundaries of structural-tectonic elements

3.2. Characteristics of the Cretaceous thermal aquifer

Hydrogeological investigations of the Zharkent Artesian Basin identify seven aquifers and aquifer systems associated with Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary deposits. Among these units, the Cretaceous thermal aquifer is of greatest practical significance for geothermal groundwater development and is distributed throughout the Zharkent Artesian Basin.

On the left bank of the Ili River, Upper Cretaceous deposits occur at depths of up to 900 m within the Karadala groundwater field. The water-bearing sediments consist mainly of yellow, grayish-white, and white quartz sands. Aquifer thickness increases northward with distance from the Ketmen Range. In the foothill zone, the water-bearing sequence is generally 3-10 m thick, whereas near the Shonzhy–Kolzhat highway it reaches 80-175 m or more. More than 100 wells drilled along this corridor have encountered thermal groundwater under high artesian heads ranging from 13.7 to 114.2 m above ground level. The hydraulic properties of the water-bearing sediments show relatively limited spatial variation, with a gradual decrease toward the north and west from the exploration profile. Hydraulic conductivity ranges from 5 to 12.3 m/day, transmissivity from 454 to 877 m^2/day, and hydraulic diffusivity from 3.4×10^5 to 3.4×10^6 m^2/day. Aquifer productivity on the left bank of the Ili River is relatively high. During experimental free-flow tests, well discharges ranged from 14.5 to 191.0 L/s, with values of 50-70 L/s being most characteristic. The groundwater reserves of the Cretaceous aquifer system at the Karadala field, summed over categories A+B+C_1+C_2, amount to 776.1×10^3 m^3/day.

Across the remaining parts of the basin, on the left and right banks of the Ili River, the Upper Cretaceous aquifer has been tested in several deep wells, including 6-G, 3-T, 1-G, 1-TP, 2-TP, 1-RT, and 5539 (Table 2) [15].

Table 2. Principal hydrogeological and hydrochemical characteristics of groundwater from the Cretaceous aquifer system

Well	Depth interval of water-bearing rocks, m	Free-flow discharge, L/s	Wellhead pressure, kgf/cm²	Ion content, mg/dm³ / %-eq/						Dry residue, g/L
				Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Ca^{2+}	Mg^{2+}	
Left bank of the Ili River										
6-G	715-755 765-798 785-798	75.2	n.m.	28.4 16	105.7 44	222.0 40	50.6 44	46.1 46	6.1 10	0.35
1028	367-420 465-500	32.4	1.4	87 10	33 20	131 70	29 33	32 50	4 17	0.80
1044	420-435 434-453	20.7	2.2	10.6 9	33.6 20	146.5 71	25.3 32	36.1 53	6.1 14	0.30
1312	427-525	14.6	1.61	71.0 23	225.8 54	122.0 23	69.0 34	84.2 48	19.5 18	0.60
963	573-642	16.6	4.0	70.9 26	115.3 32	195.3 42	131.1 75	34.1 22	2.4 3	0.50
Right bank of the Ili River										
3-G	1377-1448	60.2	26	32.0 19	45.25 21	170.8 60	71.1 67	23.9 16	4.3 7	0.26
1-G	2693-2732	46.3	36	212 43	347.7 41	106.1 16	298 95	14.6 5	n.m.	0.90
3-T	2278-2344	30.0	19.5	20.0 12	61.0 27	162.0 56	101.0 94	5.0 5	1.0 1	0.33
1-TP	2800-2900	50.0	17.37	46.1 19	91.3 27	231.9 54	154.0 97	2.0 2	2.4 3	0.50
2-TP	2718-2790	22.0	24	35.5 14	96.1 27	268.5 59	160.0 95	6.0 4	1.2 1	0.50
1-RT	2737-2817	24.5	25	103 27	62 33	154 39	223 97	5 2	0.2 1	0.60
5539	2763–2793	54,5	53,5	100 35	250 18	220 42	230 97	3,0 2	0,6 1	0,50

Note: The numerator gives the ion concentration in mg/L and the denominator gives its equivalent percentage (% eq). n.m. = not measured; n.d. = not detected

On the right bank of the Ili River, Well 1-G near the Borokhudzir oil depot penetrated Upper Cretaceous sandstones at depths of approximately 2695-2730 m. The piezometric head rose to approximately 360 m above ground level. Penetration of the aquifer produced artesian flow at 46.3 L/s, with a wellhead temperature of 96°C. The groundwater composition is represented by the Kurlov formula:

$$M_{0.90}\,\frac{\mathrm{Cl}\,43\times\mathrm{SO_4}\,41}{\mathrm{Na}\,0.5}. \qquad (4)$$

The Upper Cretaceous aquifer was tested by Well 3-T in the Usek area over the 2278-2344 m interval. Wellhead pressure reached 19.5 kgf/cm², free-flow discharge was 30.0 L/s, and water temperature was 74°C. The thermal groundwater composition is represented as:

$$M_{0.33}\,\frac{\mathrm{HCO_3}\,56\times\mathrm{SO_4}\,29}{\mathrm{Na}\,0.4}. \qquad (5)$$

Within the Priili area, the aquifer was tested by Wells 1-TP and 2-TP. In Well 1-TP, testing was conducted over the 2858-2908 m interval. Wellhead pressure was 17.37 kgf/cm². When the excess pressure was reduced to 10.5 kgf/cm², corresponding to a piezometric drawdown of 67.8 m, discharge reached 50 L/s. The discharge temperature was 89°C, and groundwater mineralization was 0.5 g/L. Dissolved gases consisted predominantly of nitrogen (97.47%) and argon (2.47%).

More recent hydrogeological information on the Upper Cretaceous aquifer was obtained from Well 1-RT at the Darbazakum site, where the 2776-2790 m interval was tested. The well yielded 24.3 L/s under free-flow conditions. The piezometric head reached 250 m above ground level, and the discharge temperature was 98°C.

