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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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ASSESSMENT OF GROUNDWATER RECHARGE AND RESOURCES IN MANGYSTAU SAND MASSIFS, WESTERN KAZAKHSTAN

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Abstract. Relevance. The aquifers hosted in the aeolian deposits of the Baskuduk, Sauskan, and Tuyesu sand massifs, located on the Mangystau Plateau in Western Kazakhstan, are one of the sources of fresh groundwater for domestic and drinking water supply in the region's settlements. Under arid climatic conditions and limited surface-water availability, assessment of natural groundwater replenishment is of particular importance. The annual groundwater recharge rate determines the renewable component of groundwater resources and makes it possible to assess the potential for long-term exploitation of the aquifers without depleting their reserves. **Objective.** To assess the groundwater resource potential of the aquifers hosted in the aeolian deposits of the Baskuduk, Sauskan, and Tuyesu sand massifs based on the determination of annual groundwater recharge and storage reserves. **Methods.** The research is based on an integrated approach combining modern hydrogeological methods, numerical hydrogeological modeling tools, and GIS technologies for data collection and analysis. Field surveys were conducted during 2021-2025 to

investigate current hydrogeological conditions. *Results.* Groundwater recharge is mainly formed by infiltration of atmospheric precipitation during the cold season, while warm-season precipitation is almost entirely lost to evapotranspiration. The recharge modulus was determined using two methods – based on infiltration coefficients and groundwater level fluctuations – and ranges from 0,46 to 0,77 L/s·km² depending on the massif. Non-renewable groundwater resources were characterized as storage reserves of aeolian aquifers, with a total volume exceeding 400 million m³ across the three massifs. Forecast resources were estimated under three scenarios – optimistic, pessimistic, and most probable – considering different ratios of renewable and storage components under varying exploitation periods. *Conclusions.* Long-term operation of water abstraction systems in the Sauskan and Tuyesu massifs (since 1966 and 1971) confirms sustainable water supply to the city of Zhanaozen under regulated abstraction. The results demonstrate the significant resource potential of fresh groundwater in aeolian sands and their key role in domestic and industrial water supply in the Mangystau region.

Keywords: groundwater recharge, precipitation infiltration, renewable resources, forecast resources, Baskuduk, Sauskan and Tuyesu sand massifs, aeolian aquifers, Western Kazakhstan

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БАТЫС ҚАЗАҚСТАНДАҒЫ МАҢҒЫСТАУ ҮСТІРТІНІҢ ҚҰМДЫ МАССИВТЕРІНДЕГІ ЖЕРАСТЫ СУЛАРЫНЫҢ ҚОРЕКТЕНУІ МЕН РЕСУРСТЫҚ ӘЛЕУЕТІН БАҒАЛАУ

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Аннотация. *Өзектілігі.* Батыс Қазақстандағы Маңғыстау үстіртінде орналасқан Басқұдық, Саусқан және Түйесу құмды массивтерінің золдық шөгінділеріндегі сулы горизонттар өңір елді мекендерін шаруашылық-ауыз сумен қамтамасыз етудің негізгі көздерінің бірі болып табылады. Аридтік климат және жерүсті суларының шектеулілігі жағдайында жер асты суларының табиғи толықтырылуын бағалау ерекше маңызға ие. Жер асты суларының жылдық қоректену шамасы олардың жаңартатын ресурстарын айқындауға және сулы горизонттарды қорларын сарқытпастан ұзақ мерзімді пайдалану мүмкіндігін бағалауға мүмкіндік береді. *Мақсаты.* Жылдық қоректену шамасы мен сыйымдылықтық қорларды анықтау негізінде Басқұдық, Саусқан және Түйесу құмды массивтерінің золдық шөгінділеріндегі сулы горизонттардың жер асты суларының ресурстық әлеуетін бағалау. *Әдістері.* Зерттеу кешенді тәсілге негізделді және гидрогеологияның заманауи әдістері мен әдіснамасын, гидродинамикалық модельдеу бағдарламалық құралдарын және ГАЗ-технологияларын қамтыды. Құмды массивтердің гидрогеологиялық және су шаруашылығы жағдайын зерттеу мақсатында 2021-2025 жылдары маршруттық зерттеулер жүргізілді. *Нәтижелері.* Жерасты суларының қоректенуі суық кезеңдегі атмосфералық жауын-шашынның инфильтрациясы есебінен қалыптасады, ал жылы кезеңдегі жауын-шашын жоғары эвапотранспирация салдарынан іс жүзінде толық жұмсалады. Жерасты суларының қоректену модулі инфильтрация коэффициенті және су деңгейінің режимдік бақылау деректері бойынша екі әдіспен анықталды және массивке байланысты 0,46-0,77 л/с·км² құрайды. Қайта жаңартылмайтын ресурстар золдық су өткізгіш горизонттардың сыйымдылық қорлары арқылы сипатталды, олардың жалпы көлемі үш массив бойынша 400 млн м³-ден асады. Жерасты суларының болжамдық ресурстары үш сценарий (оптимистік, пессимистік және ең ықтимал) бойынша есептелді, олар пайдалану мерзімдеріне байланысты жаңартылатын және сыйымдылық қорларының әртүрлі арақатынасын ескереді. *Қорытындылар.* Саусқан және Түйесу массивтеріндегі (тиісінше 1966 және 1971 жж. бастап жұмыс істеп келе жатқан) су алу ұңғымаларын көпжылдық пайдалану тәжірибесін талдау Жаңаөзен қаласын сумен жабдықтаудың есептік су алу режимдері сақталған жағдайда тұрақтылығын растайды. Алынған нәтижелер золдық құмдардағы тұщы жерасты суларының айтарлықтай ресурстық әлеуетін және олардың Маңғыстау өңіріндегі елді мекендер мен мұнай кәсіпшіліктерін шаруашылық-ауыз сумен қамтамасыз етудегі басым рөлін көрсетеді.

