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Research

Enhancing water sustainability in the Gobi Desert: processes based on IWRM principles

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Abstract
The mining industry is an important sector that contributes to economic growth and employment creation in Mongolia. Water access, water quality, and community engagement are the major challenges the Mongolian mining industry faces. Integrated Water Resource Management (IWRM) is a holistic water management approach that applies principles of economic efficiency, social equity, and environmental sustainability to ensure water sustainability. A research study was carried out to understand stakeholders' views and perspectives on IWRM and to identify water use practices, challenges, and barriers in the Gobi Desert mining region. The aim was to identify processes that help to improve access to water in the Gobi Desert region. This research applied a qualitative approach and employed three data collection methods: (1) semi-structured interviews; (2) field observations and (3) documents and academic articles reviews. Research participants were representatives from mining companies, local communities, government, and river basin administrations. In the Gobi Desert region, processes contributing to improving water management are: (1) participatory water monitoring, (2) coal processing plant educational visits, (3) local stakeholders council's meetings, (4) herder's well improvement projects, (5) independent water auditing, and (6) water advocacy events. These practices, aligned with the core principles of IWRM provide practical solutions for sustainable water management in mining regions, with the potential for global adaptation.

Keywords Mine water · IWRM · Stakeholder engagement · Sustainability · Water use practices

1 Introduction

Population and economic growth in many countries, including Mongolia, are driving an increasing demand for water resources [1, 26, 39, 45, 47]. In the Mongolian Gobi Desert, renowned for its coal, copper, and gold deposits, this demand exacerbates an already critical water scarcity challenge. The mining industry, a key economic driver [23–25, 51, 52, 58, 100–102, 108], exerts immense pressure on limited water resources, raising concerns about environmental sustainability, equitable access, and efficient allocation [5–7, 61, 62, 70, 71, 73, 74, 112]. Local herding communities, whose livelihoods depend on ecosystems and traditional water sources, are particularly affected by these challenges. Access to water resources is often limited, leading to conflicts between mining companies and local communities, including herders

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[8–10, 63–66]. While mining operations employ water management strategies such as conservation practices, advanced treatment technologies, and pollution mitigation measures [11, 12, 68, 72, 75–79], the broader implications for water sustainability and social equity remain contentious [25–28].

To address these challenges, the Government of Mongolia has adopted an Integrated Water Resource Management (IWRM) approach and developed basin-level plans for the Gobi region and other river basins. IWRM, which considers river basins as the optimal geographic unit for managing both surface and groundwater resources [13, 14, 59, 83–87] and promotes stakeholder collaboration for equitable water allocation and sustainable use across sectors [15–19, 54, 56–58, 80, 81, 91, 93, 94, 105]. It aims to balance economic efficiency, social equity, and environmental sustainability [2–4, 53, 60, 67, 69, 119]. However, the implementation of IWRM in Mongolia faces challenges, including limited local participation in decision-making and capacity constraints at governance levels. Researchers, Allouche and Ezbakhe, argue that universalized frameworks, including IWRM and the water-energy-food nexus, often prioritize theoretical principles over practical, localized solutions [145–148]. Scholars Mehta and Hussein further critique the concept of water scarcity, emphasizing its socio-political construction influenced by governance structures and institutional practices rather than physical limitations alone [147–150]. Extending these critiques, Hussein and Ezbakhe observe that while the WEF nexus usefully highlights the interdependence of resource systems, it remains underutilized in current policy frameworks. These authors emphasize the need for robust, context-specific action that can harness the nexus approach for meaningful contributions to sustainable development [147].

These critiques resonate in Mongolia's Gobi Desert, where water scarcity stems from both environmental constraints and governance frameworks. Mining companies operate within regulatory requirements, including water-use permits and fees, yet local herding communities struggle to assert their water rights due to power imbalances and exclusion from decision-making processes.

To effectively respond to these issues, the application of IWRM in the Gobi region must take into account both the physical challenges of water scarcity and the need for inclusive governance that promotes fair water allocation. Incorporating the critiques of Mehta and Hussein into IWRM implementation practices emphasizes the importance of empowering local stakeholders, recognizing the herders' direct dependence on water resources, and promoting equitable water-sharing mechanisms.

The Gobi Desert's pastoral landscape, covering 83% of Mongolia, highlights the deep cultural connection between water and traditional nomadic livelihoods. Mongolian "*urtiin duu*", or long songs, celebrate water as essential for life in the harsh desert environment, reflecting the intertwined relationship between herding life and nature [20–22, 88–90, 95–99, 118]. However, herders face increasing threats to their livelihoods due to competition for water and the environmental impacts of mining [29, 88, 100, 101, 105, 106, 109–111].

By understanding the perspectives of key stakeholders—mining companies, local herders, government agencies, and river basin organizations—policymakers can better identify practical solutions to promote water sustainability while addressing socio-economic and cultural needs.

This study applies the principles of IWRM and considers critiques of water governance frameworks to explore stakeholder perspectives, identifying challenges, barriers, and opportunities to develop practical and equitable strategies for improving water management in the Gobi Desert mining region.

2 Methods

The study employed interpretivism research philosophy to embrace the complexity of social dynamics, diverse perspectives, and subjective meanings associated with the IWRM paradigm. It recognizes that stakeholders' views are shaped by their unique contexts and experiences and allows a nuanced understanding of the perspectives, values, and interests held by stakeholders.

