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Challenges in Strip Mining of Sodium Sulfate Sedimentary Reserves in Mighan Playa, Arak: Environmental Impacts and Engineering Solutions

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Abstract

This work investigates the extraction of sodium sulfate (Na2SO4) from Mighan Playa in Arak, Iran, where 163 boreholes were drilled to depths of up to 20 m revealed a heterogeneous lithology dominated by Glauberite (Na2Ca(SO4)2) and Mirabilite (Na2SO4·10H2O) with average sodium sulfate concentrations of 25% (ranging from 2–32% and peaking at 55% in localized southwestern areas). The playa's surface is primarily clay-covered (94%) and interbedded with evaporitic facies including Gypsum, Halite, and carbonate minerals. Seasonal water inflows of 200–800 l/s from a wastewater treatment plant, together with 3.5 m-deep extraction pits and gravitational drainage, have resulted in stagnant ponds over 25% of the southern lake area and an annual reduction in surface area of 5–10%. Stratigraphic analysis further indicates pure Glauberite layers (0.5–1 m thick) at depths of 1,653–1,656 m, in contrast with thicker impure Glauberite-Mirabilite sequences (up to 9 m) present between 1,649–1,659 m. To mitigate these challenges, an integrated engineering approach is proposed that includes pumping seepage brine (with a moisture content of 40%) to solar evaporation pools, employing continuous dual-pump slurry systems for tailings management, and implementing hydraulic balancing through retaining walls and winter brine reserves—measures that enhance extraction efficiency by 30–42% in high-concentration zones. These adaptive mining practices, incorporating in-situ brine leaching and advanced wastewater treatment, are designed to meet 70% of Iran's annual sodium sulfate demand from an 8 km² operational area while reducing environmental degradation.

1. Introduction

Saline lakes that do not have much drainage and have a gentle topographic slope, which have dynamic environments under the influence of the prevailing climate and weather conditions of the region, and the salt deposits within them are formed under the influence of the prevailing geochemical conditions [1]. Despite often maintaining high water levels, the dry climate and elevated alkalinity typically result in sparse or absent plant cover [2, 3]. These lakes are seasonally filled with water during wet periods but often dry up during arid seasons [4]. Certain saline lakes remain perpetually dry, serving as remnants of pluvial lakes formed during glacial periods when rainfall was more abundant [5, 6]. As the Holocene epoch commenced, rising temperatures and diminishing rainfall caused the gradual disintegration of these lakes, leading to the formation of modern saline basins [7, 8]. The geochemical composition of saline lakes exhibits spatial variations, with evaporate minerals typically transitioning from chloride-dominant compositions at the center to sulfate-dominant compositions at the periphery [9, 10]. Sodium sulfate, one of the most important evaporative minerals found in these lakes, plays a critical role in the sedimentary processes of evaporate environments [11, 12]. These lakes, often located at the lowest points of desert basins or natural

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depressions, serve as vital sedimentary basins for evaporate mineral accumulation [13, 14].

Human activities have significantly influenced saline lake ecosystems, particularly through alterations to water quality and levels [15]. Sodium sulfate extraction methods vary globally, depending on the deposit's geological origin and the employed processes [16-18]. Efficient and environmentally compatible methods include:

- Near-surface extraction**:** Harvesting sodium sulfate from shallow layers.
- Dissolution techniques**:** Targeting deeper deposits by dissolving sodium sulfate and pumping it to the surface.
- Brine extraction**:** Utilizing wells to extract brine from evaporate sediments in saline lake plains [19].

In Canada, sodium sulfate is extracted from Lake Alberta by collecting Glauberite salt crystals from bottom layers and pumping saturated lake water to processing plants [20]. Saskatchewan producers pump brine directly into storage and crystallization tanks, while in the United States, miners dissolve brine in situ before extraction. Some regions inject hot water into deeper salt layers, extracting saturated raw Mirabilite salts, which are subsequently cooled and crystallized. In Spain, a blend of sodium and calcium sulfate is obtained through underground extraction, employing the room-and-pillar mining method. These region-specific practices underscore the adaptability of sodium sulfate extraction to local geological and economic conditions.

The extraction of sodium sulfate in Iran exhibits distinctive features shaped by geological conditions, deposit formation processes, and the nature and thickness of the deposits. The majority of known deposits are located in the provinces of Markazi, Semnan, and Qom, predominantly on Quaternary sediments [21]. In these regions, sodium sulfate is found at the surface, as exemplified by deposits in Arak Mighan Lake. Unlike many deposits worldwide, the sulfate layers in these areas are exceptionally thin, with thicknesses ranging from 15 centimeters to a maximum of 2 meters. Typically, a layer of clay and silt is present both above and below the sodium sulfate deposit, with tailing thickness varying from 15 centimeters to 1.5 meters [22].

Due to the relatively low thickness of the deposits and the associated sediments, the strip mining method (layered open-pit) is predominantly employed. At Mighan Lake, sodium sulfate is extracted from an 8 square-kilometer area, representing approximately 5% of the lake's total area, and fulfills 70% of the nation's annual demand. Extraction operations are conducted to a depth of 3.5 meters and are typically carried out over a five-month period, spanning late spring to early autumn. The extracted sodium sulfate is transported from the mine site to a processing facility approximately 5 kilometers away via a dedicated access road. Upon arrival, the material is stored with a moisture content of approximately 40%. Following the removal of surface mud tailings, which are deposited in designated areas, the primary sodium sulfate deposits are extracted. After the extraction process, tailings are returned to the mining sites to minimize environmental impacts [23].

Mighan Lake, situated in a closed catchment area, is supplied by the Qara-Kahriz, Farahan, and Shahrab rivers, as well as precipitation and treated wastewater discharge from the Arak region. All surface and groundwater flows converge in the central basin of the lake [24]. The establishment and operation of the sodium sulfate processing plant has somewhat altered the hydrological and ecological systems of the lake, and has had impacts on water quality and water level regulation that need to be investigated and effective solutions implemented before major impacts occur. These disturbances highlight the critical need for effective water management strategies to ensure the long-term sustainability of the lake ecosystem.

This work aims to characterize the primary minerals and facies of sodium sulfate within Mighan Lake, assess the surface and subsurface extent of sodium sulfate deposits, evaluate the impacts of extraction activities on groundwater levels across various timeframes, and address the challenges posed by shallow surface and subsurface water drainage during the extraction process. By integrating geological, hydrological, and environmental analyses, the research work seeks to provide a comprehensive understanding of the mineralogical composition, spatial distribution, and operational challenges associated with sodium sulfate extraction, while proposing sustainable solutions to mitigate the environmental and technical issues arising from mining activities in this semi-aquatic environment.

2. Geology of Region

The Mighan Lake basin is characterized by its ancient geological formations, some of which, date back to the Mesozoic era. During the Jurassic period, the central Iran zone, and the Sanandaj-

Sirjan zone were composed of various lithological units including schist, sandstone, shale, quartzite, and dolomitic limestone (Figure 1). Specifically, the lower Jurassic period featured shale, sandstone, and dark gray slate, while the middle Jurassic period was dominated by shale and sandstone formations. The upper Jurassic period was marked by the prevalence of dolomitic limestone. Overlying these Jurassic rocks are the Cretaceous formations, which have been significantly affected by tectonic activities including crushing and fracturing along the main Tabarteh and Talkhab faults and several associated sub-faults. The lower Cretaceous period comprises conglomerate, sandstone, and limestone, with gray dolomites. The middle Cretaceous period is characterized by gray and dark Orbitolina limestone, while the upper Cretaceous period consists of gray and pale-yellow limestone, bounded by the Tabarteh fault within the Sanandaj-Sirjan zone (Figure 2).