Түйін сөздер: жерасты суларының қоректенуі, атмосфералық жауын-шашынның инфильтрациясы, жаңартылатын ресурстар, болжамдық ресурстар, Басқұдық, Саусқан және Түйесу құмды массивтері, эолдық шөгінділердің су өткізгіш горизонты, Батыс Қазақстан

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ОЦЕНКА ПИТАНИЯ И РЕСУРСНОГО ПОТЕНЦИАЛА ПОДЗЕМНЫХ ВОД ПЕСЧАНЫХ МАССИВОВ ПЛАТО МАНГЫСТАУ В ЗАПАДНОМ КАЗАХСТАНЕ

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Аннотация. *Актуальность.* Эоловые водоносные горизонты песчаных массивов Басқұдук, Саусқан и Түйесу, расположенных на плато Мангыстау в Западном Казахстане, представляют собой важные источники пресных подземных вод для хозяйственно-питьевого водоснабжения населенных пунктов региона. В условиях аридного климата, ограниченности поверхностных водных ресурсов и возрастающей потребности в надежном водоснабжении особую значимость приобретает оценка естественного восполнения подземных вод. Интенсивность ежегодного питания определяет величину возобновляемой составляющей ресурсов и служит одним из основных показателей при обосновании возможности длительной эксплуатации водоносных горизонтов без существенного истощения их запасов. *Цель.* Оценить ресурсный потенциал подземных вод эоловых отложений песчаных массивов Басқұдук, Саусқан и Түйесу на основе определения интенсивности ежегодного питания и величины емкостных запасов. *Методы.* Исследование основано на комплексном применении гидрогеологических методов, гидродинамического моделирования и геоинформационных технологий. В 2021–2025 гг. проведены наземные маршрутные исследования, направленные

на изучение гидрогеологических условий и современной водохозяйственной обстановки песчаных массивов. Для количественной оценки питания подземных вод использованы два подхода: расчет на основе коэффициента инфильтрации атмосферных осадков и анализ данных режимных наблюдений за колебаниями уровня подземных вод. Дополнительно выполнена оценка емкостных запасов и проведены сценарные расчеты прогнозных ресурсов с учетом различных сроков эксплуатации водоносных горизонтов. *Результаты.* Установлено, что основным источником питания подземных вод является инфильтрация атмосферных осадков холодного периода года, тогда как осадки теплого периода преимущественно расходуются на эвапотранспирацию. Модуль питания подземных вод, рассчитанный на основе коэффициента инфильтрации и данных режимных наблюдений за уровнем подземных вод, составляет 0,46–0,77 л/(с·км²) в зависимости от рассматриваемого песчаного массива. Невозобновляемая составляющая ресурсов охарактеризована величиной емкостных запасов эоловых водоносных горизонтов, суммарный объем которых для трех исследованных массивов превышает 400 млн м³. Прогнозные ресурсы подземных вод оценены по трем сценариям - оптимистичному, пессимистичному и наиболее вероятному, предусматривающим различные соотношения возобновляемых ресурсов и емкостных запасов в зависимости от продолжительности эксплуатации водоносных горизонтов. *Выводы.* Анализ многолетнего опыта эксплуатации водозаборов песчаных массивов Саускан и Туйесу, функционирующих с 1966 и 1971 гг. соответственно, свидетельствует о возможности устойчивого водоснабжения города Жанаозена при соблюдении расчетных режимов водоотбора. Полученные результаты подтверждают значительный ресурсный потенциал пресных подземных вод эоловых отложений и их важную роль в обеспечении хозяйственно-питьевого водоснабжения населенных пунктов и нефтепромысловых объектов Мангыстауского региона. Рациональное использование выявленных ресурсов требует учета интенсивности естественного питания, величины емкостных запасов и продолжительности эксплуатации водоносных горизонтов.

Ключевые слова: питание подземных вод, инфильтрация атмосферных осадков, возобновляемые ресурсы, прогнозные ресурсы, песчаные массивы Баскудук, Саускан и Туйесу, водоносный горизонт эоловых отложений, Западный Казахстан

Introduction. The 2022 UN World Water Development Report *Groundwater: Making the Invisible Visible* recognized that groundwater holds considerable potential to deliver social, economic, and environmental benefits – including climate change adaptation (UNESCO, *UN-Water*, 2022). Groundwater is broadly understood as a natural resource whose value rests on renewable supplies and, in more exceptional circumstances, on non-renewable reserves (natural storage) that can be exploited and depleted (Margat and van der Gun, 2013; Foster et al., 2006).

The latter serve as an important water buffer, making abstraction regimes less sensitive to the natural rhythm of recharge.

Renewable groundwater resources represent the primary indicator of annual recharge, capturing the essential character of groundwater as a replenishable mineral resource (Osipov et al., 2019). They define the upper limit of sustainable long-term abstraction – the rate at which groundwater can be withdrawn over a multi-year period without causing depletion – and are therefore central to any assessment of resource potential.

