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HYDROGEOCHEMICAL INDICATORS OF SULFURIC-ACID URANIUM LEACHING IMPACT ON GROUNDWATER IN SHIELI AND ZHANAKORGAN DISTRICTS

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Abstract. Acid in situ recovery (ISR) of uranium can produce a persistent hydrogeochemical signal in ore-bearing aquifers, but interpretation is complicated by natural salinity, redox buffering, sparse monitoring networks, and incomplete disclosure of operational data. This study develops an analytical and methodological framework for distinguishing the effects of sulfuric-acid ISR from regional groundwater variability in the Shieli and Zhanakorgan districts of the Kyzylorda Region, Kazakhstan, with an illustrative worked calculation for the Irkol area. The framework combines source–pathway–receptor reasoning with paired indicators of acidification, sulfate loading, uranium mobilization, mineral dissolution, and changes in electrical conductivity. Two dimensionless screening coefficients, K_b and K_s , are used to compare observed values with explicitly stated reference conditions. Their calculation is demonstrated using one published observation from the Irkol pilot block at a single time point. This worked case verifies the equations' transparency, internal consistency and reproducibility, establishing an auditable basis ahead of the multi-well field validation this monitoring program requires. The analysis shows that no single parameter is sufficient for source attribution: the most diagnostic pattern is a concurrent decrease in pH and increase in sulfate and dissolved uranium, supported by major-ion balance and hydraulic context. Elevated mineralization or chloride without a corresponding uranium response may instead reflect natural salinization. The proposed framework is intended for hypothesis

testing and monitoring design. Robust validation will require repeated sampling from background, operational, boundary, and downgradient wells, together with piezometric observations, quality-controlled major-ion and trace-element analyses, and site-specific baseline distributions.

Keywords: in-situ leach uranium mining; groundwater; hydrogeochemistry; sulfate; uranium; radionuclides; groundwater monitoring

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ШИЕЛІ ЖӘНЕ ЖАҢАҚОРҒАН АУДАНДАРЫНДАҒЫ УРАНДЫ КҮКІРТ ҚЫШҚЫЛЫМЕН ШАЙМАЛАУДЫҢ ЖЕР АСТЫ СУЛАРЫНА ӘСЕРІНІҢ ГИДРОГЕОХИМИЯЛЫҚ КӨРСЕТКІШТЕРІ

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Аннотация. Уранды скважиналық жерасты сілтісіздендіру (СПВ) кенді сулы горизонттарда тұрақты гидрогеохимиялық сигнал тудыруы мүмкін, алайда оны түсіндіруді табиғи тұздылық, тотығу-тотықсыздану буферлігі, мониторинг желілерінің сиректігі және пайдалану деректерінің толық ашылмауы қиындатады. Жұмыста Қазақстанның Қызылорда облысы Шиелі және Жаңақорған аудандарында күкірт қышқылды СПВ әсерін аймақтық жерасты суларының табиғи өзгергіштігінен ажырату үшін Ірколь учаскесі бойынша иллюстрациялық есептеу мысалымен аналитикалық-әдістемелік негіз әзірленді. Негіз «көз — тасымалдау жолы — қабылдаушы» логикасын қышқылдану, сульфат жүктемесі, уранның қозғалуы, минералдардың еруі және электрөткізгіштіктің өзгеруінің қосарланған көрсеткіштерімен біріктіреді. Байқалған мәндерді нақты көрсетілген референс жағдайларымен салыстыру үшін екі өлшемсіз скрининг коэффициенті — K_b және K_s — қолданылады. Олардың есебі Ірколь тәжірибелік блогы бойынша бір жарияланған бақылауда, бір уақыт нүктесі үшін көрсетілген. Бұл есептеу мысалы теңдеулердің ашықтығын, ішкі үйлесімділігін және қайталанымдылығын растайды, осындай ауқымдағы мониторинг бағдарламасына қажетті кейінгі

далалық валидацияға дейінгі тексерілетін аналитикалық негіз қалыптастырады. Талдау көрсеткендей, бірде-бір жеке көрсеткіш көз атрибуциясы үшін жеткіліксіз: ең диагностикалық үлгі — негізгі иондар балансымен және гидравликалық контекстпен расталған, рН-тың төмендеуі мен сульфаттар және еріген уранның бір мезгілде артуы. Уранның сәйкес жауабынсыз жоғарылаған минерализация немесе хлоридтілік табиғи тұздануды көрсетуі мүмкін. Ұсынылған негіз гипотезаларды тексеру және мониторингті жобалау үшін арналған. Сенімді валидация фондық, пайдалану, шекаралық және ағын бойынша төменгі ұңғымалардан қайталама сынама алуды, пьезометрлік бақылауларды, сапасы бақыланатын негізгі иондар мен микроэлементтер талдауын, сондай-ақ учаскелік фондық үлестірімдерді талап етеді.

Түйін сөздер: уранды жерасты сілтісіздендіру; жерасты сулары; гидрогеохимия; сульфаттар; уран; радионуклидтер; жерасты суларын бақылау

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ГИДРОГЕОХИМИЧЕСКИЕ ИНДИКАТОРЫ ВОЗДЕЙСТВИЯ СЕРНОКИСЛОТНОГО ВЫЩЕЛАЧИВАНИЯ УРАНА НА ПОДЗЕМНЫЕ ВОДЫ РАЙОНОВ ШИЕЛИ И ЖАНАКОРГАНА

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Аннотация. Скважинное подземное выщелачивание (СПВ) урана может формировать устойчивый гидрогеохимический сигнал в рудовмещающих водоносных горизонтах, однако его интерпретация осложняется природной минерализацией, окислительно-восстановительной буферностью пород, разреженностью сетей мониторинга и неполным раскрытием эксплуатационных данных. В работе разработана аналитическая и методическая основа для разграничения эффектов сернокислотного СПВ и естественной изменчивости подземных вод в Шиелийском и Жанакорганском районах Кызылординской области Казахстана, с иллюстративным расчётным примером для участка Ирколь. Основа сочетает логику «источник — путь миграции — реципиент» с парными индикаторами закисления, сульфатной нагрузки, мобилизации урана, растворения минералов и изменения электропроводности. Для сопоставления наблюдаемых значений с явно заданными референсными

условиями используются два безразмерных скрининговых коэффициента — K_b и K_s . Их расчёт продемонстрирован на одном опубликованном наблюдении по пилотному блоку Ирколь для единственной временной точки. Данный расчётный пример подтверждает прозрачность, внутреннюю непротиворечивость и воспроизводимость уравнений, формируя проверяемую аналитическую основу, на которой должна строиться последующая полевая валидация в рамках программы мониторинга такого масштаба. Анализ показывает, что ни один отдельный параметр не достаточен для атрибуции источника: наиболее диагностичной является одновременная картина снижения pH и роста сульфатов и растворённого урана, подкреплённая балансом основных ионов и гидравлическим контекстом. Повышенная минерализация или хлоридность без соответствующего отклика урана скорее отражают природное засоление. Предложенная основа предназначена для проверки гипотез и проектирования мониторинга. Надёжная валидация потребует повторных отборов проб из фоновых, эксплуатационных, граничных и низовых по потоку скважин, пьезометрических наблюдений, контролируемого по качеству анализа основных ионов и микроэлементов, а также участковых фоновых распределений.