During the Paleogene period of the Cenozoic era, magmatic activities including volcanic eruptions occurred primarily during the Eocene epoch within the Urmia-Dokhtar zone. The base of the Paleogene period in the Mighan Lake basin is formed by red detrital deposits including conglomerate, pale-yellow sandstone, and marl limestone. This period also includes deposits of marl, sandstone, calcareous sandstone, calcareous marl, Nummulitic limestone, and volcanic layers of andesite, trachyte and gray tuffs. Towards the transition from the Eocene to the Oligocene, the region saw the deposition of red evaporate and detrital sediments, collectively known as the Lower Red Formation. This formation, found beneath the Eocene fossiliferous limestone sediments of the Qom Formation includes conglomerate, shale, gypsum, marl, and sandstone. The Neogene period is characterized by the Upper Red Formation, consisting of red to cream-colored sandstone, marl, clay, and interlayers of conglomerate and evaporate, representing continental lagoon sediments with significant thickness.

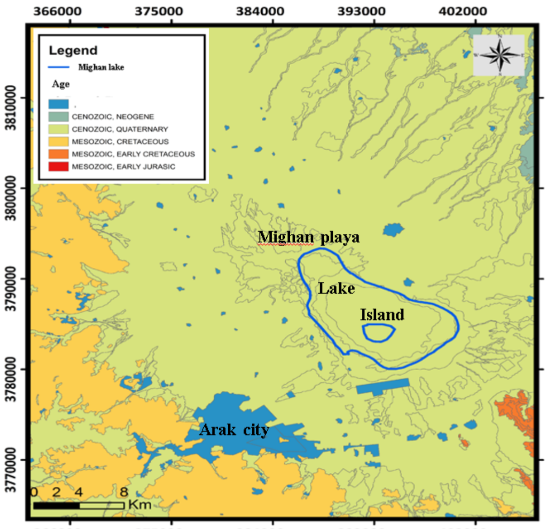


Figure 1. Geological age layers of Arak Mighan Lake basin

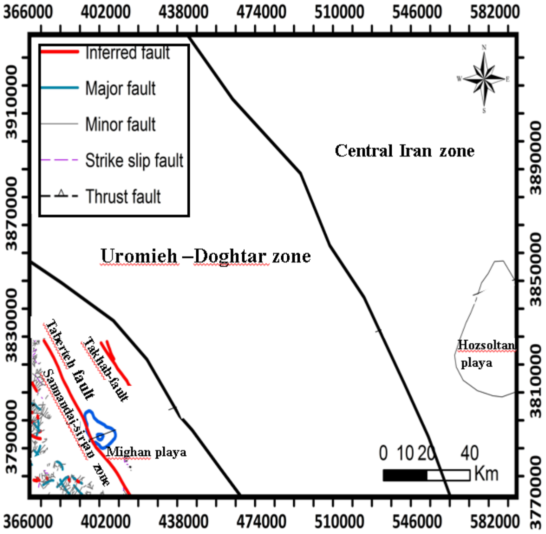


Figure 2. Geological zones in the area of Arak Mighan Lake

Mighan Lake was a permanent lake prior to the last ice age, approximately 10,000 to 28,000 years ago. This persistence can be attributed to the region's relatively cold climate and substantial precipitation during that period [25]. Borehole analyses have revealed coarse-grained alluvial sediments at a depth of 10 meters, transitioning to fine-grained alluvial sediments indicative of the New Ice Age in the northern margin. These findings suggest that sedimentation patterns shifted during arid phases, with chemical sedimentation prevailing during warmer and drier periods. Crystalline layers within the basin, approximately 4 meters thick and lenticular in form, appear to have been deposited in a climate analogous to the present, around the early Holocene (7,000 to 10,000 years ago). The Mighan seasonal lake is a prominent feature originating in the Quaternary period. Covering approximately 94% of its surface, Arak Lake a salt crust dominates the region, while intermittent swamps account for the remaining 6%. Mighan Lake serves as the terminal point for streams in the Arak basin, some, of which extend up to one kilometer into the lake’s salt flats. Notable geomorphological features within the salt bed include grooves and holes, measuring about 75 meters in length and 5 meters in width, which, are linked to the emergence of springs in the area.

The Mighan Lake basin is primarily covered by Quaternary sediments, comprising a spectrum of alluvial deposits ranging from coarse to fine grain sizes. In the northern and northeastern parts of the basin, these sediments originate from the Urmia-Dokhtar volcanic belt and consist predominantly of volcanic coarse-grained materials, forming the lower Quaternary deposits. Late Quaternary deposits in the plains are mainly composed of fine-grained alluvium, while the foothills feature alternating salty marsh sediments and lacustrine deposits. The buried lake deposits correspond to glacial phases, whereas salt marsh deposits, such as those present in the current Mighan Lake, are associated with interglacial periods. Additionally, evaporation basins or salt lakes have formed in the lower, closed parts of Quaternary depressions.

The Mighan Lake catchment area encompasses a seasonal lake spanning 110 km², primarily shaped by the Tabarteh and Talkhab faults. As an evaporation basin, Mighan Lake is rich in clay, silt, salt, and saline sediments. The deepest part of the basin, located at the border of the Sanandaj-Sirjan and Central Iran zones, predominantly comprises fine-grained clay and silty sediments interspersed with evaporate deposits. These evaporates include Halite, Gypsum, Glauberite, Thenardite, and Mirabilite [22].

3. Materials and Methods

3.1. Geographical location

Arak Mighan Saline Lake is located 5 kilometers northeast of Arak City, and situated at an elevation of 1,660 meters. Mighan Lake ranks as one of the highest salt flats in Iran, second only to Sirjan Lake, which is positioned at 1,690 meters above sea level. The lake's area fluctuates between 80 and 120 km², with a perimeter ranging from 40 to 51 km. During the wet season, the water depth varies between 100 and 150 cm across different sections of the lake, with the free water typically evaporating during the dry season. The lake's surface is predominantly swampy in its deeper regions.

In the recent years, the extraction of sodium sulfate from the central island of the lake, coupled with the failure to return the associated tailings to the extraction areas, has resulted in the formation of a permanent pond. Furthermore, the lake receives a continuous inflow of water from the sewage treatment plant of Arak City, with a flow rate ranging from 200 to 800 L/s in the southern portion of the lake. This inflow accounts for approximately 25% of the total area of Mighan Lake, particularly in the southern and southeastern regions.

The primary sources of water for Mighan Lake include atmospheric precipitation, runoff from the streams of eight sub-basins, springs dispersed across the lakebed, and the discharge from the Arak sewage treatment plant (Figure 3). The region experiences relatively mild summers and cold winters, with an average annual rainfall of 308 mm and an evaporation rate of 2,036 mm. The average temperature is 14 $^{\circ}$C, with a humidity level of 46%. The lake is subject to a dry period lasting approximately 150 days each year, from early June to early November, and enjoys an average of 2,993 hours of sunshine annually.