The Baskuduk, Sauskan, and Tuyesu sand massifs of Mangystau Region in western Kazakhstan lie on the Mangystau Plateau within the Caspian Sea basin (Figure 1). The terrain is a structurally tilted plateau dissected by residual mesa landforms and numerous enclosed depressions and basins of varying shape and size, typically bounded by steep scarps with abundant gullies; the depressions are occupied by salt flats (solonchaks) and takyrs. The plateau surface, at absolute elevations of 200-220 m, slopes southward. Surface runoff is absent throughout the area.

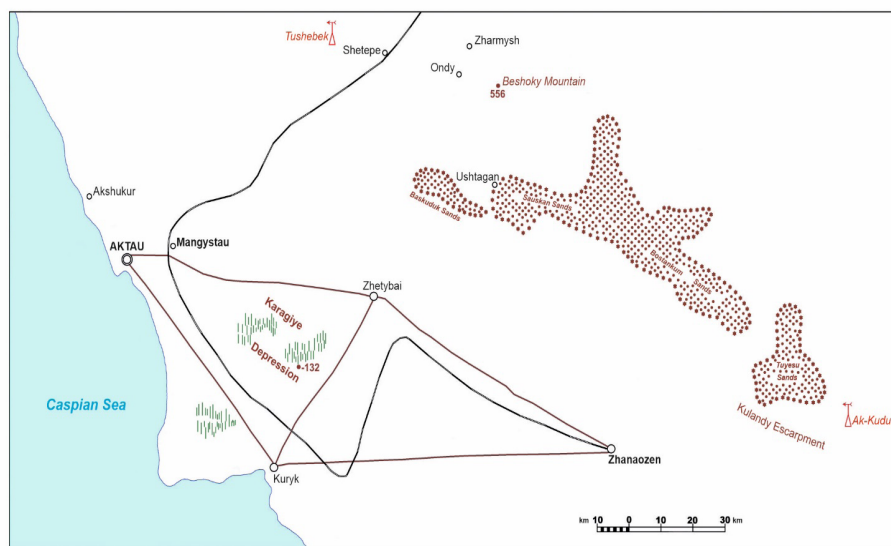


Figure 1. Overview Map of the Sand Massifs of the Mangystau Plateau.

The sand massifs form a roughly east-west belt. Baskuduk sands occupy the western margin, with the Sauskan-Bostankum sands adjoining them to the southeast. The relief of these massifs is denudational-accumulative, of barchan type, with a central elevated zone reaching 230-245 m a.s.l. The central sands are actively mobile and unvegetated; the peripheral and eastern portions are gently undulating and ridge-mound in character, partially to fully stabilized by vegetation. The relative height difference between mounds and deflation hollows ranges from

10-15 m (up to 20 m in the central zone) to 3-5 m at the margins. The northeastern boundary of the Sauskan massif is defined by a system of salt flats representing groundwater discharge zones. The Bostankum sands are essentially water-free.

At the far southeast lies the Tuyesu sand massif, an aeolian cellular-ridge plain with scattered barchans and sparse vegetation. The sands form cellular mounds 5-10 m high with cell depths of 8-10 m. The massif extends approximately 30 km from southeast to northeast, reaching a maximum north-south width of about 14 km. Absolute elevations range from 80 m in the eastern part to 210 m in the west.

The study area has a continental, hyper-arid climate characterized by high solar insolation, pronounced diurnal and seasonal temperature swings, hot dry summers, mild winters, brief transitional seasons, low atmospheric humidity, relatively low but highly variable annual precipitation, and intense solar radiation (Ongayev et al., 2022).

Review of the Hydrogeological Characteristics of the Study Area. Within the hydrogeological regionalization framework, the study area falls within the Central Mangyshlak second-order basin, part of the Ustyurt first-order basin of the Scythian-Turanian hydrogeological region. (Smolyar et al., 2022; Razakova et al., 2020; Lagutin et al., 2020).

The Baskuduk sand massif. Exploration works carried out in 1966-1967 established that groundwater is associated with a bowl-shaped depression in the relief of the underlying aquiclude rocks. In plan view, the aquifer has an elongated shape, extending up to 12 km in length with an average width of 1,9 km. The area of water-saturated sands is 24,9 km². The water-bearing deposits are composed of fine-grained, and less commonly very fine-grained sands. The aquifer is underlain by clays and clayey sands of Cenomanian age.

The waters are unconfined, pore-type groundwater. The depth to groundwater, depending on the local relief, varies from 2,1 to 39,2 m. The aquifer thickness reaches up to 28,5 m. The water-bearing capacity of the sands is characterized by well yields ranging from 1,1 to 2,5 L/s at drawdowns of 1,6-9,9 m. Hydraulic conductivity varies from 1,1 to 7,7 m/day, with a weighted average value of 4,57 m/day. The specific yield of the sands ranges from 0,072 to 0,155, with an average value of 0,12.

Low mineralization of groundwater (0,3-0,6 g/L) is observed in the central part of the massif, where vegetation is sparse and the groundwater table is relatively deep. In the northern and northeastern parts, a zone of increased groundwater mineralization is identified, locally reaching brine concentrations.

Groundwater flow is directed toward the north and northeast. The main source of groundwater recharge is the infiltration of atmospheric precipitation. Discharge predominantly occurs through evaporation processes within the zone of elevated mineralization.

The Sauskan sand massif. The hydrogeological characteristics of this sand massif are controlled by the relief of the underlying bedrock surface, which forms a

bowl-shaped, ellipsoidal depression with its long axis extending in a north-western direction and a general surface slope toward the north-north-west. The central part of the depression is complicated by a narrow local uplift of the aquiclude, which divides the massif into northern and southern parts that are locally hydraulically isolated from each other. The massif extends approximately 29 km along its long axis and reaches up to 8 km in width. The total area of water-saturated sands is 220 km², while the area of freshwater occurrence is 167,3 km².