Research problem: water access in the Gobi Desert-steppe mining region. The primary aim of this research is to contribute to sustainable water management by identifying processes that can enhance access to water in the Gobi Desert mining region. The research objectives were to understand stakeholders' views and perspectives on water management, what are current water use practices, challenges, and barriers and what processes facilitate improved water access in the Gobi Desert mining region.

This research utilized semi-structured interviews, field observations, and a review of documents and academic articles on IWRM implementation aspects. The combination of these methods aimed to get a comprehensive understanding of stakeholders' perspectives, the existing water use practices in the Gobi Desert mining region, and the broader contextual

factors influencing water management practices. Data collection spanned from February to September 2022 and field observations in August 2022. The research participants were representatives from four stakeholder groups: mining companies, local communities (including herders), local government officials and river basin administrations. The research applied purposive sampling. The study areas were chosen for their significant mining operations and water scarcity challenges. The Galba Uush Doloodyn Gobi Basin (GUDGB) was selected based on the water use contracts established between major mining companies and the river basin administration. Mining companies were selected based on active operations. Communities were chosen based on their proximity to the mines and shared water resources. Participants were specifically chosen from locations with active mining projects within the Gobi Desert mining region to ensure that participant experiences were grounded in the realities of ongoing operations and to encompass diverse perspectives. Representatives from mining companies provided insights into industry water usage practices and challenges. Community members, including herders and residents, shared their experiences and concerns about water access. River Basin Administrations (RBAs) offered perspectives on regulations and management, while local government officials shared their experiences with governance issues related to water resources in the mining sector. The sample consisted of 19 participants. This sample was sufficient to achieve data saturation. The sample was determined by identifying key stakeholders, specifically focusing on those directly engaged with or affected by mining activities. The criteria ensured that participants were knowledgeable or had experience with the water access challenges at hand. The grounded theory method by K. Charmaz [30] was used for data analysis as a suitable method for exploring social processes and interactions. Data analysis involved:

1. Initial coding: data was coded with descriptive labels capturing the essence of the information, generating numerous codes without preconceived categories.
2. Line-by-line coding: this technique was employed to ensure that no relevant information was overlooked by coding the data at a granular level.
3. Focused coding: significant codes identified during the initial coding phase were selected to establish core categories and conceptual relationships.

To validate the coding process, "Peer Debriefing" method was employed to gather external feedback and validate the coding process. Two graduate students independently coded a subset of the data. This peer debriefing method provided external feedback. All coding was performed manually, and interview recordings and transcripts were stored. This analytical process enabled the identification of common categories, recurring themes, and key processes that can be improved to enhance water use practices in mining regions. Interviews, field observations, and reviews of documents and academic literature provided a foundation for triangulating the data, thereby strengthening the study's credibility and depth. The research investigation focused geographically on the Gobi Desert region, specifically the Galba Uush Doloodyn Gobi Basin (GUDGB) as shown in Fig. 1. This figure has been adapted from the Integrated Water Management Plan of Mongolia (Dolgorsuren et al. [101], p. 89), developed by the Ministry of Environment and Green Development [98]. A mining region is defined as an area where the extraction of minerals such as gold, copper, coal, silver, and fluorspar, constitutes a significant economic activity.

3 Research context

Climate: Mongolia has a continental climate characterized by harsh, dry winters and limited precipitation, with significant regional variations. Temperatures can range from – 40 °C in winter to 35 °C in summer, with an average annual precipitation of less than 100 mm in the Gobi Desert. Most precipitation occurs in summer, and the Gobi Desert faces challenges of limited water availability due to high evaporation rates [112–114].

Pastureland: Mongolia's pasturelands have historically been state-owned but managed as common resources by local entities. Traditional views favour flexible access to grazing lands, rejecting private ownership. Since the late 1990s, there has been a shift toward promoting customary land tenure and management, with local groups managing the land while the state retains ownership [115–117].

Mining operations: The Gobi Desert is a major mining region for coal, copper, and gold [55, 119–122], featuring significant mines like Oyu Tolgoi (copper) and Tavan Tolgoi (coal). Oyu Tolgoi produced substantial amounts of copper, gold, and silver in 2021, with a projected annual copper production of around 500,000 tons. Tavan Tolgoi's reserves are