The Cretaceous aquifer system represents the principal target for fresh thermal groundwater within the Zharkent Artesian Basin, with groundwater temperatures approaching or exceed-

ing 100°C. This potential was confirmed by testing of Well 5539 in the Zharkunak area, drilled in 2015 and tested over the 2763-2793 m interval. The longest stage of the experimental discharge test lasted 30 days at a flow rate of 50.43 L/s. During this stage, the stabilized excess head was 0.1 MPa, equivalent to approximately 10 m of water head, corresponding to a piezometric drawdown of 225 m. Groundwater mineralization measured during this test was 0.71 g/L [15].

Natural hyperthermal water from Well 5539 is classified as low-mineralization, alkaline, moderately radon-bearing, siliceous groundwater of predominantly Na–Cl–HCO_3 composition, with an elevated fluoride concentration [15]. Its characteristic properties include mineralization below 1.0 g/L, alkaline pH of 8.1-9.0, fluoride concentrations up to 10 mg/L, balneologically active silicic acid concentrations exceeding 50 mg/L, and radon concentrations up to 60 nCi/L, corresponding to the moderately radon-bearing class.

According to the combined physicochemical and balneological criteria, groundwater from Well 5539 meets the requirements of ST RK 452-2002 [19]. for therapeutic natural mineral water and is classified as moderately radon-bearing, siliceous-fluoride hyperthermal mineral water. The Zharkunak field thus possesses a distinct balneological resource value alongside its geothermal-energy potential.

3.3. Recharge area of the Cretaceous aquifer

The principal recharge areas of groundwater hosted by the Mesozoic deposits coincide with those established during the Pliocene–Quaternary stage of basin development. For the Mesozoic aquifers, the main recharge zone is associated with the northern slopes of the Ketmen Range, where the water-bearing formations either crop out locally or are overlain by permeable Pliocene–Quaternary deposits. Analysis of the available hydrogeological data was used to construct a schematic map of the recharge area of the Cretaceous aquifer (Figures 3 and 4) [15]. The delineation accounted for the degree of aquifer confinement by low-permeability units at its base and top, together with hydraulic contacts between the water-bearing Cretaceous deposits, overlying aquifers, and the saturated fractured zone of Paleozoic rocks.

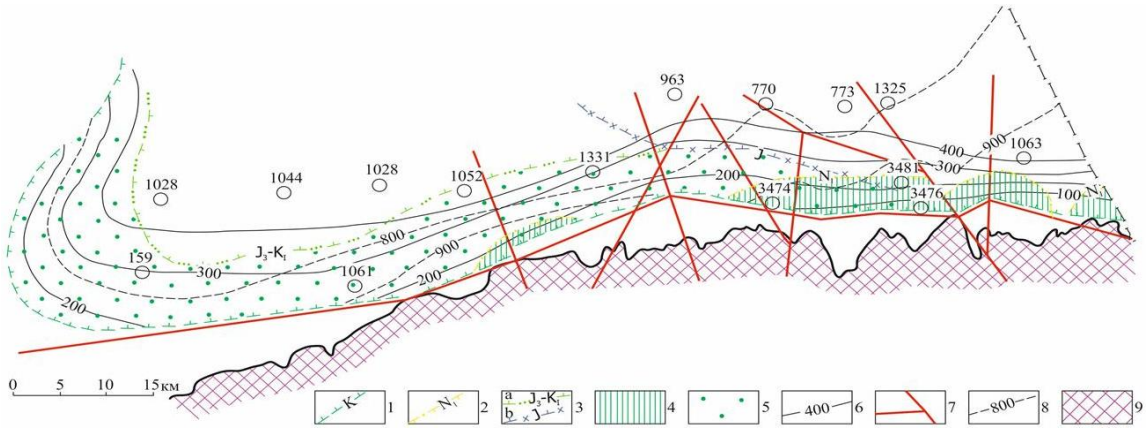


Figure 3. Schematic map of the recharge area of the Cretaceous aquifer. 1-3: boundaries of the distribution of geological units; 4 – area of Cretaceous deposits overlain by permeable Pliocene–Quaternary unconsolidated coarse-clastic sediments; 5 – area where Cretaceous deposits directly overlie Paleozoic rocks; 6 – structure contours of the base of the Cretaceous deposits; 7 – tectonic fault zones; 8 – potentiometric contours of the Cretaceous aquifer; 9 – Paleozoic rock outcrops