The water-bearing deposits are represented by sands, predominantly fine-grained and relatively homogeneous both in plan and vertical section, although very fine-grained varieties also occur in the northern part. The groundwater is unconfined and of pore-type. The depth to groundwater, depending on the relief, varies from 1,5 to 24,4 m, averaging 4-5,5 m in the north and 5-7 m in the south. The total thickness of the aeolian aquifer ranges from 0,4 to 22 m, with measured values of 9.8-20.5 m (northern part) and 10.2-19.8 m (southern part).

The water-bearing capacity of the sands is characterized by well yields ranging from 0,6 to 4,1 L/s at drawdowns of 1,4-12,8 m, with specific yields of 0,4-0,5 L/s. Hydraulic conductivity values vary from between 2,0 and 6,9 m/day, with predominant values of 2,5-5,0 m/day. The specific yield of the sands ranges from 0,126 to 0,176, with an average value of 0,14-0,15.

Minimum groundwater mineralization (0,2-0,3 g/L) is observed in the southern and central parts of the massif, which are topographically elevated, lack vegetation, and are composed of dune sands representing areas of primary groundwater formation. Along the direction of groundwater flow toward the north and northeast, mineralization increases from 1 to 10-15 g/L. A belt of saline waters, 0,35-1,5 km wide, extends along the northern boundary of the sand massif. In areas of salt flats (sor) and solonchaks, groundwater is highly mineralized, reaching brine conditions.

Groundwater flow is directed toward the northeast. The main source of recharge is the infiltration of atmospheric precipitation. Groundwater discharge occurs mainly in the northern and northeastern parts of the deposit within zones of extensive development of salt flats and solonchaks.

The Tuyesu sand massif. Groundwater in the sandy deposits is not distributed uniformly; it is confined to a bowl-shaped depression in the relief of the clay aquiclude. This depression is formed by the merging of two local valleys separated in the western part of the field by a sharp uplift of Cenomanian deposits. The area of aquifer occurrence is 82,2 km². The aquifer has an elongated shape extending from west to east, locally complicated in the northern part by a "tongue-like" extension along another valley. Its length along the major axis is 22-24 km, and its width ranges from 1,5 to 6,8 km. The water-bearing deposits are composed of quartz-feldspar sands, which are relatively uniform in grain-size composition throughout the section and are classified as fine-grained sands.

The groundwater is unconfined and of pore type. During the exploration stage, the depth to groundwater varied from 5-10 m to 40 m depending on the relief. The

aquifer thickness ranges from 0,3 to 39,0 m. Maximum thicknesses are associated with the deepest depressions in the underlying relief, which correspond to potential wellfield sites; the weighted average thickness is 18,4 m. Specific well yields range from 0,3 to 1,6 L/s, with predominant values of 0,3-0,6 L/s and an average of 0.54 L/s for the field. Hydraulic conductivity values range from 0.78 to 8.41 m/day, with prevailing values of 3-4 m/day. The weighted average hydraulic conductivity for the field is 3,73 m/day. The specific yield of the sands reaches up to 0,147.

Groundwater is fresh, with mineralization up to 1,0 g/L. Waters with mineralization ranging from 1 to 7,3 g/L are identified only in the southern and eastern parts of the field, where they form a narrow belt (0,25-1,5 km wide) surrounding the main aquifer body and abruptly transition into saline waters associated with salt-flat (sor) deposits within the groundwater discharge zone. Within the main freshwater lens, mineralization averages 0,3-0,45 g/L.

Groundwater recharge occurs periodically during the spring and autumn seasons through infiltration of atmospheric precipitation. Discharge zones are located along the southeastern and eastern margins of the massif, where mineralized waters occur and a belt of topographic depressions is observed, characterized by the development of typical phreatophytic vegetation, gradually transitioning into salt flats (sor).

Materials and Methods. From a hydrogeological perspective, the study area has been investigated in considerable detail through regional medium-scale surveys and exploration programs conducted since the 1960s. The study employed an integrated methodological approach combining modern hydrogeological methods and techniques, numerical groundwater-flow modeling tools, and GIS-based technologies for data collection, processing, and analysis (Sotnikov et al., 2025). Field reconnaissance surveys aimed at assessing the current hydrogeological and water-management conditions of the sand massifs were carried out during 2021-2025.

When assessing groundwater recharge resulting from precipitation infiltration, the total annual precipitation is of less practical importance than effective precipitation, i.e., precipitation occurring during the cold season. Precipitation falling during the warm season (April-October), under conditions of high atmospheric moisture deficit and intense evaporation, is generally consumed by evapotranspiration. The analysis was based on long-term average annual and effective precipitation data obtained from observations at two permanent meteorological stations operated by the national hydrometeorological service, [Kazhydromet](#).

Over the past two decades, a trend toward increasing mean annual air temperature has been observed, from 11,0-12,0°C during 1955-1997 to 12,2-13,4°C during 1998-2020 (Figure 2). In contrast, trend lines for both total annual precipitation and cold-season precipitation during the 1950-2020 observation period remain nearly horizontal, indicating no significant long-term changes in precipitation amounts (Figures 3-4) (Rakhimov et al., 2026).