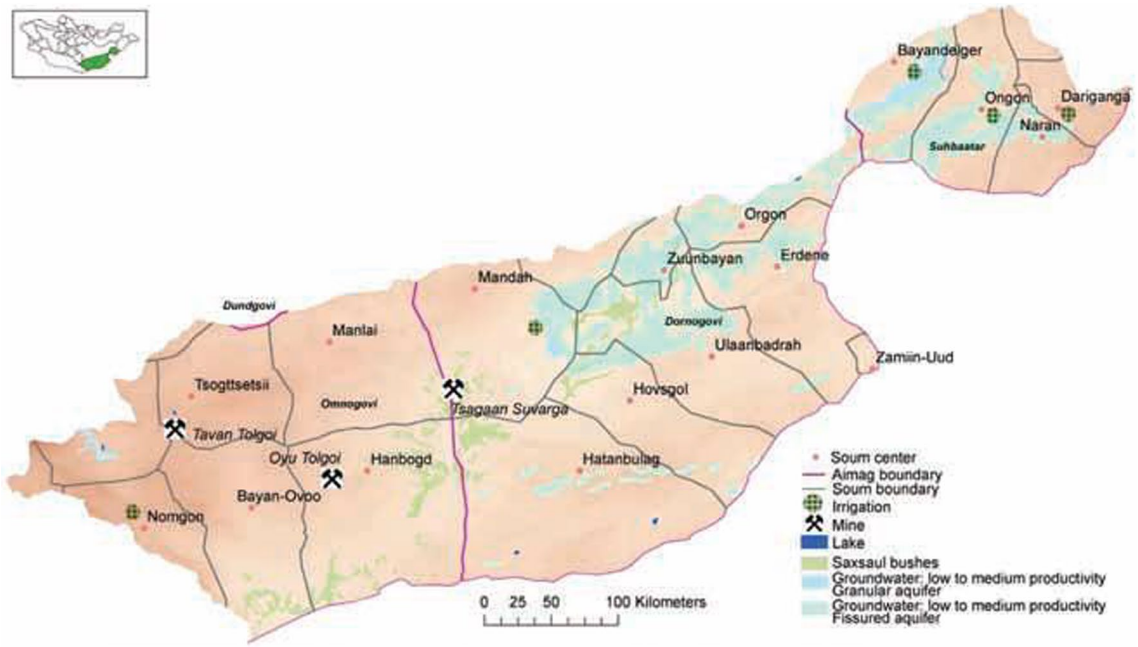

Fig. 1 Galba Uush Doloodyn Gobi Basin

estimated at 505.5 million tons, while Nariin Sukhait Mine holds 587.5 million tons. Tsairt Mineral LLC mines zinc ore with significant reserves and production capacity.

Water sources: The main water sources in the Gobi mining region are aquifers, accessed through boreholes and shallow wells, and temporary ponds formed after rainfall, which are used by herders, livestock and wildlife [98, 123, 124].

Water stakeholders: Water stakeholders in a given basin include individuals, companies, and government agencies responsible for regulating and managing water use.

4 Research findings

4.1 Water access and water use practices in the Gobi Desert mining region

Water access and use practices among different users in the Gobi Desert mining region are shaped by water regulations, climatic conditions, and the availability of water infrastructure. The research findings show the disparities in water access and consumption among stakeholders in the Gobi Desert mining region. Mining companies are the most significant consumers of water holding permits for a substantial volume[1] of 19,661,000 m^3, which reflects their extensive operational requirements. Herders rely on shallow wells and natural ponds, and their water consumption[2] is at a much smaller scale of 32,850 m^3 for 1.8 million livestock. The GUDGB administration makes contracts for water use fees and ensures payments into the local government account from mining companies. Although the local government receives over 4 million USD in revenue from water fees, it does not allocate any funds to the GUDG Basin and undermines its operational capacity.

4.2 Mining companies

Mining companies secure water use permits for 10 years, extendable for strategic deposits. These permits establish annual water use contracts with river basin administrations, which are renewable based on the company's compliance and timely

[1] Annual consumption of seven mining companies based on water use contracts with GUDGB administration. Source: Water Authority, 2022.

[2] Annual water consumption by 1.8 million livestock. Daily water intake per livestock is estimated at 50 l. Detailed information is on page 9.

Table 1 Summary of water access and consumption

Category	Water access: sources	Water consumption, 2022
Mining companies	Groundwater water permits	Seven companies: 19,661,000 m^3
Local communities	Government wells	No data
Herders	Shallow wells, natural ponds	32,850 m^3 for 1,8 mln livestock

Table 2 Revenue from water fees

Entity	Revenue from water fees
Local Government	Over 4 million USD in 2022
GUDGB	0

payment. Before starting mining operations, companies typically conduct groundwater explorations to obtain necessary approvals from the National Water Committee. Each interviewing company follows a mine water policy to minimize consumption through reuse and recycling. For example, the OT company reduces its water usage to approximately 450 m^3 per second, well below the approved limit of 918 m^3 per second by recycling used water. The Nariin Sukhait Coal Mine utilizes an innovative approach to water management -rainwater sources. This approach not only alleviated local opposition but also resulted in financial gains.

4.3 Local communities and herders

Local communities in the sub-province centres Tsogttsetsii, Khanbogd, Gurvantes and Dalanzadgad rely on water access from wells managed by the local government. Whereas herders live with livestock outside of the town and use manual shallow wells for drinking and livestock watering. The daily water intake of livestock is 110,000 m^3. It is calculated on the following basis: 50 L of water by 1,800,000 livestock (in the Gobi Desert, GUDGB area) = 90 million litres. The average annual water consumption of livestock is 32,850 m^3. Recent years have witnessed a decline in the functionality of many shallow wells, leaving them dry. Deep wells have been excavated to address this challenge to support livestock watering. However, new deep wells are experiencing depletion, leading to concerns about the sustainability of groundwater usage for livestock in the coming years.

4.4 Local government

The local government collects revenue from water use fees. In 2022, the local government received over $4 million in these fees. Table 1 provides a summary of water access and consumption in the Gobi region, GUDGB. The table is adapted from Purevjav (2024, pp. 100–101), [144]

Table 2 presents the revenue generated from water fees, offering insights into the financial aspects of water management in mining regions. The table is adapted from Purevjav (2024, p. 100) [144].