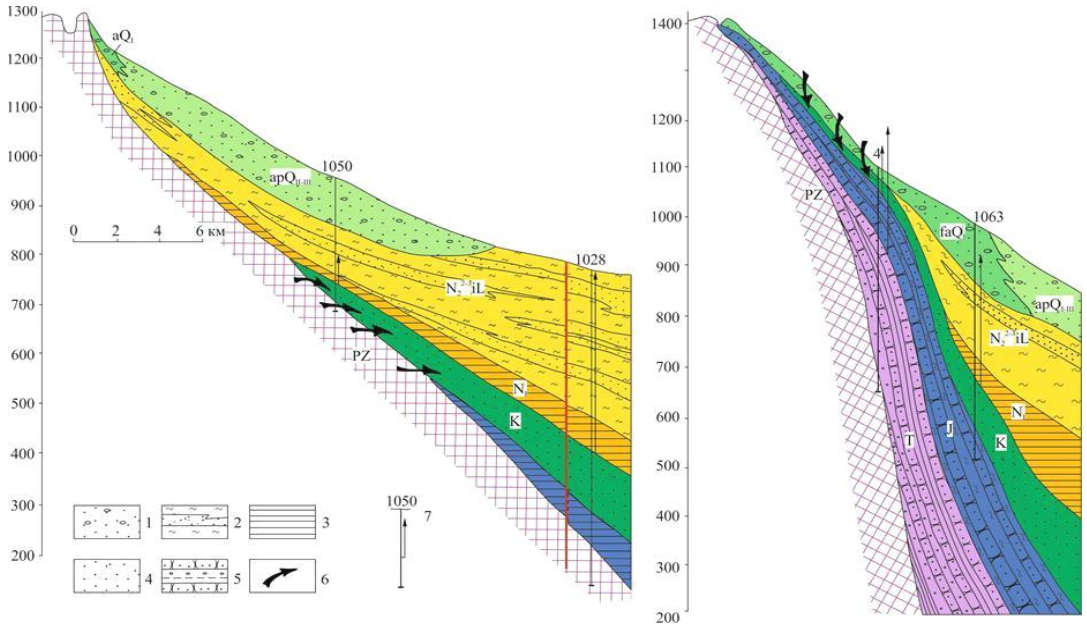


Figure 4. Hydrogeological conditions controlling recharge of the Cretaceous aquifer: 1 – gravel and pebble deposits; 2 – clay with interbeds of sand; 3 – clay and siltstone; 4 – sand; 5 – sandstone, gravelstone, and shale interbeds; 6 – direction of groundwater flow; 7 – well; arrow, piezometric level

Across most of the study area, the Cretaceous deposits are overlain by low-permeability Miocene strata. Exceptions occur within hydrogeological windows where the Miocene aquitard is absent, permitting recharge of the Cretaceous aquifer through infiltration of surface water and atmospheric precipitation. The total area of these windows is approximately 190 km^2. About 140 km^2 corresponds to Cretaceous deposits overlain by sediments of the Ili Formation. Within these areas, recharge occurs primarily through infiltration losses from surface runoff. The remaining approximately 50 km^2 consists of areas where Cretaceous deposits are overlain by coarse-grained Quaternary sediments that readily transmit infiltrating surface water and precipitation. This 5 km^2 area was adopted for calculation of recharge from atmospheric precipitation. The shallow part of the Cretaceous aquifer that receives recharge from infiltrating surface runoff occurs between the Dardamtysay and Khasansay streams. Twelve additional rivers and streams descend from the northern slope within this sector and lose their entire surface flow within an approximately 5-km-wide foothill zone.

Detailed hydrogeological observations [22] indicate that all infiltration losses from the Budutysay, Kolzhatsky, and Supatsay streams, reported as 0.83 m^3/s, contribute to recharge of the Cretaceous aquifer because the Cretaceous deposits in this sector are not overlain by the Middle–Upper Pliocene aquifer (Table 3). The remaining infiltration losses, amounting to 2.45 m^3/s, are distributed between the Cretaceous and Middle–Upper Pliocene aquifers. Quantitative partitioning between the two aquifers is difficult. Assuming equal distribution, recharge to the Cretaceous aquifer is equal to 2.05 m^3/s.

Recharge from Paleozoic rocks has been estimated differently in previous investigations. During exploration of the Cretaceous and Middle–Upper Pliocene aquifers, the contribution of tectonic faults was not explicitly considered. In contrast, large-scale hydrogeological mapping attributed a major recharge function to submeridional fault zones (Figure 4).

Table 3. Infiltration losses from surface watercourses in the Dardamtysay–Khasansay interfluve, m^3/s

Water course	Channel-flow losses during the non-growing season	Growing season				Annual groundwater recharge
		Seepage losses from canals	Losses in irrigated fields	Channel-seepage losses	Total streamflow losses	
Dartamtysai	0.27	0.097	0.062	0.37	0.53	0.40
Daulatysai	0.28	0.18	0.11	0.17	0.46	0.37
Narynkursai	0.14	0.09	0.053	0.18	0.32	0.23
Shunkursai	0.35	0.27	0.20	–	0.47	0.41
Maly Ketmensai	0.04	0.12	0.078	–	0.20	0.12
Arlykgolgsai	0.09	0.10	0.064	–	0.16	0.13
Bolshoy Ketmensai	0.15	0.18	0.13	–	0.31	0.23
Achina Kholgolgsai	0.35	0.16	0.11	0.21	0.48	0.42
Supatsai	0.19	0.16	0.11	0.21	0.48	0.42
Kolzhatsky	0.15	0.12	0.087	0.14	0.35	0.25
Budutysai	0.13	0.16	0.10	0.18	0.44	0.28
Dokenyshksai. Kenebulaksai. Khasansai (total losses)	0.12	0.09	0.063	–	0.153	0.137
Total	2.26	1.727	1.167	1.400	4.29	3.28

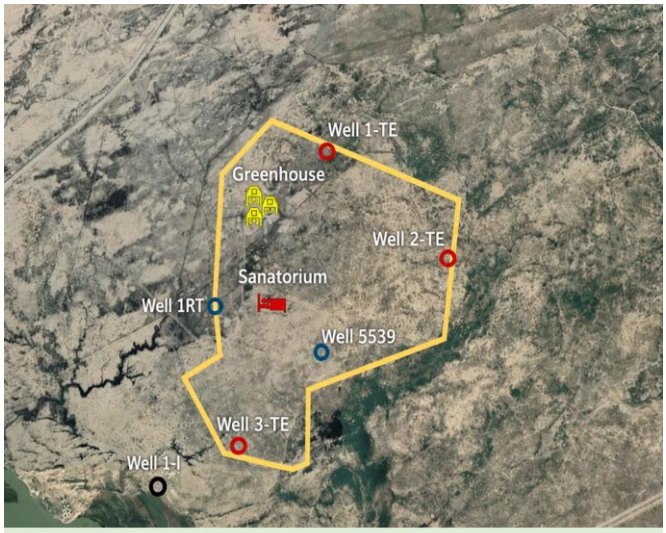


Figure 5. Layout of the Zharkunak geothermal field showing the principal characteristics of operating Wells 1-RT and 5539

Recharge from atmospheric precipitation was calculated using Equation (1) for a hydrogeological-window area of 50 km^2. A long-term mean annual runoff-generating precipitation of 224 mm, and an infiltration coefficient of 0.30 is equal to 0.107 m^3/s.