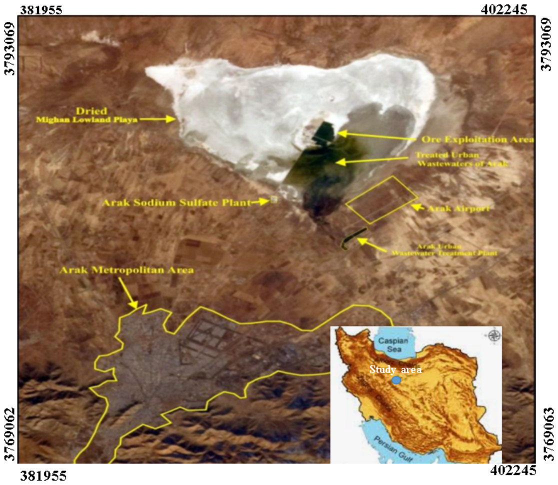
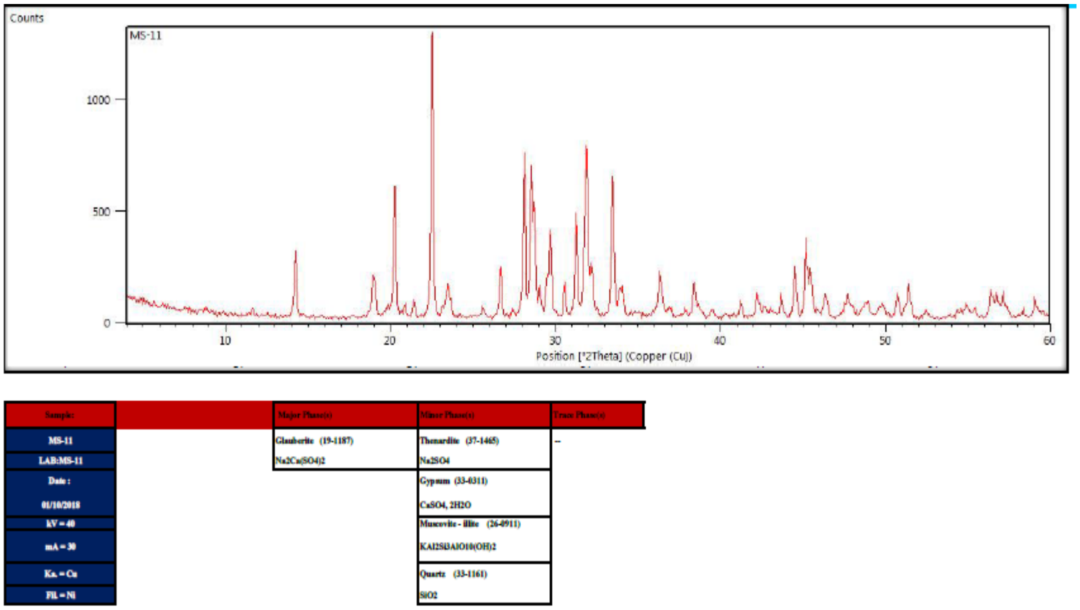


Figure 3. Arak city treatment plant to Mighan Arak Lake located in the southeast half of the Lake

3.2. Methods

A total of 163 boreholes, each with a depth of 20 meters, were drilled in the Mighan Arak Lake, which included both the lake and its islands. The cores discovered from these boreholes have been subjected to mineralogical analysis using X-ray diffraction (XRD) method in a laboratory environment. This analysis aimed to quantify the primary minerals present, including sodium sulfate (Mirabilite and Glauburite), along with other associated minerals (Figure 4). In addition, to facilitate the identification of sedimentary facies and determine the ratio of Glauburite to Mirabilite throughout the region, four borehole profiles were constructed and overlaid on a surface map, oriented in different directions. The surface water level was monitored and recorded in different years (from 1980 to 2016). The sodium sulfate extraction site was also identified and assessed for potential concerns, such as excessive water drainage into the extraction pond. Several corrective measures were proposed to reduce these issues and increase the efficiency of the sodium sulfate extraction process.



Sample:		Major Phase(s)	Minor Phase(s)	Trace Phase(s)
MS-11		Glauberite (19-1187)	Thenardite (37-1465)	--
LAB:MS-11		Na2Ca(SO4)2	Na2SO4	
Date : 01/10/2018			Gypsum (33-0311) CaSO4, 2H2O	
kV = 40			Muscovite - illite (26-0911)	
mA = 30			KAl2Si3AlO10(OH)2	
Kα = Cu			Quartz (33-1161)	
Fil = Ni			SiO2	

Figure 4. XRD analysis of a homogenized and representative sample of extracted ore

5. Results

5.1. Arak Mighan sodium sulfate deposit

The topographical map of Mighan Lake indicates a height difference of approximately 5 meters across the area, with no significant variations in elevation. The lowest point is located in the center of the southern half of the lake, at an elevation of 1,657 meters, while the majority of the area generally maintains an elevation of 1,661 meters. To gain a better understanding of the surface elevations of Mighan Lake, both before and after the extraction of sodium sulfate, it is essential to depict the surface topography of the area as it was in 2001.The extension and subsidence of Mighan Lake occur in a northwest-to-southeast direction. The elevation gradient is steeper in the northern (Dehnamak village) and southern (Mobarakabad, Tareh Mazd, and Mighan villages) regions, as compared to the eastern (Airport) and western (Davoodabad) sections.

Lithological data from 163 boreholes were analyzed using two-dimensional modeling (Figure 5) to investigate the variation in lithology, changes in the concentrations of Glauberite and Mirabilite, and the impact of extraction ponds on the groundwater of Mighan Lake. Two distinct facies detrital and evaporitic were identified within the lake's area. The detrital facies are primarily composed of sand, silt, and clay, which were deposited during the wet season by floods from nearby rivers feeding into the lake. When these deposits are deep and situated outside of the excavation zones, they are referred to as gangue. The detrital sediments are largely made up of quartz, muscovite, and clay, with clay minerals such as Illite, chlorite, kaolinite, vermiculite, and Smectite present in varying abundances. The distribution of these clay minerals within the current lake sediments provides insights into the climate and weathering patterns of the source region [26].

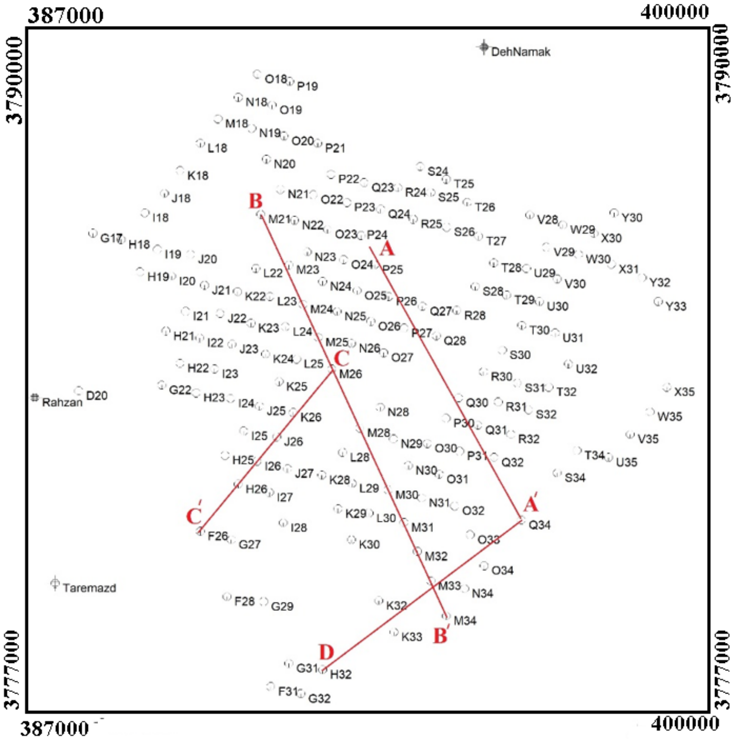
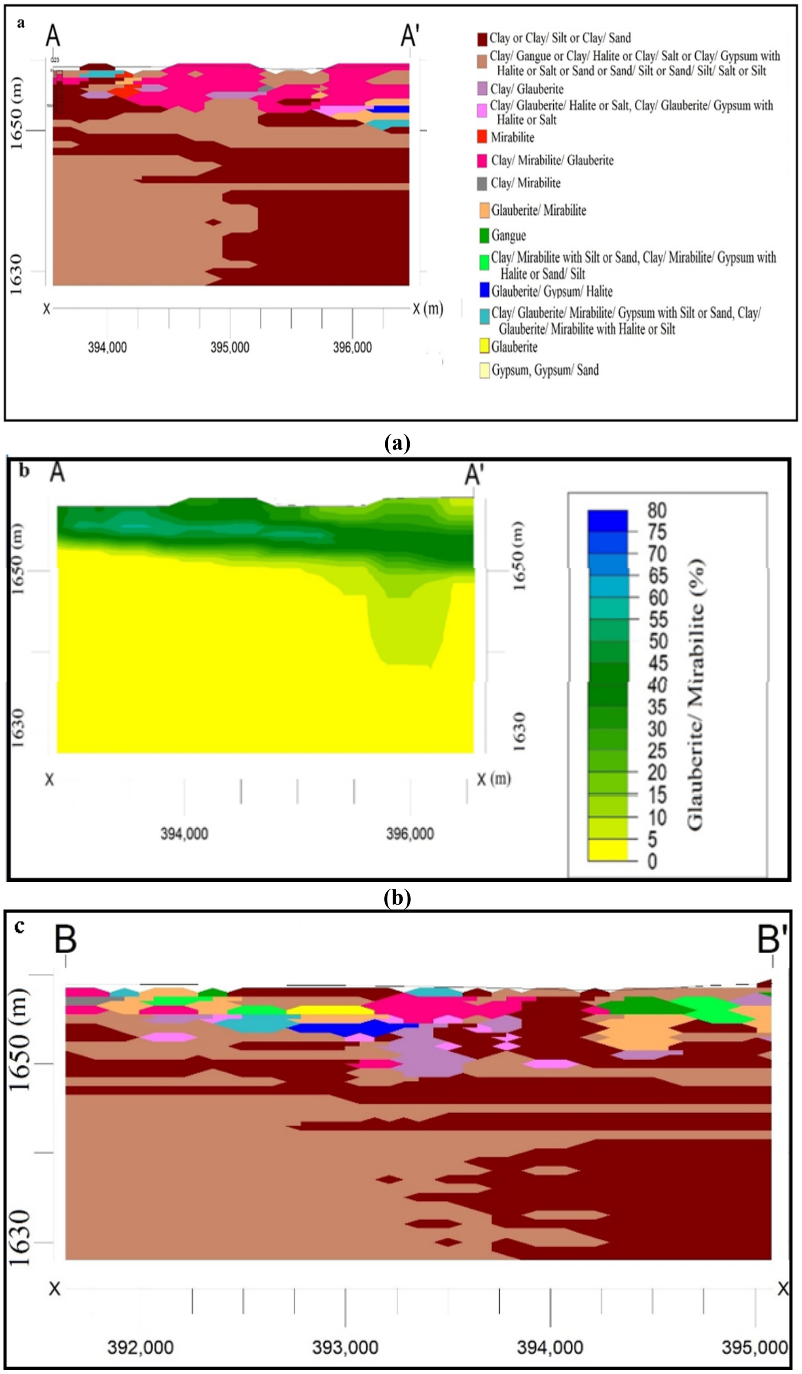