5 Views and perspectives on IWRM

The management of water resources in mining regions presents a pressing concern. Different stakeholders hold unique perspectives on water management and IWRM.

5.1 Company views and perspectives on IWRM

The participating mining companies perceive IWRM as a state policy, with the expectation that the government bears the responsibility for its implementation. The companies' role is to follow the legal requirements such as using water within approved water reserves, preventing water overuse, and being aware of ecological balance. Although all participating companies viewed IWRM as a state duty, some companies also emphasized its essence in fostering the participation of all water stakeholders, acknowledging diverse perspectives, safeguarding herders' rights, and highlighting clear responsibilities for each involved party. These views are guided by corporate water and community engagement policies as well as government regulations.

5.2 Herder views and perspectives on IWRM

Local communities perceive water as both a precious and strategic resource, recognizing its fundamental role in sustaining human, animal, and plant life. Among herding communities specifically, water holds significance as a common asset, essential for communal well-being and thus must be accessible to all members. This perspective reflects a holistic worldview that acknowledges the interdependence between water availability and the broader ecosystem's health. Water is essential for human use, for sustaining the natural environment and its biodiversity.

5.3 Local Government views and perspectives on IWRM

Local government officials' perspectives on water management reflects a dual commitment: first, to ensure the provision of water for household consumption and livestock watering, and second, to promote local development. The current state of water management indicates that the Government has not met its obligation to provide water, as evidenced by the challenges faced by herders and their livestock in accessing water. Consequently, the implementation of IWRM is regarded as unsatisfactory. This situation illustrates a discrepancy between the mandate for water provision and the realities experienced by herders.

5.4 The GUDGB administration's views and perspectives on IWRM

The GUDGB Administration see IWRM as a road map to ensure long-term water sustainability in the basin by promoting water efficiency and conservation.

6 Challenges for effective water management in the region

Mining companies, local governments, and herders face distinct issues that heighten tensions. The consequences of these issues include strained relationships among stakeholders, environmental degradation and socio-economic instability. Mining companies grapple with unclear government regulations. Misleading information about water usage erodes trust, while a lack of coordination among government entities undermines effective water management. Local governments face a challenge to provide adequate water access for herders, as broken wells and insufficient funding exacerbate water scarcity and pasture degradation. The Gobi Basin Administration faces underfunding and limited authority, hindering its ability to monitor water use and prevent illegal practices. Herders, hit by water shortages and climate change, face desertification and pasture loss. A lack of information and support on water

availability further undermines access to water. These challenges increase socio-economic instability across the region.

6.1 Challenges faced by mining companies

- Imprecise Government regulation: this led to a lack of clarity and consistency in expectations, resulting in misunderstandings among the companies.
- Misleading and inaccurate information about water use: this has fostered tension and eroded trust between mining companies and local herders.
- Lack of coordination between government entities: the absence of a coordinated approach undermined the overall effectiveness of water management by lacking actual information on water consumption.

6.2 Challenges identified by local officials

- Limited water access for livestock: as the local government—the Department of Agriculture—fails to address the water needs of the herders due to lack of funding or expertise in hydrogeology, decreases the trust of herders in the local government. Broken wells and insufficient funding for deep well construction exacerbate water scarcity and contribute to pasture desertification.
- Contentious mining and community relationships: poor relationships between mining operations and the community increase the potential for conflicts.

6.3 Challenges identified by the GUDGB administration

- Lack of funding and professional human resources hinder effective monitoring of mine water.
- Lack of Authority limits the administration's ability to stop illegal water use.

6.4 Challenges faced by herders:

- Water Shortages and Climate Change lead to desertification and pasture loss, making it difficult for herders to sustain their livelihoods.
- Lack of Information and Support: Insufficient information on groundwater locations and inadequate support for improving water access drive herders to abandon their traditional livelihoods.

7 Consequences

1. Erosion of trust: misleading information, broken wells, and ambiguous regulations contribute to mistrust between stakeholders and authorities.
2. Increased tensions: the disconnect between mining companies, local governments, and communities increases tensions.
3. Resource mismanagement: ineffective coordination and lack of monitoring can result in resource depletion and environmental degradation.

Table 3 outlines the challenges and barriers to water management, along with their consequences, emphasizing key obstacles. This table is adapted from Purevjav (2024, p. 104) [144].

Table 4 identifies key issues and the contributing factors, providing a comprehensive understanding of challenges in water management. This table is adapted from Purevjav (2024, p. 121) [144].