Groundwater inflow along submeridional tectonic faults and direct leakage from the fractured zone of Paleozoic rocks are inferred to contribute to recharge of the Cretaceous aquifer. The area in which Cretaceous deposits directly overlie fractured Paleozoic rocks, without an intervening clay aquitard, is approximately 928 km^2. During detailed exploration of the Karadala groundwater field, subsurface inflow from Paleozoic rocks was estimated from the difference between total annual precipitation and runoff-generating precipitation assigned to the autumn-winter low-flow period, when evaporative losses were considered negligible. Calculations for several catchments yielded a mean specific recharge rate of 0.48 L/(s·km^2).

Recharge to the Cretaceous aquifer from groundwater flowing out of the fractured Paleozoic zone was calculated by multiplying this mean specific recharge rate by the 1112 km^2 mountain catchment of the Ketmen Range contributing groundwater to the basin. Q_3 is equal to 0.534 m^3/s.

In the central and eastern parts of the basin, recharge along submeridional tectonic fault zones is inferred to predominate. Seven faults were identified as contributing groundwater to the Cretaceous aquifer. The Darcy-based

calculation adopted a mean hydraulic conductivity of 4.0 m/day, within a reported range from hundredths of a metre per day to 12-15 m/day; a mean hydraulic gradient of 0.07; a mean width of the hydraulically conductive part of each fault zone of 350 m; and a mean thickness of 80 m for the Cretaceous aquifer intersected by the faults. Using Equation (2) Q_4 is equal to 0.635m^3/s.

The combined groundwater inflow (Q_3+Q_4) from fractured Paleozoic rocks and tectonic fault zones is equal to 1.169m^3/s.

3.4. Recharge balance of the Cretaceous aquifer

Total recharge to the Cretaceous aquifer consists of the four components summarized in Table 4.

Table 4. Recharge balance of the Cretaceous thermal aquifer system of the Zharkent Artesian Basin

No.	Recharge component	Recharge rate, m^3/s	Recharge volume, 10^3 m^3/day	Share of total recharge, %
1	Infiltration of surface runoff through streamflow losses	2.05	177.1	43.6
2	Infiltration of atmospheric precipitation within hydrogeological “windows”	0.107	9.2	2.3
3	Groundwater inflow from the fractured zone of Paleozoic rocks across the area of direct hydraulic contact	0.534	46.1	11.3
4	Groundwater inflow along tectonic fault zones (7 zones)	0.635	54.9	13.5
Total recharge within Kazakhstan		3.326	287.4	70.7
5	Transboundary groundwater inflow from the People’s Republic of China	1.377	119.0	29.3
Total recharge of the Cretaceous thermal aquifer system		4.703	406.3	100.0

Note: Relative to the recharge generated within Kazakhstan alone (3.326 m^3/s), components 1-4 account for 61.6, 3.2, 16.1, and 19.1%, respectively.

The recharge calculations presented above include only recharge zones located within Kazakhstan. The configuration of the potentiometric contours shown in Figure 3 indicates that part of the groundwater flow generated within the territory of the People’s Republic of China enters Kazakhstan, consistent with the regional direction of groundwater movement.

Detailed geological and hydrogeological information for the Chinese sector of the Zharkent Basin is limited. Therefore, transboundary groundwater inflow was estimated using Equation (2), assuming a flow width of 17 km, a Cretaceous aquifer thickness of 100 m, a hydraulic conductivity of 5 m/day, and a hydraulic gradient of 0.014. The estimated groundwater inflow was 119000 m^3/day (1.377 m^3/s).

Including transboundary groundwater inflow from the eastern part of the basin, the total recharge to the Cretaceous aquifer is estimated at 4.703 m^3/s, equivalent to approximately 406.3×10^3 m^3/day or 148.3×10^6 m^3/year.

The values in Table 4 are internally consistent: the Kazakhstan component accounts for 70.7% of total recharge, while the estimated transboundary inflow contributes 29.3%.

3.5. Resource and energy potential and utilization options

Based on the level of hydrogeological investigation available as of 2022, the generalized characteristics of thermal groundwater within the Cretaceous aquifer system of the Zharkent Basin differ substantially between the left and right banks of the Ili River (Table 5).

Table 5. Generalized characteristics of thermal groundwater in the Cretaceous aquifer system of the Zharkent Basin, based on the state of investigation as of 2022

Parameter	Left bank of the Ili River (Uygur District, Karadala)	Right bank of the Ili River (Panfilov District)
Aquifer depth, m	400-750	1300-2900
Groundwater mineralization, g/dm^3	0.3-0.8	0.3-0.9
Water temperature, °C	35-52	75-103
Piezometric head, m above ground level	Up to +97	Up to +360
Well discharge, L/s	20-191	20-60
Dissolved-gas type	Nitrogen-dominated thermal waters	Nitrogen-dominated thermal waters

The left-bank sector, comprising the Karadala area of the Uygur District, is characterized by comparatively shallow aquifer depths and, correspondingly, low- to medium-temperature thermal waters, together with exceptionally high well yields. The right-bank sector in the Panfilov District, which includes the Zharkunak geothermal field, is characterized by substantially greater aquifer depths and high-temperature thermal waters with moderate discharge rates. Groundwater in both sectors is classified as nitrogen-dominated thermal water on the basis of dissolved-gas composition [20].