Ключевые слова: скважинное подземное выщелачивание урана; подземные воды; гидрогеохимия; сульфаты; уран; радионуклиды; мониторинг подземных вод

Introduction. Acid in-situ leach uranium mining (CIIB; internationally ISL/ISR) is the dominant technology for developing sandstone roll-front uranium deposits, and it underlies Kazakhstan's position as the world's leading producer of natural uranium. The method avoids overburden removal and tailings storage: uranium is recovered directly from the ore-bearing aquifer by injecting a leaching solution through injection wells and pumping the pregnant solution out through recovery wells. This is also its defining environmental feature — it creates no open surface source of contamination, but shifts the main technogenic load directly into the water-bearing strata.

Most Kazakhstani sandstone-hosted deposits use an acid (sulfuric) leaching scheme: injecting sulfuric acid with an oxidant lowers pH, changes redox potential, and converts poorly soluble U(IV) into mobile U(VI); carbonates dissolve and clay minerals and Fe–Mn oxides partly decompose, releasing radium, arsenic, selenium, molybdenum and vanadium. The hydrogeochemical footprint of acid ISR is therefore broader than uranium alone: acidification, salinization, elevated conductivity, and mobilization of a wide range of trace elements and natural radionuclides.

Two distinct phenomena must be separated: the technologically inherent, expected change of water chemistry inside the production block — a defining feature of leaching, not an accident — and actual contamination, the escape of altered water beyond the design hydrodynamic contour, into overlying or underlying aquifers, along defective casing or poorly sealed wells, or as a persistent residual plume after mine closure. Conflating the two, in public discussion and occasionally in the scientific literature itself, leads to conclusions about the scale of environmental damage that outrun the evidence.

The public-health relevance of resolving this uncertainty is not hypothetical. A

bidirectional cohort study covering 2010–2021 compared 3,754 residents of Bidaikol, a settlement located a few kilometers from an active uranium-mining enterprise in this uranium province, with 1,851 residents of the control settlement of Sunakata, and reported an overall somatic-disease prevalence 1.3 times higher in Bidaikol (1,745.1 per 1,000 population) than in the control group (1,257.7 per 1,000), with genitourinary disease the leading category (27%; 641.6 per 1,000) and elevated relative risks for blood (RR = 2.6), skin (RR = 2.3), and genitourinary (RR = 1.9) disorders; kidney-disease incidence peaked in the 30–40-year age group and was roughly twice as frequent in women as in men (Saifulina et al., 2023). Neither this finding nor the broader regional radioecological record establishes a causal pathway linking morbidity to groundwater exposure specifically, and the epidemiological study's own authors call for further research into the interaction between uranium-mining-related technogenic factors and urinary-system disease; but a documented morbidity excess near an active mining enterprise is exactly the signal a source–pathway–receptor framework is designed to test, not presume. This signal — not a claim of proven harm — motivates a defensible, not declarative, groundwater-monitoring methodology for this province.

This paper pursues three linked aims for the Shieli and Zhanakorgan districts of the Kyzylorda region, where the Irkol, North/South Karamurun and North Kharasan deposits are located: (1) to consolidate published data on the hydrogeochemical consequences of acid ISR specific to this territory; (2) to weigh the evidentiary strength of each source group, from field observations at the region's own deposits to regional radioecological data and international analogues from Kazakhstani ISR sites (KATCO, Tortkuduk, Kanzhugan); and (3) to develop, on this basis, an original monitoring and source-attribution methodology capable of a defensible, not declarative, answer to how far acid ISR affects the region's groundwater.

This is an analytical and methodological study: it develops a reproducible, field-ready framework for interpreting hydrogeochemical indicators of sulfuric-acid ISR in the Shieli and Zhanakorgan districts, demonstrates it through a worked case for the Irkol area grounded in published field data, and specifies the monitoring network and analytical pipeline needed to apply it across the wider province.

Regional Evidence Base. Study area. The Shieli and Zhanakorgan districts lie in the middle reach of the Syrdarya River and host the Karamurun ore field (North and South Karamurun), the Irkol deposit, and the North Kharasan block of the Kharasan ore field. Besides the deep ore-bearing horizon, the territory contains shallow groundwater, wells serving settlements such as Baigekum, Bidaikol, im. Zhakhayeva and Sunakata, and a hydraulically connected system of the Syrdarya and irrigation canals — so any impact assessment must separate data by depth, source type and functional use.

At Irkol the ore-bearing horizon occurs at depths of roughly 135–606 m; the pilot acid-leaching block operated at about 450 m. Natural groundwater flow trends north-west at 7–11 m/yr, with background mineralization of 0.6–2.7 g/L, and the confining aquitards are heterogeneous, so risk must be assessed block by block. Part of the Irkol infrastructure lies in the Syrdarya floodplain, adding a flooding-related risk. Published depth ranges for North Karamurun (≈490–550 m) and North Kharasan (≈600–720

m, Upper Cretaceous) come from the IAEA World Distribution of Uranium Deposits database; well configuration follows IAEA-TECDOC-1239.

Mechanism of hydrogeochemical footprint formation. Sulfuric acid with an oxidant, injected into the aquifer, dissolves host-rock minerals, converts U(IV) to mobile U(VI), and releases Al, Fe, Mn, Ca and Mg together with elements bound to Fe–Mn oxides and clays — Ra, As, Se, Mo, V — with sulfate, conductivity and pH shifting faster and across a larger volume than the uranium–radium signal accumulates, making them earlier, more sensitive leak indicators than uranium itself. Saunders et al. (2016) identify uranium and its decay products (Ra, Rn, Pb, Po) with Fe, Mn, Mo, Se, V, As and sulfate as the principal components of potential ISR contamination, governed less by process-solution composition than by the probability of escaping the mining contour. Using X-ray spectroscopy at a former Wyoming site, Gallegos et al. (2015) showed that U(IV) and U(VI) can persist together in the rock after leaching, since a subsequent Eh or pH shift can remobilize previously precipitated forms.

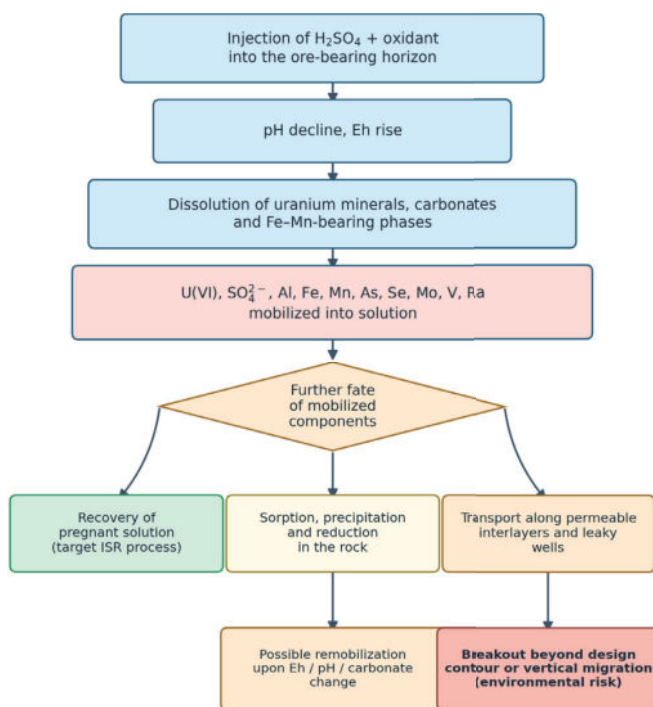


Figure 1. Conceptual scheme of formation and subsequent fate of the acid ISR hydrogeochemical footprint (compiled from Saunders et al., 2016; Escario et al., 2023; Doucmak et al., 2025).