8 Stakeholders' engagement in water resources management

Participatory water monitoring (PWM) with local communities was mentioned by two mining companies and local herders. PWM is a flagship activity that helps mining companies (OT LLC and Energy Resources) to establish long-term relationships with the local community and build trust. For instance, the participatory water monitoring program

Table 3 Challenges and barriers, consequences

Stakeholders	Challenges and barriers	Consequences
Mining companies	Imprecise government regulations	Created misunderstanding
	Misleading and inaccurate information about water use	Tension and loss of trust among stakeholders
	Lack of coordination between Government Entities	Undermines effectiveness
Local government	Limited water access for livestock	Trust in Government decreases
	Broken wells, no water in wells	Pasture desertification
	Lack of funding for constructing new deep wells	Potential conflict on rise
	Contentious mining and community relationships	
Gobi Basin Administration	Lack of funding and professional human resources	Inadequate mine water monitoring
	Lack of authority	Unable to stop illegal water use, wasteful water use
Herders	Water shortage in wells	Competition for water resources
	Climate change impact	Desertification, pasture loss
	Overall lack of support to improve water access for livestock	Giving up herding, loss of livelihood

Table 4 Issue and factors contributing to the issue

Issue	Factors contributing to the issue
Erosion of tru st	Misleading information, broken infrastructure, and ineffective regulation contribute to a breakdown in trust between stakeholders and authorities
Increased tensions	Disconnect between mining companies, local governments, and communities heightens tensions and potential conflicts
Resource Mismanagement	Ineffective coordination and lack of monitoring result in suboptimal water use and management, leading to resource depletion and environmental degradation

continued for almost 20 years in Khanbogd sub-province, indicating its effectiveness and importance. Recently local herders in the Khanbogd sub-province formed Munkh Nogoon Galba, a non-governmental organization (NGO) to continue well water monitoring but also to expand activities toward broader environmental conservation, including pasture improvements and biodiversity monitoring.

Reports of independent environmental audits conducted every 5 years at OT LLC, provided alternative perspectives to improve mine water management. The availability of reports publicly on the website contributes to transparency, building community confidence and trust, and improving the mine water monitoring.

The Triparty Committee (TPC) in the Khanbogd sub-province also supports the collaboration of stakeholders and trust building. The triparty committee consists of local herders, OT LLC and the local Khanbogd government. TPC makes decisions jointly informed by the needs of local herders and the community. Mining companies provide funding for the committee's initiatives, which are implemented through the active participation of the local government, herders, and local community. For example, in 2019, the committee addressed herders' complaints by renovating old, damaged wells, with a total of 20 manual herder wells repaired annually; a total of 56 herders' wells for livestock watering have been repaired since 2019, demonstrating the committee's ongoing commitment to improving water access for herders and livestock [31].

Community educational activities such as "Mine processing plant visit" and "Mine Open Day" events were mentioned by Energy Resource LLC in the Tsotgtsetsii sub-province as approaches to engage the local community. These activities resulted in an improved understanding and public awareness of mining and processing plants by local people.

As shown in Table 5, stakeholder engagement activities play a crucial role in effective water management [144]. This table is adapted from Purevjav (2024, p. 121) [144].

Table 5 Stakeholders engagement activities in water management

Activities	Ways of engagement
Participatory water monitoring	Herders measure the water level in their wells and conduct the monitoring measurement daily. The mining company and herders meet and verify the wells' monitoring results. Local NGO representing herders holds almost 20 years' worth of water monitoring data
Mine processing plant visit	The company organizes educational coal processing plant visits for local herders, community and youth. These educational visits improve understanding of mine processing operations. These visits organized for the last 10 years and contributed to building transparent community-mining relationships and trust
Independent auditing	Contracted independent professional entities to do environmental auditing with an aim to get unbiased technical recommendations and perspectives on reducing and mitigating negative impacts
Khanbogd soum Triparty council	TPC of Khanbogd soum was founded on June 8, 2015, and includes equal representation from local administration, herders, and OT LLC. Operating under a jointly agreed Memorandum of Understanding, the TPC develops and enforces its regulations
(TPC) meetings	It provides the opportunity to gather, and share information, address water and environmental concerns, allocate funds and make joint decisions
Herders' well projects	The company provided technical expertise, allocated funding for relevant cost and in collaboration with herders improved herders' shallow wells, thus increased access to water for livestock
Water advocacy events	Celebrating World Water and World Water Monitoring Days, increased stakeholders' engagement in dialogues in responsible water resources management

9 Discussion

The Gobi region's findings align with global issues in mining governance, such as water scarcity, regulatory ambiguity, and community tensions. However, distinct challenges area: herders as key stakeholders, a lack of regulatory authority, and trust erosion. The Pilbara Region in Australia and Chile have similar issues related to water scarcity and conflicts between communities and mines [32, 33, 54, 125]. South Africa and Zambia have similar barriers in regulatory weakness, water access, and community conflicts [34, 126]. The participatory water monitoring (PWM) program illustrates advancements in community engagement and empowerment among herders, reflecting trends observed in various international contexts [35, 43, 44, 84].

Similarities with existing literature:

1. Imprecise regulation and lack of coordination lead to mismanagement and water misallocation in mining regions like Pilbara (Australia) and Northern Chile [32, 33, 36, 54, 125].
2. Water access issues: water scarcity affecting livestock and local communities is a recurring theme in mining studies. Studies in South Africa [37, 129, 130] and Peru [38, 131, 132] show mining's impact on water availability for agriculture, leading to tensions.
3. Community-mining relationships: globally, contentious relationships between mining companies and local communities are well-documented, with miscommunication and mistrust being common. In Zambia, for example, misinformation on water use fuelled social unrest [39, 127]
4. Climate change and resource management: the Gobi region's water shortages and desertification are part of a global pattern where climate change exacerbates water scarcity and pasture degradation, as seen in Northern China and Sub-Saharan Africa [40, 41, 111]. This threatens traditional livelihoods dependent on natural resources.