The Zharkunak geothermal field was delineated in 2016 and represents the first geothermal groundwater field of this type formally explored in Kazakhstan. It occupies the central part of the Zharkent Basin and includes two operating wells, Well 5539 at the Zharkunak site and Well 1-RT at the Darbazakum site, together with three conceptual production wells, 1-TE, 2-TE, and 3-TE, included in the design scheme for a spatially distributed production well field (Figure 5). Direct-use facilities already operate within the field boundary, including a greenhouse complex and a sanatorium supplied with geothermal heat.

The approved exploitable reserves of the Zharkunak field amount to 12960 m^3/day, equivalent to 150 L/s, under categories B+C_1 for a design exploitation period of 10000 days. These reserves were converted into thermal-energy units, as summarized in Table 6. A daily thermal-energy output of 979.68 MWh corresponds to an average thermal capacity of approximately 40.8 MW. This value is consistent with an independent calculation using $W = QρcT$, based on a flow-weighted mean production temperature of 95°C and a discharge temperature of 30°C.

Table 6. Thermal-energy potential of the approved exploitable reserves of the Zharkunak geothermal field

Period/volume of thermal water	Gcal	GJ	MWh	tce
Day – 12960 m^3	842.4	3524.14	979.68	120.3
Year – 4730400 m^3	307476	1286311	357583	43909.5
Entire estimated exploitation period (10000 days) – 1.3×10^8 m^3	$8.42\cdot10^6$	$3.52\cdot10^7$	$9.80\cdot10^6$	$1.2\cdot10^6$

Note: Compiled from data reported in [20]; tce – tonnes of standard coal equivalent.

A principal condition for economically efficient development is cascading use of the geothermal resource, whereby the same thermal-water stream serves successive consumers operating at progressively lower temperature levels. The proposed seasonal allocation of the design abstraction rate of 150 L/s is shown in Figure 6.

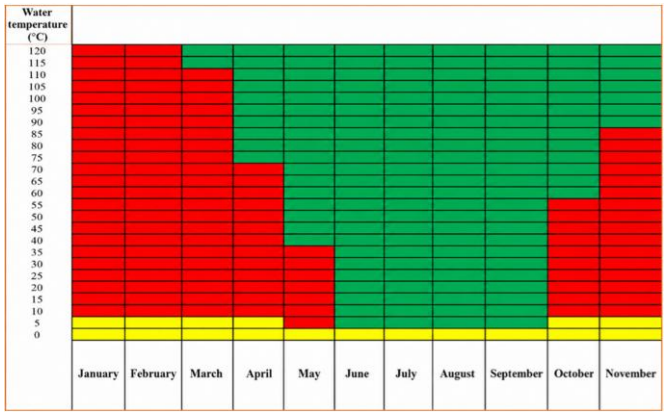


Figure 6. Seasonal allocation of the design geothermal-water abstraction rate of 150 L/s at the Zharkunak field according to end use. Red: heating of the 30-ha greenhouse complex through heat exchangers. Green: electricity generation using a binary-cycle system. Yellow: sanatorium heating, balneological applications, swimming pools, and spa facilities

During the heating season, from November through April, most of the flow is directed through heat exchangers to a 30-ha greenhouse complex. During the warmer half of the year, the released flow is redirected to electricity generation using a binary-cycle system. A relatively constant flow of approximately 10 L/s is allocated throughout the year to sanatorium heating, balneological treatments, swimming pools, and spa facilities. This allocation maintains a high annual utilization factor for the production well field.

Based on the resource assessment, a prospective integrated geothermal-development project has been proposed for the Zharkent Basin. The project includes electricity generation at a binary-cycle geothermal power plant, district heating and domestic hot-water supply for the city of Zharkent, and conveyance of geothermal water through a trunk pipeline to the Khorgos International Center for Cross-Border Cooperation. The proposed route passes through the settlements of Maly Shygan, Bolshoy Shygan, Kyrykkudyk, Alty Uy, Akkent, Avat, Pidzhim, and Nurkent (Figure 7).

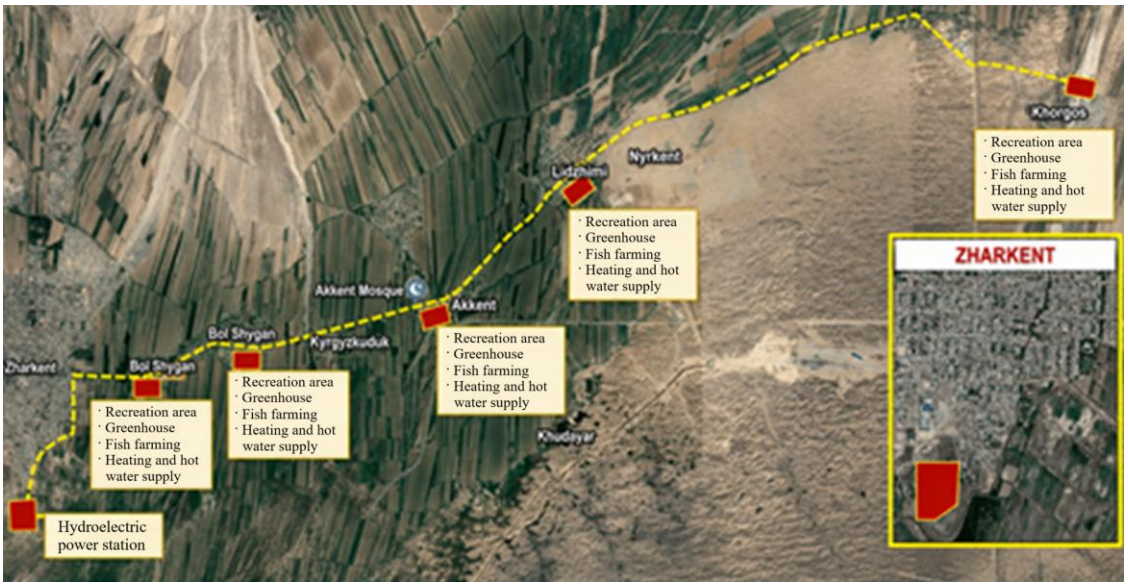


Figure 7. Schematic layout of the proposed integrated geothermal-resource development project along the Zharkent-Khorgos International Center for Cross-Border Cooperation corridor