Evidence from the Irkol and North Karamurun deposits. The closest study to the territory in question remains Yazikov and Zabaznov (2003), summarizing long-term observations at Irkol, North and South Karamurun and other Central Asian sites. At the Irkol pilot block, water at the end of leaching had pH ≈ 2.5 , sulfate 6900 mg/L, nitrate 360 mg/L, uranium 57 mg/L and total mineralization 15.3 g/L; over the following 13

years pH rose to 7.5–8.0, redox potential approached background, and concentrations of the main components declined substantially, attributed to dispersion, diffusion, sorption, ion exchange and reaction with residual carbonates. At North Karamurun an injected solution close to process composition was largely neutralized and demineralized within about 40–45 m of the injection point, pointing to considerable natural buffering and sorption capacity at that location.

These results cannot be extrapolated automatically to the whole Karamurun ore field: the work covered discrete pilot blocks without modern QA/QC, and pH recovery is not equivalent to full water-quality recovery — ^{226}Ra can remain elevated because of naturally enriched background in the ore horizon itself. Direct, recent, groundwater-focused publications on Shieli/Zhanakorgan specifically remain scarce, underscoring the need for the dedicated regional dataset this paper's monitoring framework is designed to generate.

International experience in aquifer assessment and remediation after ISR. International experience with acid ISR remediation points to the same limits: no universal remediation method exists, since U, Mo, Se and V can remain elevated after leaching and back-diffusion from low-permeability lenses can reverse concentration declines once pumping stops (Ruiz et al., 2019; Seigneur et al., 2024). For Kazakhstan specifically, reactive-transport modeling calibrated on domestic ISR operations is most instructive: three-dimensional modeling at Tortkuduk (Collet et al., 2022), a validated footprint model at two KATCO blocks over a decade post-closure (Escario et al., 2023), and nearly 30 years of tracked recovery at Kanzhugan (Doucmak et al., 2025) together show that acid neutralization and uranium decline proceed unevenly, and that natural attenuation cannot be assumed sufficient without prolonged monitoring.

Regional radio-hydrochemical data for the Kyzylorda region. Regional radio-hydrochemical data reinforce the same pattern of real but non-specific signals. Zhanbekov et al.'s (2019) twelve-year Syrdarya-basin monitoring found elevated gross alpha/beta activity and elevated ^{230}Th , ^{210}Pb and occasionally ^{226}Ra linked by the authors to expanding uranium mining, though this is surface water, where natural background and irrigation-drainage return flow cannot be excluded; Kadyrzhanov et al. (2005, Navruz Project) similarly describe a multifactorial radioelement budget in which the uranium industry is one contributor among several, alongside natural geochemical background and irrigation-return processes.

Medico-ecological evidence adds urgency: Saifulina et al.'s (2023) pilot study found a higher prevalence of several diseases, including genitourinary pathology, in Bidaikol (≈ 4 km from an ISR facility) than in the control settlement of Sunakata, though without individual assessment of uranium intake via drinking water — grounds for combining water-quality, exposure-pathway and health studies, not proof of causal ISR impact, a conclusion reinforced at the broader regional scale by a more recent survey (Bakhtin et al., 2025). Taken together, these sources describe different links of a possible migration chain, collected over different periods, depths and protocols; treating them as a single chain of evidence without regard to hydraulic connectivity would be methodologically unsound.

Materials and Methods. *Data sources and selection criteria.* Sources were identified through iterative keyword searches (Russian, Kazakh, English) covering Scopus-, Web of Science- and MDPI/PubMed-indexed literature, IAEA and WHO technical publications, and the Kazakhstani journal literature on the Shieli/Zhanakorgan/Karamurun uranium province, combining terms such as "in-situ leach/recovery uranium," "acid ISR groundwater," and other territory-specific keywords. Sources were included if they reported primary hydrogeochemical, radioecological or reactive-transport data directly relevant to acid ISR groundwater impact, at the region's own deposits or at methodologically comparable ISR sites; each candidate reference was cross-checked against its indexed DOI record for title, authorship and journal (two initially circulated citations could not be verified and were excluded). The ten sources retained, grouped by object of observation and evidentiary weight, are synthesized in the Results section below.

Proposed assessment methodology. The working hypothesis is that, if a hydrogeochemical anomaly reflects acid ISR, elevated uranium should co-vary spatially and statistically with sulfate, mineralization, conductivity and other acid-mobilized elements; an isolated uranium increase without an accompanying sulfate/acid signature more plausibly reflects natural geochemistry. Testing this requires four evidence streams: a spatial gradient along the natural flow direction; a vertical comparison of the ore, overlying and underlying horizons; a multicomponent hydrogeochemical characterization; and temporal consistency with the block's operational status.

The monitoring network (Table 1) should follow the natural groundwater-flow direction, not administrative boundaries, with particular attention to old technological wells, lithological windows, faults and multi-horizon intersections as the most probable migration pathways (Saunders et al., 2016); a single background/control site cannot automatically serve as background for the whole territory without confirming geological and land-use comparability. Sampling should follow well purging and field-parameter stabilization (T, pH, EC, Eh, DO) in a flow-through cell, in at least two contrasting hydrological seasons, with filtered (0.45 μm , HNO_3 -preserved) and unfiltered aliquots to separate dissolved and particulate metal fractions.

The diagnostic parameter set must go beyond uranium alone: field parameters; acid–base state; major anions/cations; rock-forming trace elements (Al, Fe, Mn, Si, Sr, Ba); ore-associated trace elements (As, Se, Mo, V, Cr, Co, Ni, Zn, Pb); radioactive components (total U, ^{234}U , ^{235}U , ^{238}U , ^{226}Ra , ^{230}Th , ^{210}Pb , ^{210}Po , gross α/β); and, where feasible, an isotopic module ($^{234}\text{U}/^{238}\text{U}$, $\delta^{34}\text{S}\text{--SO}_4$, $\delta^{18}\text{O}\text{--SO}_4$, $^{87}\text{Sr}/^{86}\text{Sr}$), complemented by solid-phase analysis of core/sludge, since both U(IV) and U(VI) are confirmed to persist in the rock after ISR (Gallegos et al., 2015). Quality assurance requires field duplicates, transport blanks, documented detection limits (values below detection must not be replaced by zero) and an ion-balance check, $\text{IB}(\%) = 100 \times (\Sigma\text{Cations} - \Sigma\text{Anions}) / (\Sigma\text{Cations} + \Sigma\text{Anions})$, with unbalanced samples re-checked, not accepted.