Differences with existing literature:

1. Lack of authority in water management: unlike in Chile and Australia, where water management authorities have more regulatory power, the Gobi Basin's regulatory bodies lack enforcement authority, highlighting a more acute governance failure [34, 41, 128].
2. Herders as key stakeholders: the Gobi study uniquely focuses on herders as primary stakeholders impacted by mining activities. In other regions, studies emphasize conflicts with farmers or urban communities [110].
3. Trust and mismanagement: the current study emphasizes the erosion of social trust due to regulatory failures and poor communication. This theme is less prominent in other regions where the focus tends to be on economic or environmental impacts [42, 65].

Processes toward water sustainability and similarities with existing literature.

The participatory water monitoring (PWM) program has empowered herders by providing them with data in real-time on water levels, enabling them to promptly respond to emerging issues. Over 80 herders are involved in water level measurements across 87 wells. This initiative gives herders a voice in water management decisions; equips them with skills and allows traditional knowledge to be incorporated into data interpretation, thereby promoting community ownership [94]. Collaborative verification with mining companies ensures data accuracy and transparency. For instance, there is currently a discrepancy of 0.05–0.2 m in water level measurements between the company and local herders. This process strengthens the collective capacity to address water challenges and builds trust between companies and herders. Moreover, a local NGO, representing herders, possesses 20 years' worth of monitoring data, facilitating trend tracking and supporting long-term water resource management and informed decision-making. Since 2019, repairs to 56 herder wells have improved livestock water access. Other studies have highlighted the role of PWM in improving relationships between industry and communities and fostering trust among water stakeholders [35, 44, 133]. PWM achieves this by involving communities in the measurement of water levels, promoting transparency, and opening communication channels. The current research findings align with successful studies on PWM from South Africa, where mining companies engage with local communities to address water management issues through participatory frameworks [44, 133]. PWM allows transparency and dialogue and building trust, resulting in improved relationships and joint problem-solving.

The educational plant visits to the Ukhaa Khudag coal mine, organized by Energy Resources for the community are similar to initiatives in Australia, where mining companies have conducted tours to educate residents about water

treatment processes [46, 135, 136]. Such educational efforts enhance community awareness and foster positive interactions between industry and local stakeholders, promoting sustainability. During the visit, participants are guided through the plant's water treatment facilities and technologies, where the various stages of water treatment such as filtration, purification, and recycling are explained. Additionally, the company introduces the plant's water consumption patterns, emphasizing the imperative of water savings. The company employs a dry cooling technology and reduces water consumption by utilizing air cooling mechanisms, minimizing reliance on freshwater resources. Over the past decade, this educational visit has been a regular initiative, originally occurring monthly, then transitioning to quarterly visits, and most recently reduced to biannual occurrences. These educational visits have played a pivotal role in developing relationships and facilitating the successful implementation of local development programs by the company. Furthermore, during times of water scarcity, the company has assisted herders by providing access to one of its wells. Overall, the processing plant visit effectively disseminates knowledge, contributing to community awareness and engagement in water resource conservation and management. Many research studies in the field of sustainable water management emphasize stakeholder engagement as a key element for achieving sustainability and the findings of this research align with those of other studies in the field [56, 57, 136].

The importance of independent environmental audits for enhancing transparency is consistent with studies from Canada, which highlight how audits can facilitate stakeholder trust in resource management practices [11, 47, 48, 137, 138]. Independent environmental audits identified gaps and shortcomings in mine water management practices. For instance, the audit identified a seepage from tailings storage facility (TSF) Cell #1. To address this issue the company installed a seepage collection system under TSF Cell #2 and created a deep clay trench around it as per the audit recommendations. The OT mine built a new seepage pond away from existing structures and dug trenches to redirect drainage. The OT mine also improved the (Dugt/Khaliv) surface water diversion. The most recent audit report suggests installing permanent or semi-permanent groundwater monitoring wells downstream of mine licensed area (MLA) to track the extent of seepage migration offsite. By providing objective assessments and insights, these audits contribute to enhancing water stewardship. Local communities and the government perceive independent audits as credible sources of information, thereby enhancing trust and improving sustainability practices. Moreover, independent audits promote transparency and accountability by providing communities with access to objective assessments of mine water management practices, fostering trust in the mining companies' commitment to environmental stewardship. The research [11] highlights the need for regular audits, particularly for those whose production processes have direct environmental implications. The insights from environmental audits were useful in improving designs, products, or processes and fostering innovation and leadership in environmental stewardship [139–141].

Water advocacy events during World Water Day on 22 March provided platforms for local stakeholders to engage in discussions and dialogues on water-related issues, fostering active participation and knowledge sharing. The celebration of World Water Day has transformed from a traditional 1–2 day event into an extended period lasting 2–3 months. During this time, schools and children have become increasingly involved, playing an active role in water advocacy. Furthermore, organizations involved in the water advocacy day witness increased engagement and participation, reflecting a growing commitment to addressing water challenges. These findings align with the research in the field that open dialogue develops a common understanding and commitment toward sustainable water management [49, 140, 141].