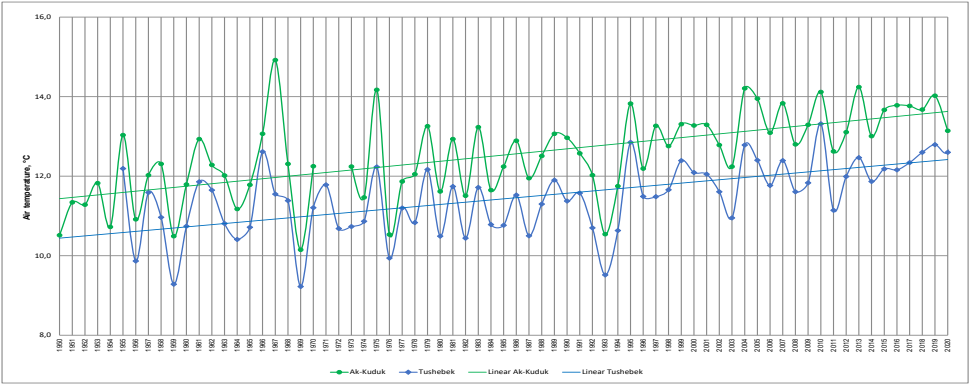


Figure 2. Dynamics of annual air temperature at Tushebek and Ak-Kuduk meteorological stations.

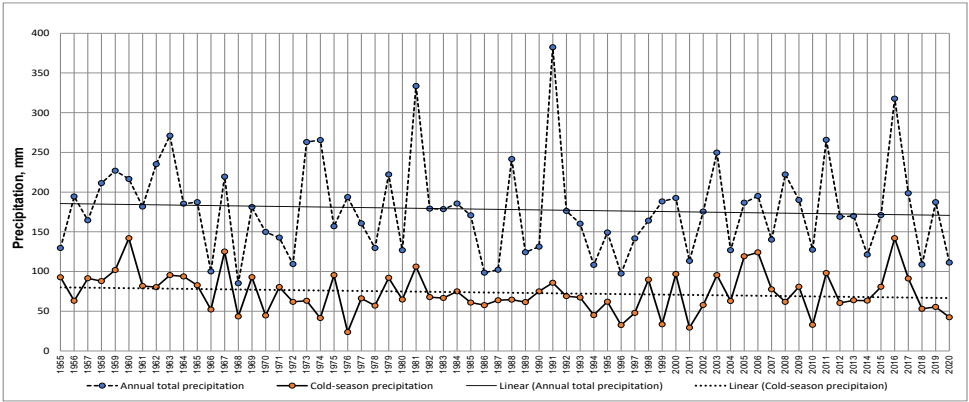


Figure 3. Variations in annual precipitation and cold-season precipitation during the observation period at Tushebek meteorological station.

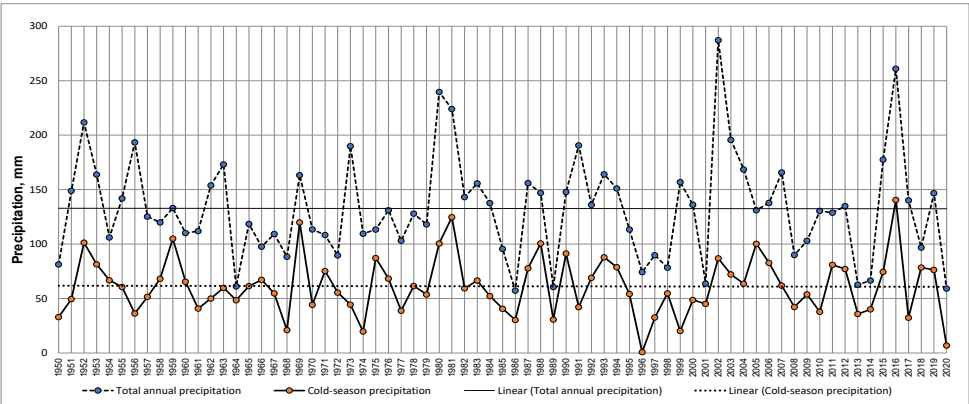


Figure 4. Variations in annual precipitation and cold-season precipitation during the observation period at the Ak-Kuduk meteorological station.

Groundwater recharge forms the groundwater runoff and determines the renewable resources of aquifers hosted in aeolian sandy deposits. Recharge is commonly expressed as a discharge rate, usually in L/s. It may also be represented by the groundwater runoff depth (h_{gw}), defined as the thickness of the water layer entering the aquifer per unit time (typically mm/year), or by the groundwater runoff modulus (M_{gw}), which is equivalent to the renewable resource modulus (M_{ren}) and represents the recharge rate per unit area of aquifer extent (typically L/s·km²). The runoff modulus is related to the runoff depth by the following equation:

$$M_{gw} = 0,0317 h_{gw} \quad (1)$$

Two methods were used to estimate groundwater recharge from atmospheric precipitation (Ali and Mubarak, 2017; Caschetto et al., 2016; Chenini and Ben Mammou, 2010).

(a) Estimation based on the infiltration recharge modulus, calculated using the following equation:

$$M_{inf} = 0,0317 \alpha X_{eff} \quad (2)$$

where M_{inf} is the infiltration recharge modulus (L/s·km²); α is the infiltration coefficient (dimensionless); and X_{eff} is the annual effective precipitation (mm/year). Values of the infiltration coefficient (α) were determined from pumping-test and field-investigation data, as well as by analogy with similar hydrogeological conditions reported in the literature.