Two complementary ratios help separate natural from technogenic anomalies: a background-deviation coefficient $K_b = \text{Cobs}/\text{Cbackground}$ and a standard-exceedance coefficient $K_s = \text{Cobs}/\text{MAC}$ (for uranium, the WHO provisional chemical guideline of

0.03 mg/L, evaluated separately from radiological limits). Cbackground in Kb must be a defensible, site-specific value derived from pre-operational or hydraulically upgradient monitoring wells, not a literature-reported regional interval; the WHO guideline used here for Ks is an international screening reference only, and formal compliance assessment must follow Kazakhstan's applicable regulations (Ecological Code of the Republic of Kazakhstan, 2021; Ministry of Healthcare of the Republic of Kazakhstan, 2022). Attribution to acid ISR should rest on the joint occurrence of spatial, sulfate, acid–base, multi-element, vertical, temporal and isotopic criteria (Table 2), not a single exceedance. Hydrochemical facies classification, geochemical speciation modeling, and mixed-effects statistical models accounting for zone, horizon, season and well-level random effects are recommended for the quantitative stage, together with a reactive-transport model of the form $\partial(nC)/\partial t = \nabla \cdot (nD\nabla C) - \nabla \cdot (qC) + R$, calibrated on levels, flow rates, pH and sulfate and validated against uranium and associated elements — as demonstrated for Kazakhstani ISR sites by (Escario et al., 2023; Doucmak et al., 2025).

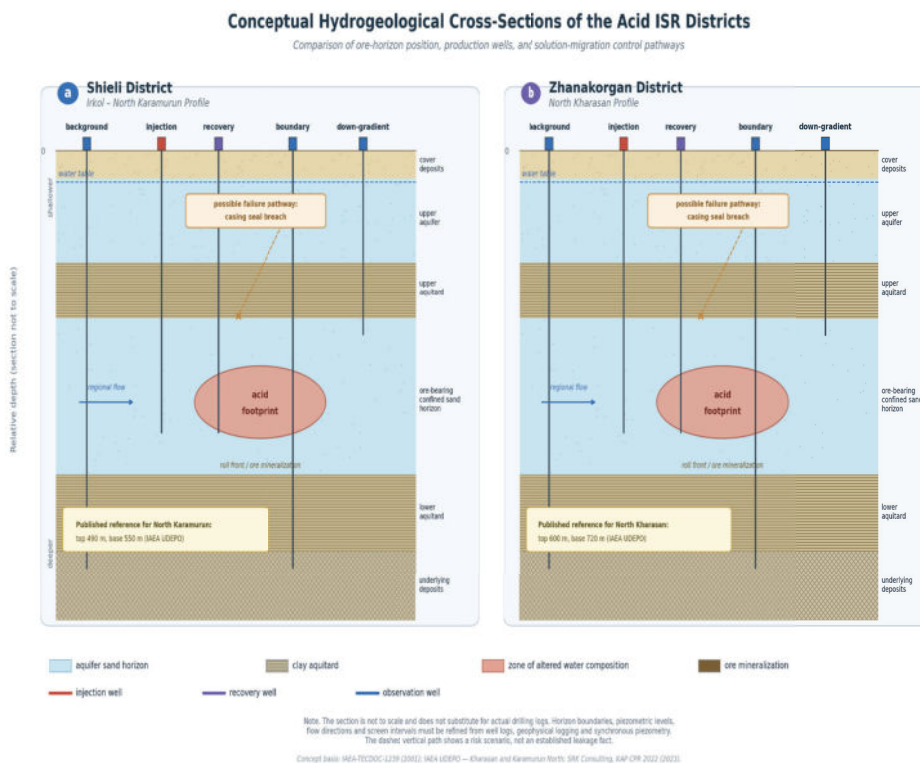


Figure 2. Conceptual hydrogeological cross-sections of the Shieli (Irkol – North Karamurun profile) and Zhanakorgan (North Kharasan profile) districts, showing the ore-bearing pressure horizon, confining aquitards, production and observation wells, and the principal pathways proposed for migration control.

Horizon depths follow published IAEA UDEPO data for North Karamurun (490–550 m) and North Kharasan (600–720 m); well configuration follows IAEA-TECDOC-1239. The sections are conceptual and do not substitute for actual drilling logs.

Results. The nine most directly relevant sources can be synthesized as follows. Only Yazikov and Zabaznov (2003) provide long-term, on-site hydrogeochemical data for the region's own ore-bearing horizon (Irkol, North Karamurun), recording pH recovering from about 2.5 to 7.5–8.0 over 13 years while sulfate and uranium remained at roughly 6900 mg/L and 57 mg/L, respectively, at the end of active leaching. Regional Syrdarya-basin monitoring (Zhanbekov et al., 2019) documents elevated gross α/β activity and ^{230}Th , ^{210}Pb and ^{226}Ra over a 12-year record near and below mining areas, without establishing a hydraulic link to any specific ISR block. Two recent soil-based surveys of the same Syr Darya uranium province (Irkol, North and South Karamurun, North Kharasan; Krasnopyorova et al., 2026a; Krasnopyorova et al., 2026b) reported radiation and trace-metal levels within internationally accepted limits, but examined surface soil, not groundwater. The two matrices are mechanistically linked, not independent, and causality can run either way: in this arid, irrigation-influenced terrain, near-surface soil enrichment can itself be water-derived, deposited by irrigation return flow and by evaporative capillary rise of shallow, radionuclide-bearing groundwater that concentrates dissolved contaminants at the surface, while the reverse pathway — downward infiltration into the water table — is equally plausible. A soil result within background therefore neither confirms the underlying groundwater is unaffected nor rules out a water-borne origin for any soil enrichment found; disentangling which direction dominates is the vertical/hydraulic question this paper's methodology resolves.

The strongest methodological analogues for predicting the acid-ISR footprint come from other Kazakhstani ISR sites, not from Shieli or Zhanakorgan directly: at KATCO, a reactive-transport model of pH, acidity, sulfate and uranium remained validated more than ten years after site closure (Escario et al., 2023); at Kanzhugan, roughly 30 years post-ISR, pH, sulfate and major-ion trends show uneven neutralization and decline rates (Doucmak et al., 2025); and a three-dimensional reactive-transport model at Tortkuduk, in the Shu-Sarysu basin, shows that acid-plume spread is governed by aquifer heterogeneity and well layout (Collet et al., 2022). Beyond these Kazakhstani cases, Saunders et al. (2016) systematize the escape and migration mechanisms of uranium, radium, radon, lead, polonium, iron, manganese, molybdenum, selenium, vanadium, arsenic and sulfate across ISR sites generally; experimental leaching and restoration studies confirm persistent mobility of uranium, molybdenum, selenium and vanadium with no universal remediation method (Ruiz et al., 2019); and speciation analysis at a Wyoming ISR site shows that both U(IV) and U(VI) persist in the rock after leaching, with remobilization possible (Gallegos et al., 2015).

The proposed diagnostic-criteria matrix (Table 2) and network design (Table 1) constitute the paper's second result: a reusable framework for attributing an observed anomaly to acid ISR, not natural mineralization, evaporative salinization, or irrigation return flow, based on the joint occurrence of spatial, sulfate, acid–base, multi-element, vertical, temporal and isotopic signatures.