Khanbogd Triparty Stakeholders' Council promotes joint decision-making and collaboration among diverse stakeholders ([31] TPC 2021, n.d.). As of 2019, 56 herders' hand wells were repaired, and 12 exploration boreholes were handed over to the local government to support pasture water supply. A study on a triparty process illustrates that the triparty process was a key element for inclusive development in that communities, companies and governments come together to discuss responsibilities, costs and benefits [50, 142, 143].

The 'Herder's Well Improvement' project serves as an example of a successful collaboration between the OT mine and local herders to address water access for livestock. With the technical expertise of the company, in 2021, nineteen herders' wells in Khanbogd soum were repaired to improve water access for the herders. This initiative highlights collaborative approaches to achieving sustainable water management and the effectiveness of dialogue.

These processes, illustrated in Fig. 2, facilitate improved access to water and foster long-term collaboration toward water sustainability. This Fig. 2 is adapted from Purevjav (2024, p. 127) [144].

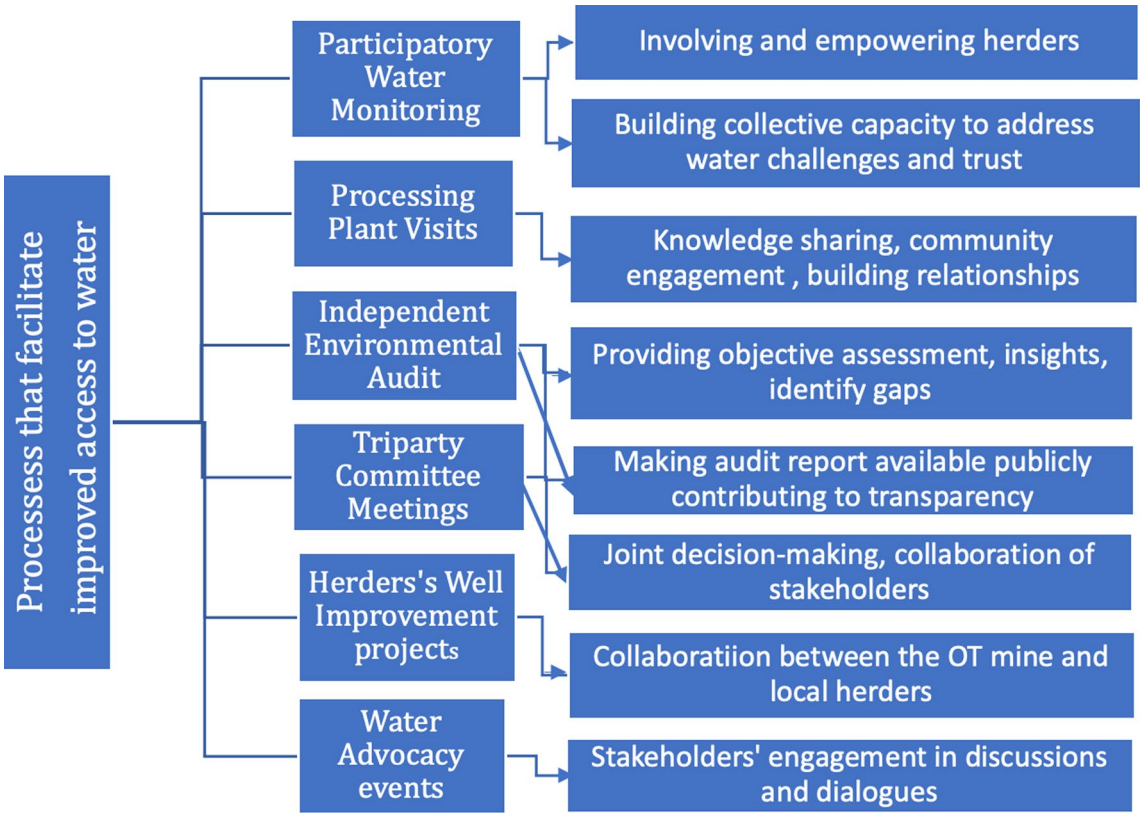

Fig. 2 Processes that facilitate improved water access are based on IWRM principles

10 Conclusions

In the arid landscape of the Gobi Desert, where water is vital but scarce, applying IWRM principles is essential to promote sustainable and equitable water use among diverse stakeholders. The challenges posed by mining operations underscore the necessity for a collaborative approach to water management. Key processes, such as participatory water monitoring, independent environmental auditing, educational processing plant visits, and the establishment of triparty stakeholder councils, exemplify the effective application of IWRM principles. These initiatives illustrate how participatory processes enable local communities to engage in water management decisions while increasing transparency and trust among stakeholders. Stakeholders' engagement facilitates joint decision-making and adaptive management strategies. Collectively, these approaches enhance sustainability in water resource management, demonstrating the vital role of IWRM in the Gobi Desert.

1. Key elements of IWRM principles in participatory water monitoring (PWM)
2. Stakeholder involvement: PWM engages local herders in water level measurements, ensuring that community voices are integral to the water management process and in decision-making.
3. Knowledge integration: potential to combine traditional ecological knowledge with scientific data collection, PWM fosters a better understanding of water resources.
4. Transparency and accountability: the collaborative verification of water data with mining companies promotes trust and transparency between companies and herders.
5. Key elements of IWRM principles in independent auditing
6. Transparency: independent environmental audits provide objective assessments of water management practices, promoting accountability within the mining sector.
7. Trust building: by identifying gaps and recommending improvements, audits foster trust among stakeholders, including local communities, companies, and government bodies.