The proposed development program includes drilling a 5000-m exploration well to penetrate the deepest prospective intervals of the Cretaceous aquifer system, with an anticipated artesian discharge of 40-50 L/s and a water temperature anticipated to reach approximately 110-120°C or higher, subject to confirmation by drilling and well testing. Subsequent stages include resource assessment and reserve approval by the State Commission on Mineral Reserves, construction of a binary-cycle geothermal power plant and trunk pipeline, and development of direct-use facilities along the pipeline corridor. Proposed applications include recreation facilities, greenhouse heating, aquaculture, space heating, and domestic hot-water supply.

3.6. Discussion

The calculated recharge balance indicates a dual mechanism governing the formation of groundwater resources within the Cretaceous thermal aquifer system. Near-surface recharge sources, comprising infiltration losses from surface watercourses and infiltration of atmospheric precipitation through hydrogeological windows, contribute 2.157 m^3/s. equivalent to 45.9% of total recharge. The second major component, 1.169 m^3/s or 24.9%, is associated with deeper groundwater circulation through leakage from the fractured Paleozoic basement and inflow along submeridional fault zones. The remaining 29.3% is attributed to transboundary groundwater inflow.

This interpretation agrees with an independent study of the geological controls on the Zharkent geothermal system [23]. which identified two principal recharge mechanisms from structural and hydrogeochemical evidence: mountain-front recharge and mountain-block recharge through fractured basement rocks. The present groundwater-balance calculations provide a quantitative expression of this conceptual interpretation. Within Kazakhstan, the relative contributions of near-surface and deep recharge are approximately 65:35.

Hydrogeochemical characteristics provide indirect evidence for the contribution of fault-controlled deep circulation. Groundwater from Well 5539 contains elevated fluoride concentrations of up to 10 mg/L, silicic acid concentrations exceeding 50 mg/L, and radon concentrations of up to 60 nCi/L, while retaining low total mineralization of 0.3-

1.0 g/L and alkaline pH. This geochemical association is consistent with prolonged water–rock interaction and groundwater circulation along deeper fault-controlled pathways. A similar interpretation was reported independently in [24]. The influence of geological composition on water chemistry has also been examined in eastern Kazakhstan [25], where was investigated the relationship between rare-metal mineralization in salt lakes and the composition of the associated granite massifs. The coexistence of high groundwater temperature and low mineralization is a characteristic feature of the Zharkent Basin. Relative to many geothermal reservoirs hosted by sedimentary basins, this hydrochemical condition reduces several constraints associated with mineral scaling and fluid treatment during utilization.

From a resource-assessment standpoint, comparison between estimated natural recharge and approved exploitable reserves is particularly informative. The approved reserves of the Zharkunak geothermal field, 12960 m^3/day under categories $B+C_1$, represent only 3.2% of the estimated total recharge of 406.3×10^3 m^3/day and 4.5% of the recharge generated within Kazakhstan, estimated at 287.4×10^3 m^3/day. The practically recoverable fraction of natural groundwater resources is expected to be lower than the total recharge estimate. Even under this restriction, the ratio indicates a substantial undeveloped resource and supports further exploration of adjacent sectors, particularly the Priili and Usek areas, where well tests have already yielded approximately 50 L/s at temperatures of 74-89°C.

The estimated thermal-energy potential is supported by two independent calculations that yield nearly identical values. Conversion of the approved groundwater reserves into energy units [20] gives 3524.1 GJ/day, corresponding to an average thermal capacity of 40.8 MW. Calculation using $W = Q\rho c\Delta T$, using a production rate of 150 L/s, a flow-weighted production temperature of 95°C, and a discharge temperature of 30°C yields approximately 40.9 MWth. Well 5539 alone, at a discharge of 50.5 L/s and a production temperature of 103°C, provides an estimated thermal capacity of approximately 15.4 MWth, more than one-third of the capacity of the planned production system. The estimated annual substitution of 43.9×10^3 tonnes of standard fuel corresponds to an avoided CO_2 emission of approximately $90\text{-}110\times10^3$ tonnes per year, depending on the carbon intensity of the displaced fuel. This estimate links geothermal development with Kazakhstan's emission-reduction commitments under the Paris Agreement.

For project economics, the temporal distribution of resource use is as significant as the nominal thermal capacity. The proposed cascade-utilization scheme shown in Figure 6 addresses the strong seasonal variation in heat demand. During summer, when heating demand declines, a larger proportion of the geothermal flow is assigned to binary-cycle electricity generation, while balneological applications maintain a continuous base demand throughout the year. This operating strategy supports an annual utilization factor approaching 0.8, a value consistent with continuously operated geothermal systems and substantially higher than the capacity factors generally associated with intermittent solar and wind generation [26, 27]. Under such operating conditions, the energy values reported in Table 6 represent technically attainable production levels rather than purely nominal estimates. The calculated values are also comparable with those reported for integrated heat-and-power supply schemes previously proposed for the Zharkent Basin [5, 6].

The relationship between the estimated resource base and the proposed development projects also warrants consideration. The combined geothermal-water demand of the prospective projects, approximately 40-50 L/s for the exploration well associated with the integrated energy-supply project for Zharkent and 30-40 L/s for wells along the route toward the Khorgos International Center for Cross-Border Cooperation, together with the approved production rate of 150 L/s remains below approximately 250 L/s. This corresponds to 21.6×10^3 m^3/day, or about 5.3% of the estimated natural recharge to the Cretaceous aquifer. On this basis, the proposed development program remains well below the calculated recharge magnitude. The principal constraints are associated instead with the capital cost of deep drilling to depths of up to 5000 m and the availability of concentrated heat and electricity demand. In the proposed scheme, the Khorgos International Center for Cross-Border Cooperation represents such a major demand center.