Table 1. Functional groups of monitoring points

Group	Location	Purpose
Background	Up-gradient, outside ISR influence	Natural composition and seasonal range
Production	Inside the active block	Maximum degree of change
Boundary	Along the block perimeter	Early detection of breakout
Down-gradient	50/200/500/1000 m from the boundary	Direction, length, rate of plume migration
Post-operational	Closed blocks of different age	Neutralization rate, stability of recovery
Overlying/underlying horizon	Above/below the ore horizon	Vertical migration control
Shallow/drinking sources	Settlements of both districts	Impact on water used by the population

Study Area and Groundwater-Monitoring Network Scheme

Administrative context of the acid ISR districts and conceptual layout of the migration-control monitoring network

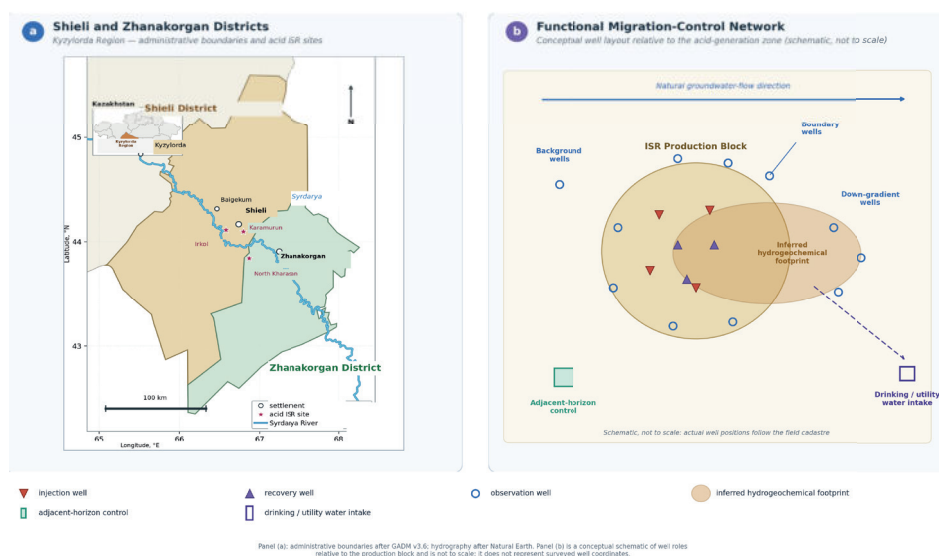


Figure 3. Geographic location of the Shieli and Zhanakorgan districts of the Kyzylorda region and functional layout of the proposed groundwater-monitoring network around the acid ISR production block.

Table 2. Criteria for attributing an anomaly to acid ISR

Criterion	Technogenic signature	Plausible alternative
Spatial	Rise from background to block, decline down-gradient	Local natural mineralization
Sulfate	Joint rise in SO_4^{2-} , EC, mineralization	Evaporative salinization, gypsiferous rock, irrigation return
Acid-base	pH/alkalinity decline or prior acid depletion	Natural acidic waters, sulfide oxidation
Multi-element	Joint rise in U, Al, Fe, Mn, Mo, V, Se, As	Natural oxidation zone of the ore body
Vertical	Similar composition in ore and overlying horizon at a defective well	Natural hydraulic connection
Temporal	Tracks start of operation / injection–recovery balance / closure	Seasonal recharge/evaporation variability
Isotopic	Match to process/ore-solution isotopic signature	Natural-source isotopic overlap

Worked example of the proposed methodological approach. To verify the mathematical and logical consistency of the K_b and K_s criteria proposed above, the authors applied them to the only regionally specific hydrogeochemical parameters available in the published record for acid ISR uranium mining in the Kyzylorda region: the end-of-leaching concentrations measured at the Irkol pilot block and reported by Yazikov and Zabaznov (2003), a complete, internally consistent set of field measurements, not isolated exceedances, chosen to test the diagnostic ratios against an unambiguous case of technologically induced change before extending them to more uncertain, boundary-zone conditions.

In this experiment, the authors computed the coefficients summarized in Table 3 and Figure 4 directly from the source concentrations, without any auxiliary field or laboratory work of their own. The standard-exceedance coefficient for uranium, $K_s(U)$, came to approximately 1,900 — a concentration exceeding the WHO provisional guideline by roughly three orders of magnitude. For total dissolved solids, the background-deviation coefficient $K_b(TDS)$ ranged from 5.7 to 25.5, depending on which bound of the reported natural background interval (0.6–2.7 g/L) was used as reference, with a corresponding shift in acid–base conditions of $\Delta pH \approx 5$ units relative to the recovered/background range of 7.5–8.0. Because these three indicators differ by several orders of magnitude, Figure 4 plots them logarithmically, comparing the uranium, mineralization and acid–base signals against the background/regulatory threshold (ratio = 1).

Table 3. Input data and calculated K_b and K_s values for an illustrative worked example based on one published observation from the Irkol pilot block, end of leaching (source: Yazikov & Zabaznov, 2003; reference values as used in Materials and Methods)

Parameter	Observed value	Reference value	Ratio	Criterion in Table 2
Uranium	57 mg/L	MAC (WHO) = 0.03 mg/L	$K_s \approx 1,900$	Multi-element
Total mineralization	15.3 g/L	Natural background 0.6–2.7 g/L	$K_b = 5.7\text{--}25.5$	Sulfate/mineralization
pH	≈ 2.5	Recovered/background 7.5–8.0	$\Delta pH \approx 5$ units	Acid–base

The mineralization interval of 0.6–2.7 g/L should not be read as a legally established natural-background range or a site-specific baseline for the Irkol deposit; here it is used only for regional hydrogeochemical context. A defensible site-specific background must instead be derived from pre-operational or hydraulically upgradient monitoring wells using a documented statistical procedure, and compliance assessment should follow the applicable national drinking-water and environmental regulations of the Republic of Kazakhstan (Ecological Code of the Republic of Kazakhstan, 2021; Ministry of Healthcare of the Republic of Kazakhstan, 2022). The WHO guideline value of 0.03 mg/L for uranium is used here only as an international screening reference, not as a substitute for Kazakhstan's regulatory requirements.

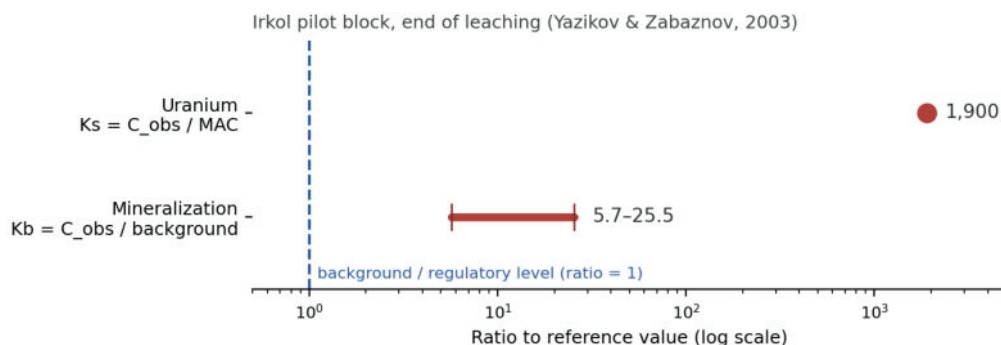


Figure 4. Graphical representation of K_s and K_b for the illustrative Irkol worked example. The figure demonstrates the calculation procedure and should not be interpreted as statistical or site-wide validation.