Figure 5. Location map of vertical sections among lithological boreholes in Arak Mighan Lake

The evaporitic facies appear in two forms: pure and mixed evaporate minerals (Figure 6). The pure evaporate facies consist of crystal layers ranging in thickness from 10 cm to two meters, and include minerals such as sodium sulfate (Glauberite, Thenardite, Mirabilite, and Eugsterite), magnesium sulfate (hexahydrite and starkeyite), calcium sulfate (bassanite and gypsum), calcium carbonate (Calcite), Iron sulfate (Amarantite), and sodium chloride (halite). These facies formed under dry conditions, with minimal influence from flooding.

Most of the evaporate units are a combination of detrital and evaporate materials, manifesting as mud, silt, and sand sediments mixed with Mirabilite and Glauberite. These two rock types serve as the primary raw materials for sodium sulfate production at the Arak sodium sulfate plant. Additionally, there are mixed rock types that include mud, silt, sand, gypsum, anhydrite, Glauberite, Mirabilite, and halite. These mixed rock types formed in an environment, where evaporate units were being deposited and detrital material was introduced by flooding [4]. The total thickness of the pure and mixed evaporitic rock types is approximately four meters, and they account for 20% of the raw materials utilized at the Arak Sodium Sulfate Plant. Below this depth, the deposits consist solely of green, yellow, red, and black mud rock types.

An impure Glauberite-Mirabilite layer, with a maximum thickness of 9 meters, is observed across four cross-sections at depths ranging from 1,659 to 1,649 meters. The most extensive distribution of this impure layer is noted in the western, southern, and northwestern regions, at depths between 1,655, and approximately 1,660 meters (Figure 6a, b). Pure Glauberite deposits are identified in boreholes O27 and M26 at levels between 1,653 and 1,656 meters, with thicknesses varying from 0.5 to 1 meter. The highest concentration of Glauberite is found along section BB', extending from the central to the western parts of the study area, particularly near boreholes O27 and M26, where pure Glauberite is located (Figure 6c, d). The cross-sections also reveal the lenticular shape of the Glauberite deposits (Figure 6b, d, f, h).

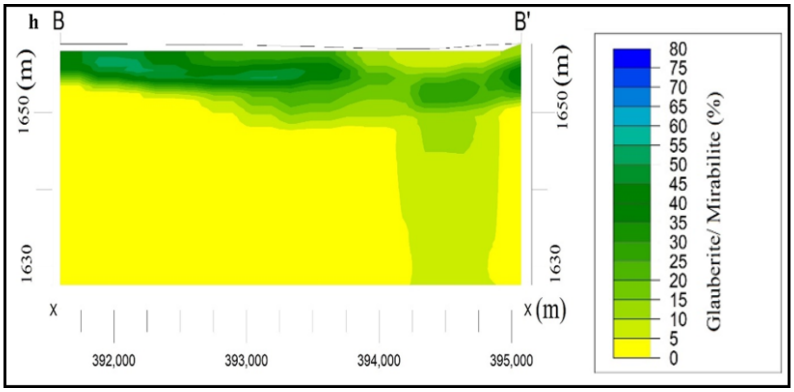


(a)

(b)

(c)

Figure 6. Two-dimensional cross-sections of lithology and percentage of Glauberite and Mirablite in Arak Mighan Lake



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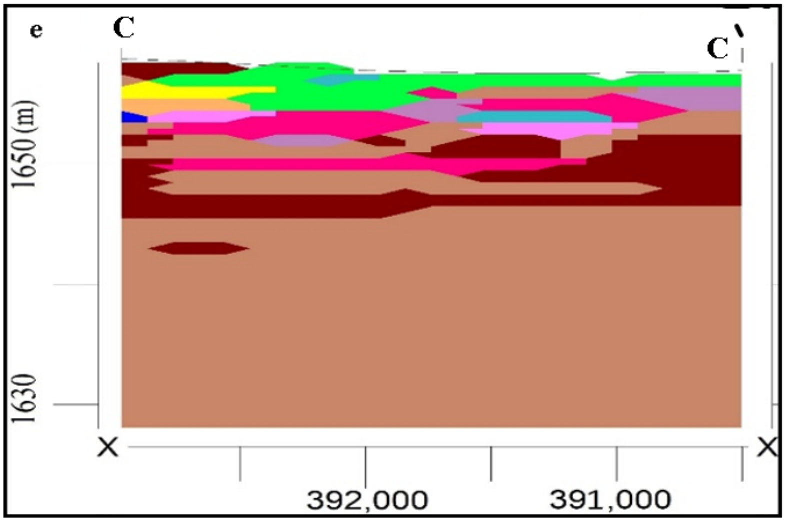