(b) Estimation based on groundwater-level fluctuations, using the annual recharge modulus calculated as:

$$M_{ann} = 31,7 \mu \Delta h_{avg} \quad (3)$$

where M_{ann} is the annual groundwater recharge modulus (L/s·km²); μ is the average specific yield of the aquifer deposits (dimensionless); and Δh_{avg} is the mean annual groundwater-level fluctuation derived from monitoring observations (m).

Hydrodynamic methods for estimating groundwater recharge are based on the solution of differential equations describing transient or steady-state groundwater flow. These equations can be solved using analytical and numerical approaches implemented in modern computer-based modeling software. Analytical methods for estimating groundwater flow rates are generally based on Darcy's law. A widely applied approach involves the estimation of groundwater recharge through inverse modeling, in which recharge values are derived from hydrogeological flow models calibrated against observed groundwater levels at different points in time and known aquifer parameters. The importance of hydrodynamic methods is expected to increase as areas with natural groundwater and surface-water flow regimes

continue to decline (Águila et al., 2019; Gee and Hillel, 1988; King et al., 2017; Sanford, 2002).

Renewable (natural) groundwater resources are characterized by long-term average values of groundwater runoff calculated over periods of 10-30 years, thereby accounting for both interannual and seasonal variability. These estimates provide an indication of groundwater availability within the sand massifs and define the upper limit of sustainable groundwater abstraction over extended periods without resource depletion. Consequently, they represent a key component in the assessment of groundwater resource potential (Kuruppath et al., 2018; Spanov et al., 2019; Tekenov et al., 2017; Mukhamedzhanov et al., 2019).

Non-renewable groundwater resources are represented by the storage reserves of aeolian aquifers and are defined as the volume of water released during aquifer drainage. Calculations of storage reserves were performed for the unconfined pore-water aquifers of the sand massifs. The assessment was based on refined estimates of aquifer extent, saturated thickness, and the specific yield of the water-bearing deposits (Goodarzi et al., 2015).

The hydrogeological basis for forecasting the rational utilization of groundwater resources lies in the assessment of forecast groundwater resources, which are estimated using general hydrogeological concepts together with specialized local- and regional-scale investigations. In the present study, forecast groundwater resources were calculated using a methodology that relates regional forecast resources to renewable resources and storage reserves of aeolian aquifers through the following equation:

$$Q_{for} = a_1 Q_r + a_2 \frac{V_s}{t} \quad (4)$$

where Q_{for} is the forecast groundwater resource; Q_r is the renewable groundwater resource; V_s is the aquifer storage reserve; t is the exploitation period; and a_1 and a_2 are utilization coefficients for renewable resources and storage reserves, respectively.

The assessment of forecast groundwater resources in the sand massifs was carried out under three scenarios (Mukhamedzhanov et al., 2020).

Scenario 1 – optimistic. Forecast resources are estimated exclusively based on the evaluated renewable groundwater resources to prevent aquifer depletion. The utilization coefficient is assumed to be 0,7, based on long-term forecasting practice. The exploitation period is considered unlimited.

Scenario 2 – pessimistic. Forecast resources are calculated solely from the estimated storage reserves of the sand massifs. This scenario assumes the absence of aquifer recharge. The utilization coefficient is taken as 0,2 to minimize the risk of aquifer depletion, and the exploitation period is set to 15 years, representing a prolonged drought period.

Scenario 3 – expected and most probable. Forecast resources are determined

by considering both renewable resources and storage reserves of aeolian aquifers. The utilization coefficients are 0,7 for renewable resources and 0,2 for storage reserves. The exploitation period is assumed to be 25 years, based on long-term hydrogeological practice in Kazakhstan.

Thus, the resource potential of the sand massifs is characterized on the one hand by renewable and non-renewable (storage) groundwater resources, and on the other hand by forecast resources representing the potential for groundwater utilization.

Results and Discussions. The assessment of annual groundwater recharge and resource potential of aeolian deposits was carried out separately for each sand massif.

The Baskuduk sand massif. Hydrogeological exploration works aimed at identifying water supply sources for local oil fields were conducted within the sand massif in 1966-1967. The storage reserves of groundwater in the aeolian deposits are estimated at 49,7 million m³ (Table 1). Groundwater recharge was calculated based on both precipitation infiltration and hydrodynamic methods. The recharge modulus varies from 0,46 to 0,57 L/s·km², with an average value of 0,55 L/s·km² and an average groundwater runoff depth of 17,5 mm/year. Renewable groundwater resources are estimated at 13,8 L/s (Table 2). Forecast groundwater resources of the aeolian aquifer, calculated under three scenarios, range from 9,7 to 22,3 L/s (Table 3).

Groundwater abstraction has been carried out since 1996 using individual wells, with abstraction rates not exceeding 1,0 L/s, which corresponds to approximately 10% of the forecast resources under the optimistic scenario. The ecological condition of the sand massif and surrounding area has remained largely unchanged. Local occurrences of mobile sands are associated with overgrazing and the cutting of shrubs and saxaul for fuel. The forecast groundwater resources indicate the potential to increase abstraction for domestic and potable water supply in nearby oil fields and rural settlements.

The Sauskan sand massif. Hydrogeological exploration works in the sand massif were carried out during 1964-1965 and 1966-1967 to identify water supply sources for regional oil fields. The storage reserves of groundwater in the aeolian aquifer are estimated at 177,3 million m³ (Table 1).