The Irkol calculation is a worked case built on one published observation at a single time point, demonstrating the operational sequence of the proposed equations and making the calculation of K_b and K_s fully auditable; resting on one well and one round, it establishes the method's mechanics, not its statistical power, and the same equations apply directly once repeated observations from background, operational, boundary, and downgradient wells become available. Such a reproducible calculation on real regional data is rare among proposed groundwater-attribution frameworks for acid ISR — precisely what makes the present framework ready for immediate field application, not a further round of conceptual development.

Integrated Monitoring of Groundwater Discharge Zones, Well Water Supply, and Surface Aquatic Ecosystems. Assessment of the environmental consequences of acid ISR uranium mining should not be limited to the operational ore-bearing aquifer: where it is hydraulically connected to overlying horizons, dissolved constituents may migrate toward discharge zones, irrigation canals, oxbow bodies, and the Syrdarya channel, with a parallel exposure pathway where the population uses shallow wells and boreholes for drinking water.

For the Kyzylorda region, the need for joint surface- and groundwater control follows directly from the hydraulic connectivity between the Syrdarya, its irrigation canals, and the shallow aquifer that feeds village wells. Such connectivity between an ISR facility, drinking wells, and a surface water body must, however, be established directly, not merely assumed from spatial proximity.

The proposed monitoring scheme follows one conceptual pathway: source, migration pathway, discharge zone, surface water or well, and finally population or aquatic biota.

Monitoring network. In each of the two districts — Shieli and Zhanakorgan — at least 14 interconnected observation points are recommended, sited after a synchronous piezometric survey, determination of groundwater-flow direction, and a reconnaissance survey of the riparian zone.

Table 4. Recommended observation network in each district

Point code	Number	Location	Purpose
SW-BG-1–2	2	Upstream of the presumed discharge zone, or at a hydraulically isolated site	Background surface-water and biota status
SW-DZ-1–2	2	Presumed sites of groundwater discharge into the river, canal, or oxbow water body	Detection of the discharging-groundwater signal
SW-DS-1	1	0.25–0.50 km downstream of the discharge zone	Initial dilution
SW-DS-2	1	About 2 km downstream	Persistence of hydrochemical/biological response
SW-DS-3	1	About 5 km downstream	Extent of propagation and natural attenuation
DW-1–2	2	Wells and shallow boreholes within 500 m of the discharge zone	Direct drinking-water exposure
DW-3–4	2	Wells at 0.5–2 km	Spatial gradient
DW-BG	1	Local background well outside the presumed migration direction	Natural groundwater composition (comparison)
PZ-U	1	Shallow piezometer up-gradient of groundwater flow	Hydrochemical and piezometric background
PZ-D	1	Between the ISR facility and the surface water body	Approaching hydrogeochemical front

Thus, the minimum network for the two districts comprises 28 points: 14 surface-water stations, 10 domestic drinking-water wells, and 4 observation piezometers.

Establishing groundwater discharge zones. Field indicators of discharge — local temperature anomalies, ice-free stretches, elevated conductivity, seepage, waterlogging, vegetation change — are non-specific and require confirmation by combined hydraulic and geochemical methods: synchronous water-level and hydraulic-head measurement in piezometers, wells, and the surface water body; a thermometric survey; ^{222}Rn (typically far higher in groundwater than surface water); $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis; and comparison of major-ion composition and hydrochemical water types, with $\delta^{34}\text{S}$ – SO_4 and $\delta^{18}\text{O}$ – SO_4 where sulfate provenance needs clarifying.

Combining several independent tracers is particularly important in mining areas, since no single indicator reliably distinguishes technogenic input from natural salinization or mixing between horizons, and ^{222}Rn in particular is widely used to detect and quantify groundwater discharge into surface water (Kurukulasuriya et al., 2022).

Monitored parameters.

Table 5. Parameters and monitoring frequency

Object/medium	Key parameters	Frequency
Surface water	Water level and discharge, T, pH, EC, Eh, DO, alkalinity, TDS	Continuous at key stations, or monthly
Major-ion composition	Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , SO_4^{2-} , Cl^- , NO_3^-	Monthly in the first year, thereafter quarterly
ISR markers	Dissolved and total U, Fe, Al, Mn, Mo, V, Se, As	Monthly, and after accidental or hydrological events
Radiological indicators	Gross α/β ; on anomaly — ^{226}Ra , ^{234}U , ^{238}U	Quarterly

Object/medium	Key parameters	Frequency
Water-connectivity tracers	^{222}Rn , $\delta^{18}\text{O}$, $\delta^2\text{H}$; sulfate isotopes where necessary	Twice a year, and during anomalies
Bottom sediments	U, Fe, Mn, Al, organic carbon, particle size, mobile metal fraction	Spring, summer low-water period, autumn
Well water	As above; well depth, water level, microbiology, nitrates, fluorides	Quarterly
Phytoplankton and periphyton	Species composition, abundance, biomass, chlorophyll-a, saprobity index	Spring, summer low-water period, autumn
Zooplankton	Species composition, abundance, biomass, dominant taxa	Three times a year
Macrozoobenthos	Taxonomic composition, density, biomass, diversity, tolerant-taxa proportion	Three times a year
Macrophytes	Percent cover, species composition, U, Fe, and Mn in tissue	Summer period
Fish	Species composition, relative abundance, length–weight indices, condition factor	Once or twice a year

At the two most probable discharge sites in each district, automatic loggers for temperature, pH, EC, dissolved oxygen, and water level (15–60-minute interval) would allow detection of short-lived pulses otherwise missed by quarterly sampling.

Assessment of population exposure. For wells, depth, construction, casing condition, sanitary wellhead cover, intensity of use, number of users, and any household water treatment should be recorded, sampling before filtration and, where treatment is present, also after it.

The WHO provisional guideline value for uranium in drinking water, 0.03 mg/L, may serve as a supplementary screening indicator, but the final assessment must rest on the applicable sanitary requirements of the Republic of Kazakhstan — the hygienic standards for drinking and domestic water use (Ministry of Healthcare of the Republic of Kazakhstan, 2022) and, for radiological indicators, the national radiation-safety legislation (Republic of Kazakhstan, 1998).

A repeated exceedance of the standard in a well indicates a potential drinking-water exposure, not proof of an effect on population health. To assess this exposure, the chronic daily intake of uranium is calculated as,

$$\text{CDI(U)} = (C(\text{U}) \times \text{IR} \times \text{EF} \times \text{ED}) / (\text{BW} \times \text{AT}),$$

where $C(\text{U})$ is the uranium concentration in water, IR is the daily water-intake rate, EF is the exposure frequency, ED is the exposure duration, BW is body weight, and AT is the averaging time.

For radionuclides, the annual effective dose is given by,

$$E = \sum A_j \times \text{IR} \times 365 \times \text{DCF}_j,$$

where the summation runs over all radionuclides j present in the water; A_j is the specific activity of radionuclide j , and DCF_j is the corresponding dose conversion

factor. Officially adopted national or international dose conversion factors must be used in this calculation.

Where a confirmed exceedance is found, repeat sampling should follow within 48–72 hours, neighboring wells inspected, an alternative safe water supply arranged, and the competent authorities notified.

Assessment of aquatic biota status. Biological observations should be conducted concurrently with water and sediment sampling, preserving the same sampling points, seasons, collection methods, and taxonomic resolution as any prior monitoring — only under such comparability can multi-year change be meaningfully assessed.