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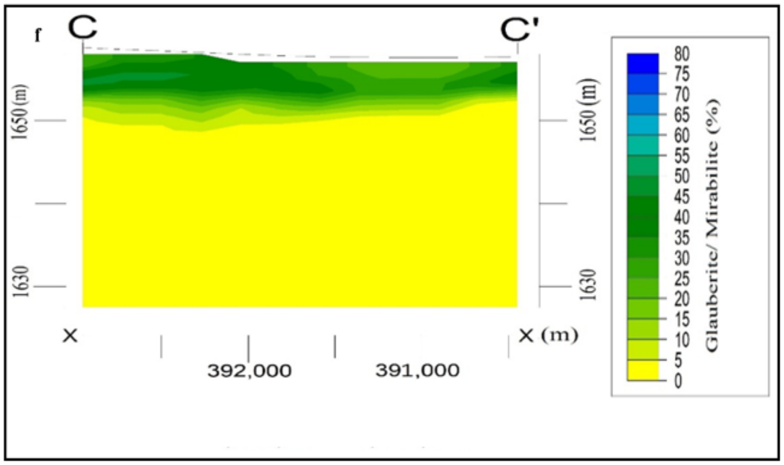
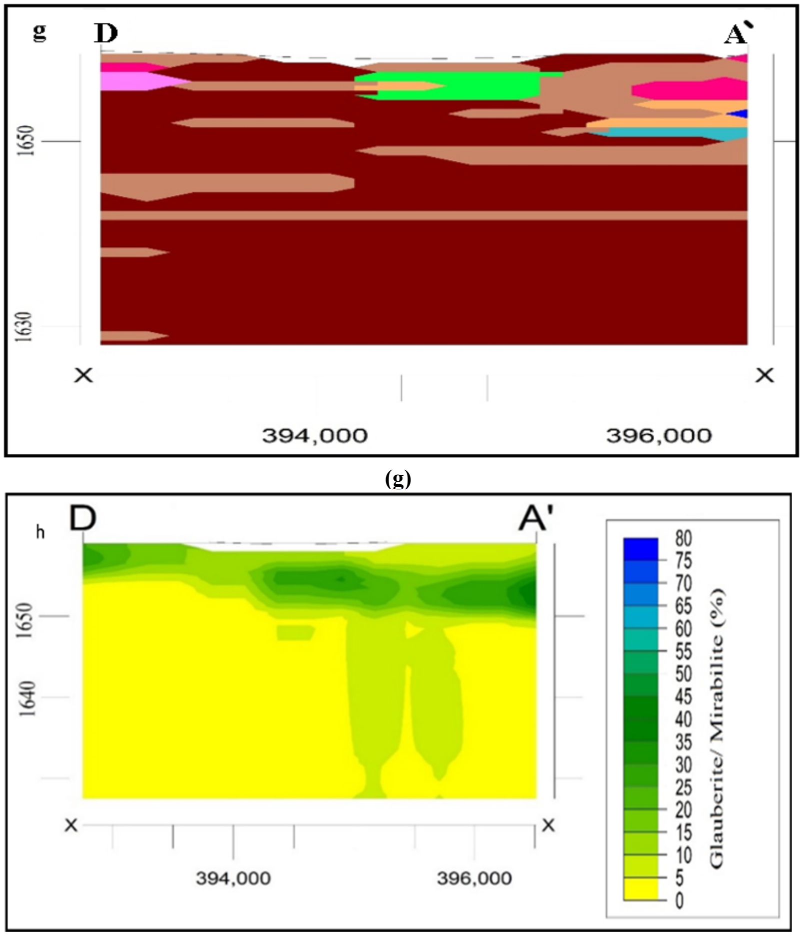


(f)

Continuous of Figure 6. Two-dimensional cross-sections of lithology and percentage of Glauberite and Mirablite in Arak Mighan Lake



(g)

(h)

Continuous Figure 6. Two-dimensional cross-sections of lithology and percentage of Glauberite and Mirablite in Arak Mighan Lake

At a depth of 1,648 meters, no minerals, either pure or impure, are detected. However, in the depth plan map at 1,649 meters, Glauberite with clay impurities is evident, primarily in the central to eastern portions of the region. As the depth increases, both the extent and variety of impurities associated with Glauberite become more pronounced in the lower-depth plan maps. Depth plan maps for levels between 1,655 and 1,658 meters confirm the presence of pure Mirabilite, primarily near the central parts of the region. Additionally, plan maps at levels 1,653 and 1,656 meters indicate a minor presence of pure Glauberite.

An examination of Fig. 6 highlights an association of Glauberite and Mirabilite, along with clay impurities, in two distinct sections: one at depths between 1,658 and 1,649 meters, and the other between 1,650 and 1,649 meters. From depths of 1,658 to 1,655 meters, Mirabilite is found in conjunction with clay and various impurities, including gypsum, halite, and occasionally sand and silt, with a maximum thickness of 3 meters. Similarly, between depths of 1,659 and 1,651 meters (Figure 7), Mirabilite is associated with Clay, Gypsum, Halite, Sand, and Silt.

Lithological diagrams and gradations have been prepared for a 370 km² area, encompassing depths of up to 30 meters, from an elevation of 1,665 to 1,628 meters (Figure 8). These diagrams represent different geographical directions, and are based on lithological data from borehole cores. Evidence of impure Glauberite is observed at the surface between depths of 1,665 and 1,656 meters, with a maximum thickness of 9 meters, entirely covered by waste material (mud) in all diagrams.

Beneath the surface clay-tailings layer, a substantial layer of impure Glauberite is present between depths of 1,656 and 1,650 meters, with a maximum thickness of 6 meters. This layer lies interbedded with clay, gypsum, and Mirabilite. From a depth of 1,650 to 1,634 meters, the area is characterized by layers of pure and impure clay, interspersed with sand, silt, and gypsum, forming a

16-meter-thick section. Below this, from a depth of 1,634 to 1,628 meters, a cohesive layer of very thick and sticky clay, with a maximum thickness of 6 meters, is observed.

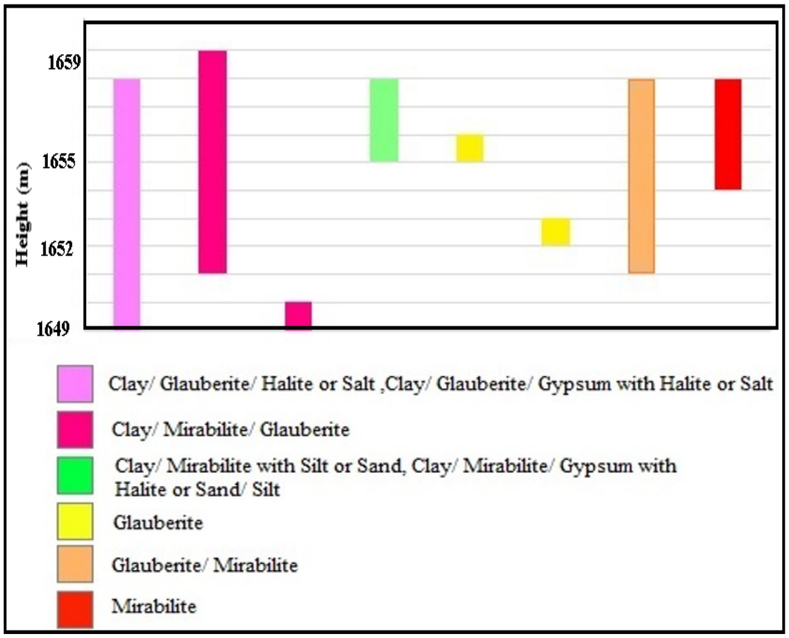


Figure 7. Scatter chart of Glauberite and Mirabilite minerals in pure form with different impurities at different heights of Arak Mighan Lake