Recharge estimates were obtained using the same approach described above. The recharge modulus varies from 0,39 to 0,77 L/s·km², with a calculated value of 0,77 L/s·km² and an average groundwater runoff depth of 24,1 mm/year. Renewable groundwater resources are estimated at 128,1 L/s (Table 2). Forecast groundwater resources of the aeolian aquifer, calculated under three scenarios, range from 75,0 to 134,6 L/s (Table 3).

Regular groundwater abstraction in the northern part of the sand massif has been carried out since 1966 for domestic and potable water supply to the city of Zhanaozen. A linear well field with a total length of 17,7 km consists of 24 production wells with spacing of 65-1,060 m and depths ranging from 27 to 52 m.

In 1998, the operational performance of the aeolian aquifer was analyzed for

the period 1967–1997. The total annual groundwater abstraction during 1966–1980 ranged from 13,3 to 60,2 L/s, with an average of 38,5 L/s, corresponding to 43% of the forecast groundwater resources under the optimistic scenario. During 1981–1987, annual abstraction varied from 34,1 to 54,4 L/s, with an average value of 40,8 L/s (45,5% of the forecast resources under the optimistic scenario). Despite seasonal fluctuations in dynamic groundwater levels, no long-term decline of mean annual groundwater levels in production wells was observed.

A hydrogeodynamic model was developed for forecasting groundwater abstraction up to 2022, based on the solution of an inverse steady-state problem for 1967 and simulation of groundwater withdrawal in the northern part of the sand massif over the period 1967–1997. Starting from the hydrogeological conditions established for 1997, a predictive simulation was carried out for a 25-year abstraction period with a total discharge of 59,6 L/s (66,4% of the forecast resources under the optimistic scenario). No deterioration in groundwater quality or increase in mineralization is expected under the simulated abstraction regime. Environmental impacts associated with groundwater withdrawal were assessed as negligible.

In 2021, an additional assessment of the aeolian aquifer was performed for the northern part of the sand massif covering the period 2003–2020. During this period, groundwater abstraction ensured domestic and potable water supply for the city of Zhanaozen and the settlements of Sazdy, Ushtagan, and Kyzylsay. The ecological condition of the sand massif and surrounding area remained essentially unchanged compared to 1997, and no evidence of intensified modern geological processes (such as surface subsidence) was observed. Sand outflow from the aeolian aquifer and ground subsidence in the vicinity of wells were not detected. No soil salinization or vegetation degradation was identified within the well field area. Periodic high-recharge years play an important role in the system: during such periods, moisture infiltration contributes to replenishment of the aquifer storage.

Total annual groundwater abstraction in the northern part of the sand massif during 2003–2020 ranged from 30,4 to 57,6 L/s, with an average of 42,4 L/s, corresponding to 47,3% of the forecast resources under the optimistic scenario. Mean annual dynamic groundwater levels varied from 6,3–15,4 m in 1997 to 7,0–16,3 m in 2020, while drawdowns increased from 2,8–10,9 m to 4,6–11,6 m, respectively. In 11 wells, no increase in drawdown was observed. In the remaining wells, the average rate of drawdown increase was estimated at 0,09 m/year.

A new hydrogeodynamic model of the aeolian aquifer was developed, and its consistency with the hydrogeological conditions of the sand massif was verified by solving an inverse steady-state problem for 1997 and simulating aquifer exploitation over the period 1998–2020. Based on the hydrogeological conditions established for the end of 2020, a predictive simulation was performed for a 10,000-day projection period with a total abstraction rate of 59,6 L/s (66,4% of the forecast groundwater resources under the optimistic scenario).

Analysis of long-term aquifer exploitation and results of hydrogeodynamic

modelling for the Sauskan sand massif indicate that an abstraction rate of 59,6 L/s in the northern part is optimal. Further increases in groundwater abstraction may be achieved through the construction of additional production wells in the southern part of the sand massif.

Table 1. Estimated storage reserves of groundwater in sand massifs.

No.	Sand massif	Area, km ²	Aquifer thickness, m		Specific yield (dimensionless)		Storage reserves, million m ³
			min - max	average	min - max	average	
1.	Baskuduk	24,9	0,5-28,5	16,6	0,07-0,16	0,12	49,7
2.	Sauskan	167,3	0,4-22	7,3	0,12-0,18	0,145	177,3
3.	Tuyesu	96,4	0,3-39	13,5	0,12-0,16	0,14	182,8
Total		288,6	7,3-16,6	10,1	0,12-0,15	0,14	409,8

Table 2. Estimated infiltration recharge of groundwater.

No.	Sand massif	Area, km ²	Recharge modulus, L/s·km ²		Groundwater runoff depth, mm/year	Renewable resources, L/s	
			min - max	calculated		min - max	average
1	Baskuduk	24,9	0,46-0,57	0,55	17,5	11,5-14,2	13,8
2	Sauskan	167,3	0,39-0,77	0,77	24,1	65,0-132,4	128,1
3	Tuyesu	96,4	0,18-0,64	0,46	14,6	11,5-52,2	44,7
Total		288,6	0,46-0,55	0,65	20,4	13,8-128,1	186,6

Table 3. Estimated groundwater resource potential.