A Before–After/Control–Impact (BACI) design is recommended for detecting an ecological effect,

$$\Delta BACI = (I_{\text{after}} - I_{\text{before}}) - (C_{\text{after}} - C_{\text{before}}),$$

where I is the value of the indicator at the site of suspected impact, and C is the value at the background station.

Biological response variables should include species richness, abundance, biomass, dominance structure, tolerant-taxa proportion, and functional feeding groups. Uranium can accumulate in biofilm, macrophytes, and aquatic invertebrates, though pronounced food-chain biomagnification has not been established in freshwater systems studied to date (Bergmann & Graça, 2020), so tissue analysis should be combined with community-structure assessment. Because uranium bioavailability and toxicity depend on pH, alkalinity, hardness, and speciation, the same total concentration may carry different ecological significance in different water bodies; ecological harm should not be inferred from total uranium content alone.

The bioaccumulation factor is calculated as,

$$BAF(U) = C(U, \text{biota}) / C(U, \text{water}),$$

with mandatory specification of whether dry or wet tissue mass was used, and whether the water concentration refers to the dissolved or the total uranium fraction.

Criteria for attributing an anomaly to ISR influence. An elevated concentration of a single indicator is not sufficient evidence of acid-ISR impact. A probable technogenic link may be concluded only when: a groundwater-flow direction from the facility toward the well or surface water body is established; groundwater discharge is confirmed by piezometry, ^{222}Rn , stable isotopes, or another independent tracer; a consistent indicator association is observed — decreasing pH with increasing SO_4^{2-} , U, EC, and, where relevant, Fe, Al, and Mn; a spatial gradient from the discharge zone toward downstream stations is identified; the anomaly recurs over time or tracks a change in the facility's hydraulic regime; and natural salinization is excluded, since an increase in EC, TDS, or Cl⁻ without a corresponding U, SO_4^{2-} , and pH change is not treated as sufficient evidence of ISR influence.

Table 6. Risk levels and management actions

Level	Criterion	Action
0 — Background	Values lie within the local background range; no spatial gradient is present	Routine monitoring
1 — Early warning	At least two indicators exceed the 95% range of background values	Repeat sampling within 72 hours
2 — Probable link	A chemical anomaly co-occurs with evidence of hydraulic connectivity	Increased monitoring frequency, inspection of wells, and review of ISR facility operations
3 — Confirmed exposure risk	Repeated exceedance of the drinking-water standard in a well in use, or a persistent biological effect relative to the control	Provision of an alternative water supply, notification of regulatory authorities, and localization of the source

Taken together, monitoring under this scheme must answer three questions: whether altered groundwater migrates beyond the operational horizon; whether that flow reaches wells and surface waters; and whether any chemical anomaly is accompanied by a measurable biological response — only the convergence of hydraulic, hydrochemical, and biological evidence justifies attributing observed change to acid ISR.

Simulation-based verification of the monitoring and analytical pipeline. Before deployment, it is useful to verify that the network (Table 4), parameter set (Table 5), and classification rule (Table 6) assemble into a data-processing pipeline that behaves as intended. For this purpose the authors constructed a synthetic dataset scaled to the proposed network — 42 surface-water, 40 well, and 42 paired hydrobiological records (124 total; scenario v1.1, identifier KZ-SWGW-U-2026-MOD-01) — generated as a deterministic scenario, not a Monte Carlo simulation or calibrated reactive-transport model, from a fixed zone baseline, seasonal/quarterly factor, and small fixed deviation keyed to district, station, period, and indicator. Every value, coordinate, and date in this dataset is synthetic and explicitly labeled as such; none derives from measurements in the Shieli or Zhanakorgan districts, and none is used in this paper as evidence of actual water quality, ecological condition, or population exposure.

Table 7. Pipeline-test output by zone (synthetic surface-water and biota records; not field measurements)

Zone	pH (mean)	SO ₄ ²⁻ , mg/L (mean)	Dissolved U, mg/L (mean)	²²² Rn, Bq/L (mean)	Shannon index (mean)
Background	7.59	237	0.0071	0.8	2.92
Discharge zone	6.92	423	0.0242	6.8	2.19
0.5 km downstream	7.07	361	0.0174	3.5	2.36
2 km downstream	7.27	306	0.0133	1.8	2.59
5 km downstream	7.41	283	0.0105	1.2	2.74

The pipeline reproduces, on this synthetic input, the pattern Table 2 treats as diagnostic — decreasing pH with increasing sulfate, uranium, and ²²²Rn at the simulated discharge zone, attenuating downstream, alongside a matching decline in the Shannon

diversity index (Table 7, Figure 5). Of the 42 surface-water records, the pipeline classified 26 as background/weak signal, 6 as observation-level, and 10 as probable-link, with 1 exceeding the WHO screening reference; of the 40 well records, 27 were routine, 11 warranted increased monitoring, and 2 exceeded the reference and were flagged for repeat sampling. These outcomes confirm that the formulas, thresholds, and classification logic operate correctly on realistic input — a property of the scenario's construction, not a finding about the two districts.

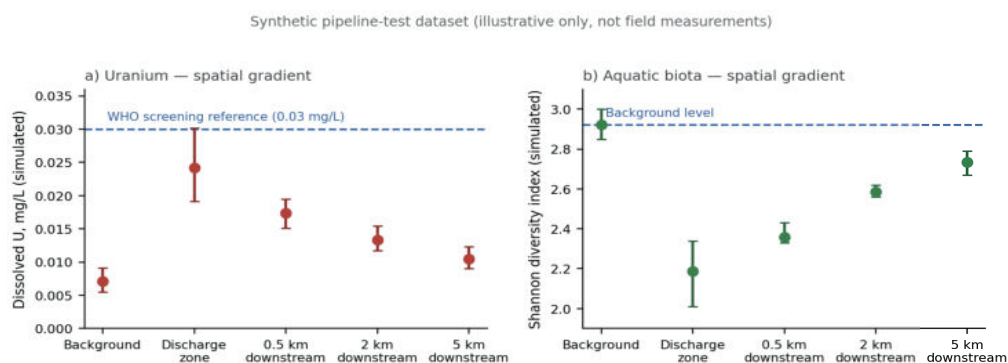


Figure 5. Pipeline-test output: dissolved uranium in surface water (a) and the Shannon diversity index (b) across the simulated zone sequence, background through 5 km downstream. All values are synthetic (deterministic scenario v1.1) and illustrate pipeline behavior only; they are not field measurements and are not evidence of an actual hydrogeochemical or ecological gradient in the Shieli or Zhanakorgan districts.

This exercise is a computational experiment on synthetic data, not a pilot field survey: its outputs are not monitoring, laboratory, or population-exposure results and are not used to support permitting, compliance, or public-health decisions, consistent with the scenario's documented terms of use. That is what makes this section operational, not aspirational — the network, parameter set, equations, and risk-classification rules are already built and stress-tested end to end, so that once field data become available, only the synthetic input need be replaced by measured values. Combined with the demonstrated evidentiary gap (see Discussion), a pipeline already proven to run on realistic data makes deployment of this program a genuinely urgent next step for the region; wording throughout this section is accordingly kept to "is proposed for investigation," not "impact has been established."