A further result of the study is the quantitative identification of a transboundary recharge component. The estimate that nearly one-third of total recharge originates beyond the national border implies that the hydraulic regime and resource availability of the Zharkunak field are potentially sensitive to groundwater abstraction and subsurface-resource development within the adjacent territory of China. Sustainable development of the geothermal system thus has a transboundary water-management dimension. The result also supports establishment of a dedicated groundwater-monitoring network along the border zone to track hydraulic heads, discharge, temperature, and hydrochemical indicators over time.

The principal limitations of the present assessment arise from parameter uncertainty. Two recharge components are particularly sensitive to the adopted assumptions. Inflow along tectonic fault zones depends strongly on the assigned hydraulic conductivity, for which reported values range from hundredths of a metre per day to 12-15 m/day, spanning approximately three orders of magnitude. The transboundary groundwater inflow is subject to similar uncertainty because aquifer parameters for the Chinese sector were inferred by analogy with the better-characterized Kazakhstan sector. A further source of uncertainty is the assumed equal partitioning of streamflow infiltration losses between the Cretaceous and Middle–Upper Pliocene aquifers. This partitioning is an analytical assumption rather than a directly measured quantity.

Reducing these uncertainties requires isotope-hydrological investigations using $\delta^{18}O$, $\delta^{2}H$, ^{3}H, and ^{14}C to constrain groundwater origin, recharge zones, and residence characteristics. Regional numerical groundwater-flow and solute-transport modelling is also required to test the recharge estimates, quantify hydraulic connections among aquifer units, evaluate fault-zone contributions, and assess the response of the system to long-term abstraction.

4. Conclusions

The Cretaceous thermal aquifer system of the Zharkent Artesian Basin constitutes a major high-temperature geothermal groundwater resource in Kazakhstan. Deep wells intersect the aquifer at depths of 1680-3702 m, including 2670-3702 m in the most prospective right-bank sector, where the water-bearing succession is 54-130 m thick. Artesian conditions are pronounced, with excess wellhead pressures of 1.4-53.5 kgf/cm^2, free-flow discharge rates of 22-75 L/s and groundwater temperatures of 74-103°C. The waters are weakly mineralized, at 0.26-0.90 g/L, alkaline, and predominantly of Na–Cl–HCO_3 composition. Groundwater

from Well 5539 also has balneological value because of elevated fluoride, silicic acid, and radon concentrations and satisfies the criteria of ST RK 452-2002 for moderately radon-bearing, siliceous-fluoride hyperthermal mineral water.

Recharge to the Cretaceous aquifer is derived from several hydrogeological pathways. Infiltration of surface runoff contributes 2.05 m^3/s, infiltration of atmospheric precipitation through hydrogeological windows contributes 0.107 m^3/s, groundwater inflow from fractured Paleozoic rocks contributes 0.534 m^3/s, and inflow along seven tectonic fault zones contributes 0.635 m^3/s. Recharge generated within Kazakhstan is estimated at 3.326 m^3/s, equivalent to 287.4×10^3 m^3/day. Transboundary groundwater inflow from the Chinese sector of the basin is estimated at 1.377 m^3/s and accounts for 29.3% of total recharge. Inclusion of this component gives a total recharge estimate of 4.703 m^3/s, or 406.3×10^3 m^3/day and approximately 148.3×10^6 m^3/year.

The approved exploitable reserves of the Zharkunak geothermal field amount to 12960 m^3/day and represent approximately 3.2%, represent approximately 3.2% of the estimated natural recharge. This ratio indicates that the presently approved abstraction occupies only a limited proportion of the calculated basin-scale groundwater resource. The approved reserves correspond to a thermal-energy potential of 3524.1 GJ/day and an average thermal capacity of approximately 40.8 MW_{th}. Annual thermal-energy production reaches approximately 1.286×10^6 GJ, equivalent to 357.6×10^3 MWh and 43.9×10^3 tonnes of standard coal equivalent. Over the 10000-day design exploitation period, the corresponding thermal-energy potential is approximately 3.52×10^7 GJ.

The most effective development strategy is based on cascade utilization of the geothermal flow. Seasonal allocation between greenhouse heating, binary-cycle electricity generation, and year-round balneological and sanatorium use provides a basis for maintaining high annual utilization of the production system. The assessed resource base also supports further exploration in adjacent sectors of the Zharkent Basin and the proposed integrated geothermal supply scheme extending from Zharkent toward the Khorgos International Center for Cross-Border Cooperation. The combined projected water demand remains below approximately 5.3% of the estimated natural recharge.

The results support expansion of geological and hydrogeological exploration beyond the currently developed Zharkunak field. They also indicate that long-term development should be accompanied by systematic monitoring of hydraulic heads, discharge, temperature, and groundwater chemistry, particularly along the Kazakhstan–China border. Reduction of uncertainty in fault-controlled and transboundary recharge estimates will require isotope-hydrological investigations and regional numerical groundwater-flow modelling before large-scale expansion of abstraction.