8. Adaptive management: the insights gained from audits inform management practices, enabling continuous improvement and adaptation to changing conditions and challenges.
9. Key elements of IWRM principles in educational processing plant visits
10. Knowledge dissemination: educational visits to processing plants enhance community understanding of water management practices and technologies.
11. Capacity building: by educating local residents on water treatment processes, these visits empower communities to engage more effectively in water management discussions and decisions.
12. Collaboration: these initiatives foster positive relationships between industry and community stakeholders, supporting a collaborative approach to managing water resources sustainably.
13. Key elements of IWRM principles in the Triparty Committee (TPC)
14. Inclusive decision-making: the TPC brings together representatives from communities, companies, and government agencies, facilitating joint decision-making and ensuring diverse perspectives are considered.
15. Shared responsibility: by promoting shared responsibilities among stakeholders, the TPC enhances cooperation and collective action in managing water resources.
16. Conflict resolution: the council provides a platform for addressing conflicts and negotiating agreements, improving relationships among water users.
17. Key elements of IWRM principles in well improvement projects
18. Community empowerment: projects that repair and improve herders' wells directly address local water access issues of the community.
19. Sustainability focus: these initiatives enhance immediate water access and consider long-term sustainability.
20. Collaboration: the collaborative nature of these projects between herders and mining companies exemplifies the partnerships essential for successful water resource management.
21. Key elements of IWRM principles in water advocacy events
22. Public awareness and engagement: World Water Day events promote community engagement and awareness, encouraging broader participation in water stewardship.
23. Knowledge sharing: these gatherings facilitate knowledge exchange among stakeholders, which is essential for informed decision-making and collective action in water management.
24. Community empowerment: involving schools and local organizations in advocacy initiatives nurtures a culture of water stewardship and empowers future generations to participate in sustainable water management practices.

Each of these processes embodies core IWRM principles: stakeholder participation, promoting transparency and accountability, joint decision-making, integrating diverse knowledge, and collaboration among water users. Thus, these processes contribute to sustainable water resource management in the Gobi Desert mining region.

11 Recommendation

The findings of this study highlight processes—PWM, independent auditing, water advocacy events, well improvement projects, TPC initiatives, and educational plant visits—that are essential for supporting water sustainability in the Gobi Desert mining region. To effectively address the water access challenges faced by herders in mining regions, the following targeted recommendations and solutions are proposed:

11.1 Proposed recommendations

1. Continue and elevate current good practices:

It is vital to sustain and enhance existing processes that promote water sustainability, including PWM, independent auditing, and water advocacy events. These initiatives have proven effective in community engagement and transparency in water management.

2. Conduct hydrogeological studies:

Undertake studies to assess water availability, quality, and recharge rates in the region. Mapping groundwater reserves will provide data to inform targeted interventions.

3. Assess climate change and mining impacts:

Evaluate the effects of climate change and mining activities on local water resources. Understanding these effects will help to identify vulnerabilities and inform adaptive management strategies.

11.2 Proposed solutions

1. Develop evidence-based policies: formulate policies that prioritize water access for herders and livestock and ensure that water resources are protected and equitably allocated.
2. Effective communication: ensure that these policies are communicated effectively to all stakeholders through transparent and accessible channels.
3. Establish mechanisms for water consumption data collection: create systems for the reliable collection of water consumption in the mining region for informed decision-making.
4. Implement nature-based solutions: rainwater harvesting and natural water storage to enhance water availability and ecosystem resilience.
5. Facilitate stakeholder engagement sessions: organize water planning sessions with herders, local authorities, and NGOs and funds allocation for water harvesting, storage and pond construction projects.

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Authors contributions BP and BK conceptualized the research aim and objectives. BK provided supervision. BP drafted the original manuscript. JD and NK contributed to the research methodology and data analysis. AX and SMF reviewed the manuscript. All authors approved the final manuscript.

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Data availability Data supporting the findings of this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate The protocol was approved by the Behavioural Research Ethics Board (BREB) of the Office of Research Ethics at the University of British Columbia, by the Guidance Notice on Behavioural Applications and BREB Guidance Notice in January 2022.

Informed consent Research information was provided to all potential research participants before their involvement in the study. Their involvement was entirely voluntary, and participants gave consent by agreeing to participate in the interview. Participants were fully informed about the nature of the research, including their right to withdraw from the interview at any time without any consequences. The researcher followed the organizational internal procedure of involving staff in a research interview. The researcher got permission well before the interview and focus group discussion to avoid the potential vulnerability of the staff. The research did not collect identifiable data. The research data are stored in a locked cabinet and password-protected computer. The researcher followed the approved procedure for interviews with research participants:

The researcher introduced herself and explained the research objectives.
Informed that participation is voluntary and that they can withdraw from the study at any point.
Answered and clarified any questions that participants had.
Distributed research objective overview and researcher's contact information.
Interviews were conducted for 40–60 min. By participating in the interview, participants have given consent to participate.

Consent for publication The authors are informed and agree to publish.

Competing interests The authors have no competing interests to declare relevant to this article's content.

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