No.	Sand massif	Area, km ²	Renewable resources, L/s	Storage reserves, million m ³	Forecast resources, L/s		
					Scenario 1	Scenario 2	Scenario 3
1	Baskuduk	24,9	13,8	49,7	9,7	21,0	22,3
2	Sauskan	167,3	128,1	177,3	89,7	75,0	134,6
3	Tuyesu	96,4	44,7	182,8	31,3	77,3	77,7
Total		288,6	186,6	409,8	130,6	173,3	234,6

The Tuyesu sand massif. The storage reserves of groundwater in the aeolian aquifer are estimated at 182.8 million m³ (Table 1). Recharge estimates were derived using the same methodology as described above. The recharge modulus varies from 0,18 to 0,64 L/s·km², with a calculated value of 0,46 L/s·km² and an average groundwater runoff depth of 14,6 mm/year. Renewable groundwater resources are estimated at 44,7 L/s (Table 2). Forecast groundwater resources of the aeolian aquifer, calculated under three scenarios, range from 31,3 to 77,7 L/s (Table 3).

Regular groundwater abstraction in the northern part of the sand massif has been carried out since 1971 for domestic and potable water supply to the city of Zhanaozen. Twenty-seven production wells with depths of 44-62 m have been constructed and grouped into three linear well fields: southern (18 wells), northern (5 wells), and central (4 wells). The spacing between well lines ranges from 500 to 2,000 m, while the distance between individual wells varies from 500 to 1,800 m.

In 1998, an analysis of aquifer exploitation was performed for the period 1971-

1997. The mean annual groundwater abstraction was 104,2 L/s, reaching 121,5-133,1 L/s in individual years. The well fields operated under non-steady-state flow conditions with a continuous decline in groundwater levels.

For forecasting groundwater abstraction up to 2022, a hydrogeodynamic model was developed based on the solution of an inverse steady-state problem for 1967 and simulation of abstraction processes in the northern part of the sand massif for 1971-1997. Based on the hydrogeological conditions established for 1997, a predictive simulation was performed for a 25-year period with a total abstraction rate of 103,0 L/s. No deterioration in groundwater quality or increase in mineralization is expected under the simulated conditions. Environmental impacts associated with groundwater abstraction were assessed as negligible. Long-term abstraction during 1971-1997 did not indicate any deterioration of environmental conditions.

In 2021, an additional assessment of the exploitation history of the aeolian aquifer in the sand massif was carried out for the period 2003-2020. During this time, groundwater abstraction ensured domestic and potable water supply for the city of Zhanaozen and the settlements of Sazdy, Ushtagan, and Kyzylsay. The ecological condition of the sand massif and surrounding areas remained essentially unchanged compared to 1997, and no evidence of intensified modern geological processes (such as surface subsidence) was observed. Local occurrences of mobile sands were mainly associated with overgrazing and the cutting of shrubs and saxaul for fuel. No sand migration from the aeolian aquifer or ground subsidence in the vicinity of wells was detected. No soil salinization or vegetation degradation was identified within the well field area. Periodic high-recharge years play an important role in the system: during such periods, increased moisture infiltration contributes to the replenishment of aquifer storage.

Total annual groundwater abstraction during 2003-2020 ranged from 48,6 to 99,2 L/s, with an average value of 81,5 L/s. Abstraction was carried out from 20-24 wells, with 22 wells operating most frequently. Mean annual dynamic groundwater levels changed from 17,2-36,3 m in 1997 to 23,8-38,9 m in 2020, while drawdowns increased from 2,8-10,9 m to 4,6-11,6 m, respectively. In eight wells, no increase in drawdown was observed. In the remaining wells, the average rate of drawdown increase since 1997 was estimated at 0,24 m/year.

A hydrogeodynamic model of the aeolian aquifer was developed, and its consistency with the hydrogeological conditions of the sand massif was verified through the solution of an inverse steady-state problem for 1997 and simulation of aquifer exploitation for 1998-2020. Based on the hydrogeological conditions established for the end of 2020, a predictive simulation was performed for a 10,000-day period with a total abstraction rate of 103 L/s.

Thus, the total long-term groundwater abstraction from the aeolian aquifer of the Tuyesu sand massif during 1971-2020 exceeds the estimated forecast resources under the most probable scenario and is sustained mainly by depletion of aquifer storage, accounting for up to 42,2% according to modelling results. The adopted well-field scheme represents an efficient configuration for maximizing groundwater

extraction from the sand massifs. Long-term sustainability of abstraction can only be ensured through artificial recharge of the aquifer. The implementation of such measures requires further investigation, including detailed hydrogeological studies and numerical modelling.

Conclusion. The specific natural and climatic conditions result in extreme aridity of the Mangyshlak Peninsula. Despite the supply of surface water from the Volga River via pipeline, the issue of domestic and potable water supply for settlements and oil fields remains critical. One of the main sources of high-quality drinking water is groundwater in sand massifs, where favorable conditions exist for enhanced infiltration of atmospheric precipitation compared to surrounding areas, as well as for its accumulation in bowl-shaped depressions of the underlying formations. Fresh groundwater in aeolian sands represents the most promising resource for domestic and potable water supply, as confirmed by nearly 60 years of continuous exploitation of the Sauskan and Tuyesu sand massifs for the city of Zhanaozen.

In recent years, the importance of replenishing storage reserves in sand massifs has increased due to the availability of fresh surface water from the Volga River in the region. This issue warrants further investigation, and, where appropriate, implementation of a dedicated set of hydrogeological studies.

Use of Artificial Intelligence. Artificial intelligence (AI) tools were used solely for language translation, editorial assistance, and literature search during manuscript preparation. ChatGPT (OpenAI, GPT-5.5) was employed to support the translation of the manuscript from Russian into English and to improve language clarity. Microsoft Copilot was used to assist in literature search and retrieval of relevant scientific sources. All scientific content, interpretations, calculations, results, conclusions, and final text revisions were prepared, verified, and approved by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.

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