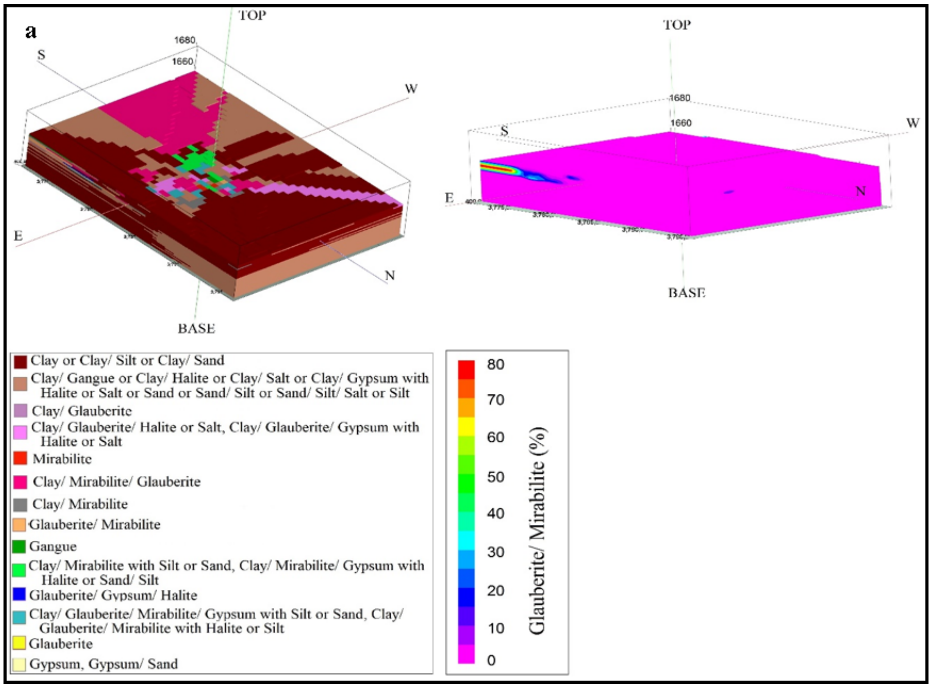


Figure 8. Three-dimensional model of Mighan Lake sodium sulfate deposit in the four main geographical directions N, S, W, and E

The Glauberite-Mirabilite concentration ranges between 2% and 32%, with an average of 25%, as illustrated in the Glauberite-Mirabilite concentration model diagram. The concentration increases progressively from north to west, peaking at 42% in the western region. Glauberite concentrations, varying from 2% to 32% and averaging approximately 25%, are also highest in the west. A similar trend is observed from the west to the south, where Glauberite concentrations increase up to 32% in both deep and shallow sections. In the southeastern region, Glauberite-Mirabilite concentrations of about 32% are observed over a large area. In contrast, the northeast and northern regions exhibit Glauberite concentrations ranging from 22% to 25%

Analysis of the mineral distribution on the surface of Mighan Lake, as illustrated in the surface concentration map, indicates that the majority of the lake's surface in the northern and northwestern regions contains a Glauberite-Mirabilite concentration of 0–5%. In contrast, the central to southern areas of the lake commonly exhibit concentrations ranging from 15–35%. Notably, a small area in the southwestern part of the lake shows concentrations reaching as high as 55% (Figure 9).

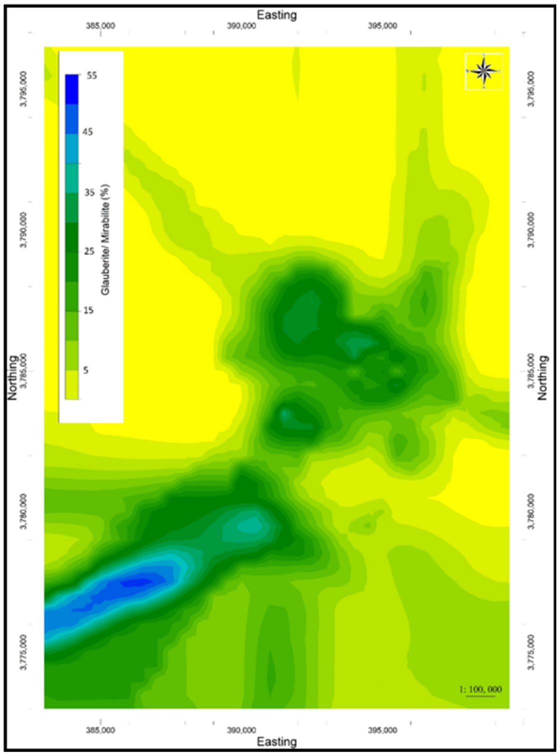


Figure 9. Qualitative concentration map of Glauberite-Mirabilite on the surface of Mighan Lake

5.2. Effect of sodium extraction on the groundwater level sulfate

The Arak Mighan Lake is one of the largest natural sodium sulfate reserves in the Middle East, encompassing an average area of 110 km². Sodium sulfate deposits in Mighan Lake consist of various compounds, the most significant being: Then Tenardite at approximately 100%, Mirabilite at about 44%, and Glauberite at around 51%. The thickness of the sodium sulfate deposits ranges from 0.5 to 1.2 meters, with an average concentration of 22%. Surface geology maps have been developed based on the presence of Glauberite, Mirabilite, mud, silt, and a mixture of Mirabilite-Glauberite, clay, and gypsum (Figure 9).

Within the exploitation area of the sodium sulfate plant, small and large mineral deposits are being extracted. Approximately one-third of these deposits can be identified in the northwest region and outside the exploitation area. These minerals, which are highly soluble in water, are also evident on the surface in the southwest, central, and scattered northeastern parts of the exploitation area. The majority of the Mighan Lake surface comprises clay minerals. The dominant minerals, both on the surface and at depth, include Mirabilite-Glauberite, accompanied by impure clay and gypsum. These minerals are superficially buried in the center and southwest regions, while in the southeast areas, they are buried deeper under clay overburden. Mirabilite, often accompanied by small amounts of waste minerals, forms circular halos around the central island in areas near the surface. Impure Glauberite deposits are predominantly located at depth in the center of the island, whereas impure Mirabilite is more abundant at the surface.

Profiles AA', BB', and CC' were created to evaluate the current extraction conditions of the sodium sulfate layer and their impact on the mineral lithology, gravitational water flow of the overburden wall, and groundwater levels (Figure 10). These profiles span from areas outside the extraction zone to the interior, encompassing both pre- and post-extraction conditions. Beneath the dark clay layer on the mining floor (approximately 2–3 meters below the mining base), an impure Glauberite layer is present. The sodium sulfate mineral layer persists along the walls of all extraction spaces. As gravitational water from sources such as the treatment plant, atmospheric precipitation, rivers, and sewage drains into the extracted pits, sodium sulfate salts dissolve at varying rates and accumulate within the excavated areas.

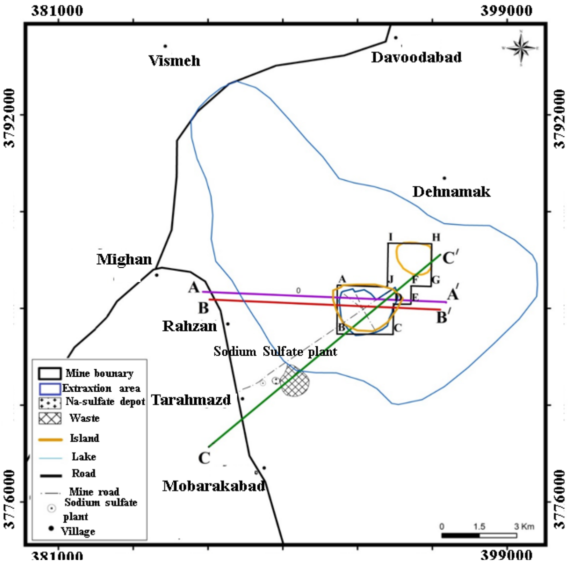
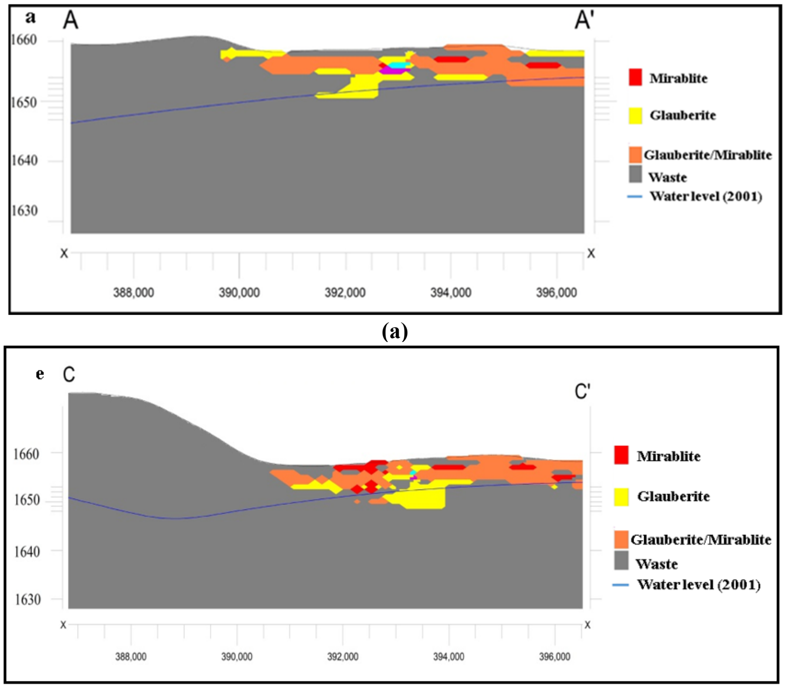