Author contributions

Conceptualization: DKK; Data curation: BRK; Formal analysis: VAZ; Funding acquisition: DKK; Investigation: DKK; Methodology: DKK; Project administration: DKK; Resources: DKK, VAZ; Software: BRK; Supervision: ADK; Validation: MBK; Visualization: ADK, BRK; Writing – original draft: DKK; Writing – review & editing: VAZ. 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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Жаркент артезиан алабының бор кешені жерасты термалды суларының қалыптасу жағдайлары, ресурстық әлеуеті және пайдалану перспективалары

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Аңдатпа. Мақалада Жетісу облысының Панфилов ауданында, Іле тауаралық ойпаңының шығыс бөлігінде орналасқан Жаркент артезиан алабының бор кешенінің қалыптасу жағдайлары мен ресурстық әлеуеті қарастырылған. Зерттеудің нақты негізін 1957-2016 жылдары бұрғыланған 18 терең ұңғыманы бұрғылау және сынау нәтижелері, өндірістік есептер материалдары мен бұрын жарияланған деректер құрайды. Құрылымдық-геологиялық талдау, қоректену аймағының гидродинамикалық картасын құру және Дарси заңы бойынша жерасты ағынын есептейтін баланс әдісі қолданылды. Жоғарғы бор сулы горизонты 1680-3702 м тереңдікте (алаптың ең перспективалы оң жағалау бөлігінде – 2670-3702 м) ашылады, су сыйыстырушы қабаттың қуаттылығы 54-130 м; ұңғыма сағасындағы су температурасы 74-103°C, өздігінен ағу дебиті 22-75 л/с, артық арын 1.4-53.5 кгс/см^2. Сулар әлсіз минералданған (0.26-0.90 г/дм^3), сілтілі, негізінен хлоридті-гидрокарбонатты натрийлі, фтор мен кремний қышқылының жоғары мөлшерімен сипатталады. Бор горизонтының қоректенуі төрт құраушыдан тұрады: жер үсті ағындысының сүзілуі – 2.05 м^3/с (43.6%), атмосфералық жауын-шашынның инфильтрациясы – 0.107 м^3/с (2.3%), палеозой жыныстарының жарықшақтық аймағынан ағу – 0.534 м^3/с (11.3%) және тектоникалық бұзылыс аймақтары бойынша ағын – 0.635 м^3/с (13.5%); Қазақстан аумағындағы қоректену жиынтығы 3.326 м^3/с деп бағаланды. ҚХР аумағынан келетін трансшекаралық ағынды (1.377 м^3/с) ескергенде жалпы қоректену мөлшері 4.703 м^3/с немесе тәулігіне 406.3 мың м^3-ге жетеді. Жаркунак кен орнының бекітілген пайдалану қоры (B+C$_1$ санаттары бойынша тәулігіне 12 960 м^3) есептелген табиғи ресурстардың небәрі 3.2%-ын құрайды, бұл алаптың айтарлықтай резерві бар екенін көрсетеді. Бекітілген қордың жылуэнергетикалық әлеуеті тәулігіне 3524.1 ГДж-ды құрайды, бұл 40.8 МВт орташа жылу қуатына, жылына 357.6 мың МВт·сағ өндіруге және 43.9 мың т шартты отынды алмастыруға сәйкес келеді. Ресурсты каскадты пайдалану бағыттары негізделіп, Жаркент ойпаңын игерудің екі перспективалы жобасы қарастырылған.

Негізгі сөздер: *геотермалды сулар, бор сулы кешені, Жаркунак кен орны, жерасты суларының қоректенуі, трансшекаралық ағын, гидрогеотермия, геотермалды энергетика, бинарлы цикл, каскадты пайдалану.*

Условия формирования, ресурсный потенциал и перспективы использования термальных подземных вод мелового комплекса Жаркентского артезианского бассейна

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Аннотация. В статье рассмотрены условия формирования и ресурсный потенциал мелового термоводоносного комплекса Жаркентского артезианского бассейна (восточная часть Илийской межгорной впадины, Панфиловский район области Жетісу). Фактическую основу работы составили результаты бурения и опробования 18 глубоких скважин, пройденных в 1957-2016 гг., материалы производственных отчётов и опубликованные данные предшествующих исследований. Использованы структурно-геологический анализ, гидродинамическое построение карты области питания и балансовый метод с расчётом подземного притока по закону Дарси. Установлено, что верхнемеловой водоносный горизонт вскрывается скважинами на глубинах 1680-3702 м (в наиболее перспективной правобережной части бассейна – 2670-3702 м) при мощности водовмещающей толщи 54-130 м; температура воды на устье скважин составляет 74-103°C, дебиты самоизлива – 22-75 л/с, избыточный напор – 1.4-53.5 кгс/см^2. Воды слабоминерализованные (0.26-0.90 г/дм^3), щелочные, преимущественно хлоридно-гидрокарбонатные натриевые, с повышенным содержанием фтора и кремнекислоты. Показано, что баланс питания мелового горизонта складывается из четырёх составляющих: инфильтрация поверхностного стока – 2.05 м^3/с (43.6%), инфильтрация атмосферных осадков – 0.107 м^3/с (2.3%), подток из зоны трещиноватости палеозойских пород – 0.534 м^3/с (11.3%) и подток по зонам тектонических нарушений – 0.635 м^3/с (13.5%); суммарное питание в пределах территории Казахстана оценено в 3.326 м^3/с. С учётом трансграничного притока с территории КНР (1.377 м^3/с) общая величина питания достигает 4.703 м^3/с, или 406.3 тыс. м^3/сут. Утверждённые эксплуатационные запасы Жаркунакского месторождения (12 960 м^3/сут по категориям В+C_1) составляют лишь около 3.2% расчётной величины естественных ресурсов, что указывает на значительный резерв бассейна для расширения освоения. Теплоэнергетический потенциал утверждённых запасов составляет 3524.1 ГДж/сут, что соответствует средней тепловой мощности 40.8 МВт, годовой выработке 357.6 тыс. МВт·ч и замещению 43.9 тыс. т условного топлива. Обоснованы направления каскадного использования ресурса и рассмотрены два перспективных проекта освоения Жаркентской впадины.

Ключевые слова: *геотермальные воды, меловой водоносный комплекс, Жаркунакское месторождение, питание подземных вод, трансграничный приток, гидрогеотермия, геотермальная энергетика, бинарный цикл, каскадное использование.*

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