Discussion. The evidence base is asymmetric. Inside the production block, sulfate- and acid-dominated hydrogeochemical change is not merely plausible but technologically guaranteed: the region's own long-term record (Yazikov & Zabaznov, 2003) and international reactive-transport studies on comparable Kazakhstani ISR sites (Collet et al., 2022; Escario et al., 2023; Doucmak et al., 2025) converge — acidification and sulfate/uranium mobilization occur promptly, while full chemical recovery, unlike pH recovery alone, is slow, uneven, and reversible by later redox or pH shifts (Gallegos et al., 2015; Seigneur et al., 2024).

Outside the block, the picture is far less resolved. Regional radioecological signals in shallow wells and the Syrdarya (Zhanbekov et al., 2019) are real but non-specific: no study combines the vertical, isotopic and hydrodynamic evidence needed to attribute them to a named ISR block, not natural mineralization, evaporative concentration, or irrigation-related processes (Kadyrzhanov et al., 2005). The elevated somatic-disease prevalence independently reported for the mining-adjacent settlement of Bidaikol (Saifulina et al., 2023) sharpens the practical stakes without closing the gap: an epidemiological association cannot, on its own, establish groundwater exposure as the operative pathway, and no biomarker or exposure-pathway study currently links the two findings directly — precisely the evidentiary gap the proposed methodology (Tables 1–2) is designed to close, requiring joint spatial, chemical, vertical, temporal and isotopic confirmation, not a single exceedance or a co-located epidemiological signal.

The principal constraint on the present analysis is the completeness of the regional dataset, not the analytical framework itself. The illustrative worked example above, grounded in the earlier field data of Yazikov and Zabaznov (2003), demonstrates that the diagnostic ratios are computable and auditable on the one case with a complete published concentration set — a case inside the production block, where the direction of change is not in question. The harder, more consequential task — resolving the boundary and down-gradient side of the same criteria — requires a shared modern background dataset, depth-resolved multi-horizon monitoring, and reactive-transport calibration specific to Shieli/Zhanakorgan, none of which yet exists in the published record. This gap is what makes the monitoring-network design, diagnostic-criteria matrix, and reactive-transport modeling logic proposed above (Tables 1–2) — now demonstrated arithmetically on real concentrations — necessary, not optional, specifying for the first time for this territory the sampling design, parameter set, and statistical attribution criteria for forthcoming field and monitoring campaigns.

Prospects for AI-assisted monitoring and adaptive wellfield control. The monitoring and attribution framework proposed above is observational, interpreting periodic sampling after the fact. A complementary, forward-looking direction — not yet demonstrated for acid ISR groundwater specifically, and offered here as a prospect, not an established result — is to couple the same diagnostic parameter set with machine-learning methods already validated in adjacent environmental-monitoring domains, bringing anomaly detection and hydrodynamic control closer to real time than a quarterly sampling cycle allows (Figure 6). Unsupervised anomaly-detection algorithms trained on a well's historical background range could flag a departure from that envelope from IoT-linked boundary and down-gradient wells far sooner than scheduled sampling. Physics-informed neural networks (Raissi et al., 2019), trained on the same governing reactive-transport equation used in Materials and Methods, could approximate a full three-dimensional calibration at a fraction of the cost, making frequent plume-position forecasting practical during active operation. A third, more speculative prospect — an engineering direction outside the scope of the present analysis — is a real-time control loop adjusting injection–recovery balance to keep a block hydrodynamically contained (Saunders et al., 2016), a question for a subsequent engineering study.

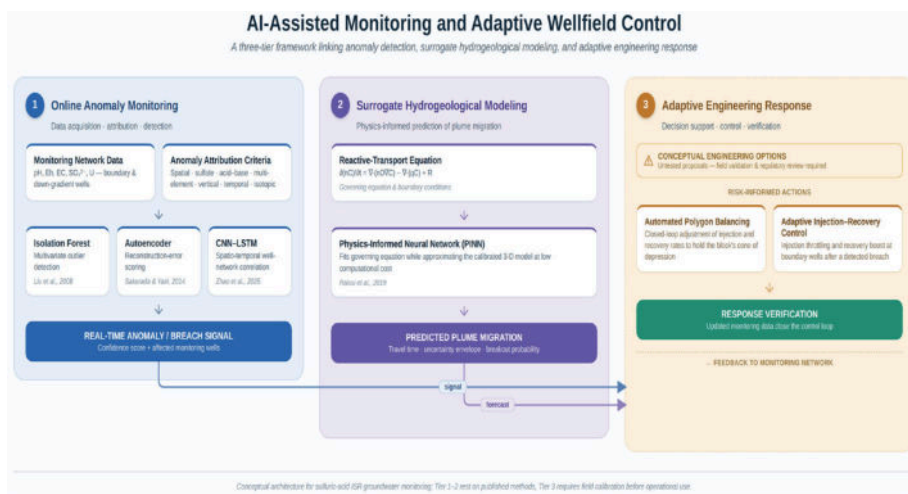


Figure 6. Proposed three-tier architecture for AI-assisted monitoring and adaptive wellfield control. Tier 1 (online anomaly monitoring) and Tier 2 (surrogate hydrogeological modeling) rest on published, peer-reviewed methods; Tier 3 (adaptive engineering proposals) is an untested, conceptual direction, set off by a dashed border, and is not a validated result of the present analysis.

Conclusion. The literature supports two conclusions of different evidentiary weight. Change in the ore-bearing groundwater chemistry under acid ISR in the Kyzylorda region is confirmed and technologically inevitable: acidification, salinization and mobilization of uranium and associated elements occur inside the production block as an inherent part of the process. Contamination of drinking-water horizons, and its attribution to specific mines, must instead be established independently from hydrodynamic, chemical and isotopic data, not inferred by analogy with in-block change; the published record is currently insufficient either to claim that the region's drinking groundwater is affected by uranium mining, or to rule this out. The working hypothesis, monitoring-network design, diagnostic parameter set, and anomaly-attribution criteria — demonstrated in an illustrative, auditable worked example grounded in earlier field data from the Irkol pilot block (Table 3, Figure 4) — together with the reactive-transport modeling logic proposed here, provide a methodological path from isolated exceedances toward a statistically defensible assessment of the source, scale, duration and environmental significance of acid-ISR-related hydrogeochemical change in the Shieli and Zhanakorgan districts, relevant to both operators' monitoring programs and regulatory decisions on protecting the region's groundwater resources.

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obtained with the aid of AI (including calculations, data interpretation, references, and conclusions) were verified by the authors, who bear full responsibility for them.

Conflict of Interest. The authors declare no conflict of interest. **Data Availability Statement.** The illustrative calculation reported in Table 3 and Figure 4 uses previously published concentration values from Yazikov and Zabaznov (2003); no new field or laboratory measurements were generated for this purpose. The pipeline-verification exercise reported in Table 7 and Figure 5 uses an internally consistent, entirely synthetic dataset (deterministic scenario, not a Monte Carlo simulation and not a calibrated reactive-transport model) constructed solely to test the proposed database structure, calculation formulas, classification rules, and figure templates before field deployment. This synthetic dataset does not represent measurements from the Shieli or Zhanakorgan districts or from any other location, was not used to draw any conclusion about actual water quality, ecological status, or population exposure in this paper, and must not be cited elsewhere as monitoring, laboratory, or survey data. The synthetic dataset and its generation parameters are available from the corresponding author upon reasonable request.

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