Figure 10. Location of sections AA', BB', and CC'

In section BB', a higher concentration of sodium sulfate salts was identified compared to section AA' (Figure 11a). As a result, the evaporate deposits primarily consist of Mirabilite and Glauberite (Figure 11b), most of which were removed during extraction (Figure 11c). The mining activities also resulted in clay sediment deposits on the extraction floor.

Section CC', a vertical profile, extends from the area between Tarmazd and Mobarakabad villages to the east of the sodium sulfate plant, crossing the plant's tailings dam, and encompassing the first mined island and the second unmined island. According to modeling results, the elevation levels of Tarmazd and Mobarakabad villages are approximately 5–10 meters higher than the natural topographic level of the lake. The primary minerals in this area include Mirabilite, impure Glauberite, and impure Mirabilite. Small amounts of impure glauberite are also observed along the walls and at the bottom of the extraction layer (Fig. 11f). The majority of the Mirabilite-Glauberite deposits, interspersed with impurities, are found in the unmined space between the first and second islands.



(a)

(c)

Figure 11. Geological section of sodium sulfate before and after extraction at different stages and groundwater levels

5.3. Impact of climate change on mining extraction and urban pollution

The study of climatic variables including precipitation and evaporation at various meteorological stations such as Davoodabad, which significantly influences the climate of Mighan playa in Arak, reveals critical insights into the region's hydrological dynamics (Figure 12). By analyzing satellite imagery and GIS data from 1984 to 2016, the research work highlights the interplay between climatic changes and water levels in Mighan playa. The findings indicate that fluctuations in rainfall, evaporation, and ambient temperature are predominantly driven by regional climatic shifts. Although the lake's water levels have historically experienced significant variations even prior to mining activities, the overall trend has been a gradual decline. Notably, the water surface in the central island area showed a sharp increase post-2001, while the extraction ponds exhibited a declining trend.

The total water area in Mighan playa has not displayed anomalous behavior, suggesting that the reduction in water levels is largely influenced by the prevailing climatic conditions. By 2017, the extraction ponds accounted for approximately 1.7% of the total water surface, a relatively minor proportion. Comparative analysis of precipitation and evaporation data from Davoodabad station, the closest to Mighan playa, indicates no significant correlation between these climatic factors and the expansion of extraction ponds from 2001 to 2017.

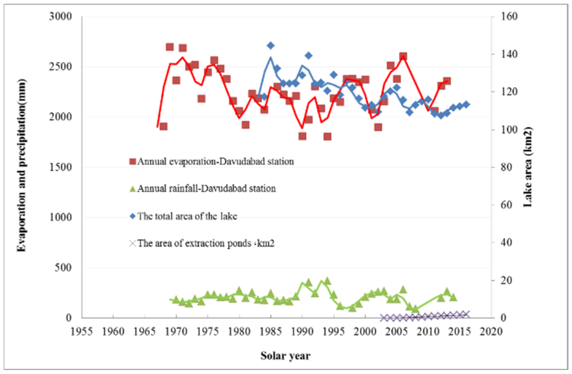


Figure 12. Comparison of changes in evaporation rate, rainfall, total area of the lake and extraction Ponds during different years [37].

A critical concern is the release of treated urban wastewater from Arak, which began before the mining operations. This has led to increased pollution levels over the years, exacerbated by the natural decline in the lake's water levels (Figure 13). The rapid rise in pollution from urban sewage suggests that, in the near future, contamination could spread across the entire lake and potentially beyond provincial and national borders. To mitigate this, it is recommended to install advanced treatment facilities to repurpose contaminated water for industrial and agricultural use, thereby preventing further pollution spread by migratory birds.

Considering the changes in the elevation of the groundwater level in the center of the mining island and comparing it with the changes in the water level of underground wells within a radius of about 6 km from the villages of Tarmazd and Rahzan, it has been shown that over the years, the changes in the groundwater level of the mining area have been consistent with the changes in the surrounding areas under the influence of weather conditions (Figure 14). In all these conditions, the groundwater level in the center of the extraction island (ponds) was higher than the surrounding areas, and this issue can naturally be related to the hydrographic focus of all surface and groundwater in the center of Meghan Island, Arak. In addition, due to the presence of the lowest layer of water-rich clay on the groundwater level of the center of the island and the absorption of water saturation in the clay and the effect of its capillary properties, nature usually shows its excess as evaporation in hot conditions of the year to balance the accumulation of water with the dry air around it. Due to the larger population, different soil and alluvial rock types, and the use of overcapacity agricultural water wells, the groundwater level in the village of Tarmazd is lower than in the village of Rahzan, and both are even lower than the center of the island.

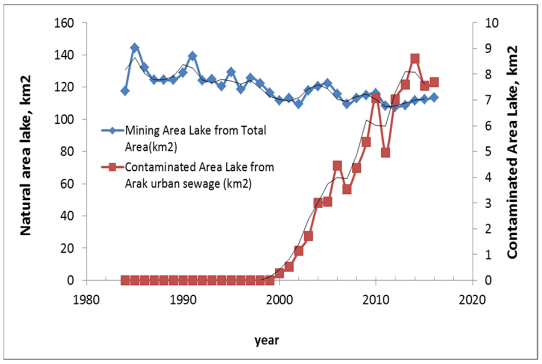


Figure 13. Changes in the total area of the catchment (lake) of Mighan desert compared to the area of pollution resulting from Arak urban sewage entering Mighan desert during the last 36 years (from 1980 to 2016) [37]

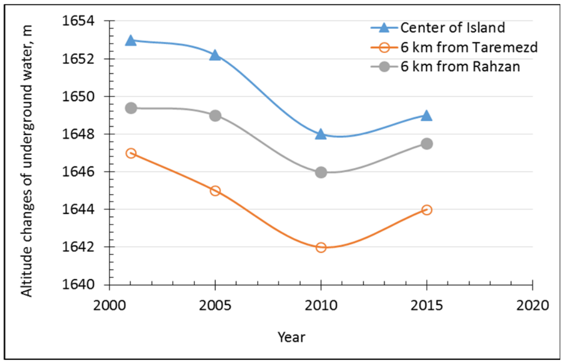


Figure 14. Changes in groundwater elevation levels over different years in the center of the extraction island and surrounding areas

In general, the natural restoration of the area occurs through the filling of mining voids after extraction and the rise of water levels during the winter and spring seasons. The center of the island is the lowest point of the Mighan Desert, and due to salt extraction and the creation of mining pits, the drainage of surface water from surrounding areas such as Arak, Farahan, and the Hezardarreh Mountains is accelerated toward the center of the island. This process intensifies the transport of sediments from the surrounding regions, leading to faster sedimentation and natural restoration at the island's center.

This phenomenon significantly enhances the efficiency of drainage for seasonal rivers in nearby areas including Arak, and improves the safety of access roads, particularly during flood seasons. By facilitating quicker water drainage and sediment deposition, the system not only aids in the natural rehabilitation of the desert ecosystem but also mitigates the risks associated with flooding, ensuring safer conditions for transportation and infrastructure in the region.

In summary, the study underscores the significant impact of climate change on water resources in Mighan playa, highlighting the urgent need for sustainable water management practices to address both declining water levels and escalating pollution.

5.4. Current method of extracting deposit from Arak Mighan Lake

The extraction process for sodium sulfate begins with the removal of the soil overburden from the sodium sulfate layer using specialized extraction machinery. Careful attention is given during this stage to prevent the mixing of tailings with the deposit, ensuring the purity and concentration of the extracted material. After the overburden is cleared, the area is divided into strip-shaped sections called extraction zones. Each zone is designated as a work front for mineral extraction (Figure 15a). Before removing the mineral layer, brine present in the mine is directed into a designated extraction pond. To prevent water discharge into the extraction zones, barriers constructed from mineral tailings are erected around the mining front areas (Figure 15b). Subsequently, a coordinated use of mechanical excavators, trucks, and loaders is deployed to extract the sodium sulfate layer. The excavated material is loaded onto trucks and transported to a storage depot near the Sodium Sulfate plant for further processing. Over time, the balance in hydraulic levels, combined with the inflow of sewage water from the Arak sewage treatment plant in the southern region, leads to the transformation of extracted areas into water ponds, particularly in the central part of the lake and islands (Figure 15c). These water ponds, along with water leakage during the extraction process, present significant challenges for the sodium sulfate plant.

To address the issues of water leakage and the formation of water ponds, several solutions have been proposed [37]:

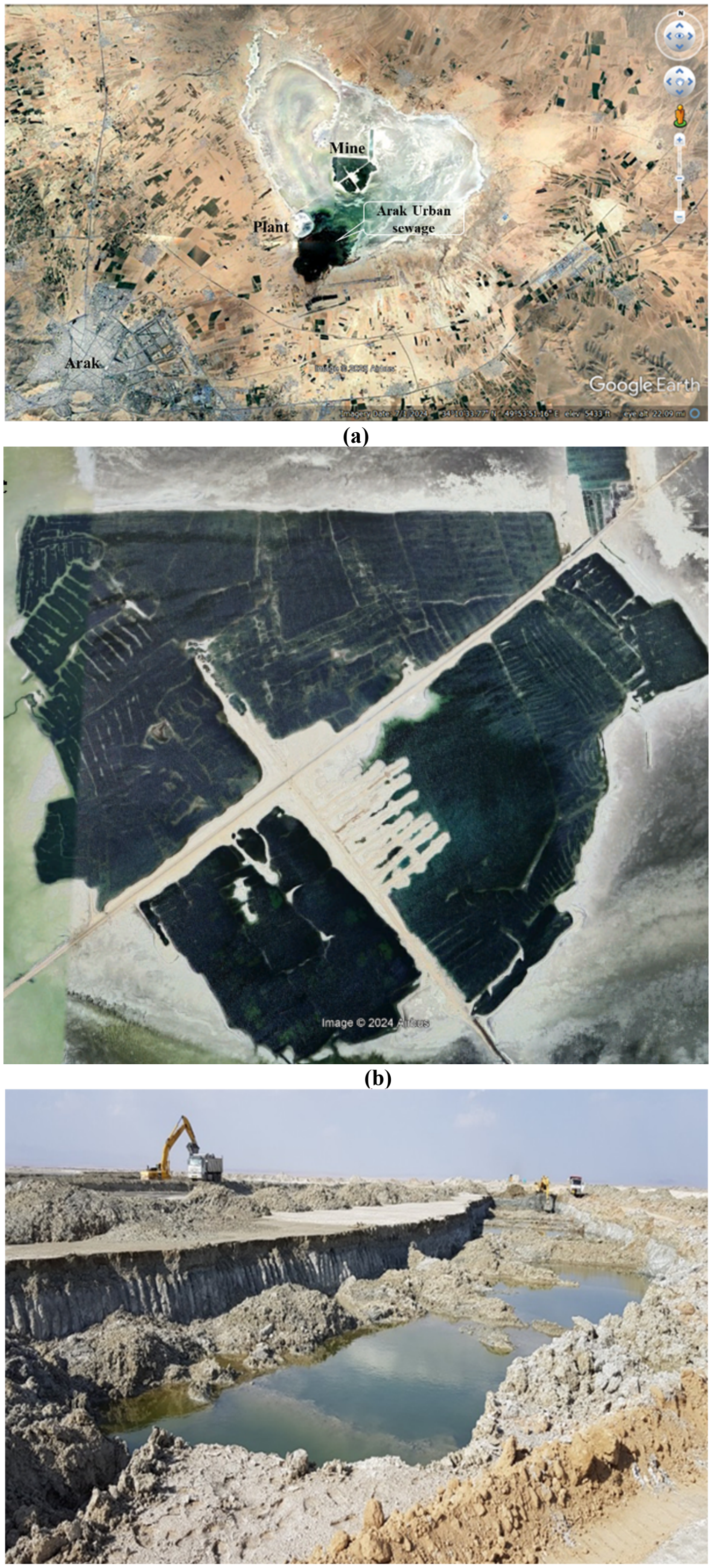
(a) Improved barrier systems: Enhancing the design and durability of tailings-based barriers to prevent water ingress into extraction zones.

(b) Water management strategies: Implementing efficient water drainage and diversion systems to regulate subsurface water levels and minimize flooding in extracted areas.

(c) Hydraulic balance monitoring: Regular monitoring and adjustments of hydraulic levels to ensure stability in the areas surrounding the extraction zones.

(d) Sewage flow management: Coordinating with the Arak sewage treatment plant to optimize sewage discharge patterns and reduce unintended contributions to water pond formation.

(e) Rehabilitation measures: Developing and implementing land reclamation techniques for extracted areas to prevent long-term ponding and enhance the environmental sustainability of the site.



(a)

(b)

(c)

Figure 15. a) An overview of the entry of Arak urban wastewater into the mining area of Mighan sodium sulfate; b) The sodium sulfate extraction pond and the residual sludge in it; c) Sodium sulfate extraction ponds [37]

These strategies aim to mitigate the operational and environmental challenges associated with sodium sulfate mining, ensuring the continued efficiency and sustainability of extraction activities.

To mitigate operational challenges such as water leakage and pond formation during sodium sulfate extraction, the following strategies have been proposed and are recommended for implementation:

(a) Creation of a new pool with retaining walls: A new pool should be constructed adjacent to the mine to accommodate pumped water. This pool must be surrounded by a robust retaining wall to contain the water effectively and prevent overflow into nearby ponds.

(b) Spraying extractive brine into preparation pools: The brine extracted during mining operations should be sprayed into designated preparation pools. This process will aid in producing dense brine, which can be further utilized in downstream processes.

(c) Concentrated brine transfer: Concentrated brine should be transferred either through pumping systems or by tanker trucks to the storage pool located near the Sodium Sulfate plant. This approach minimizes the need for extensive extraction by leveraging the brine's concentration for solar pooling and crystallization, particularly during the winter season.

(d) Pit leaching and pumping to solar pools: Leaching pits should be used to dissolve sodium sulfate deposits effectively. The resulting brine should then be pumped directly to solar pools near the Sodium Sulfate plant for further processing and evaporation.

(e) Water recycling and freshwater reintroduction**:** Recycling water from pools and the sodium sulfate plant should be prioritized. Unsaturated fresh water can then be returned to the mine to enhance mineral dissolution and maintain a balanced water level within the mine, ensuring sustainable operation.

(f) Continuous pumping of plant tailing slurry: Continuous pumping of tailing slurry from the Sodium Sulfate plant to the extraction ponds (Figure 16) will assist in managing waste material and reducing environmental impact.

These integrated strategies aim to improve the efficiency of sodium sulfate extraction, while addressing water management challenges and minimizing environmental consequences.

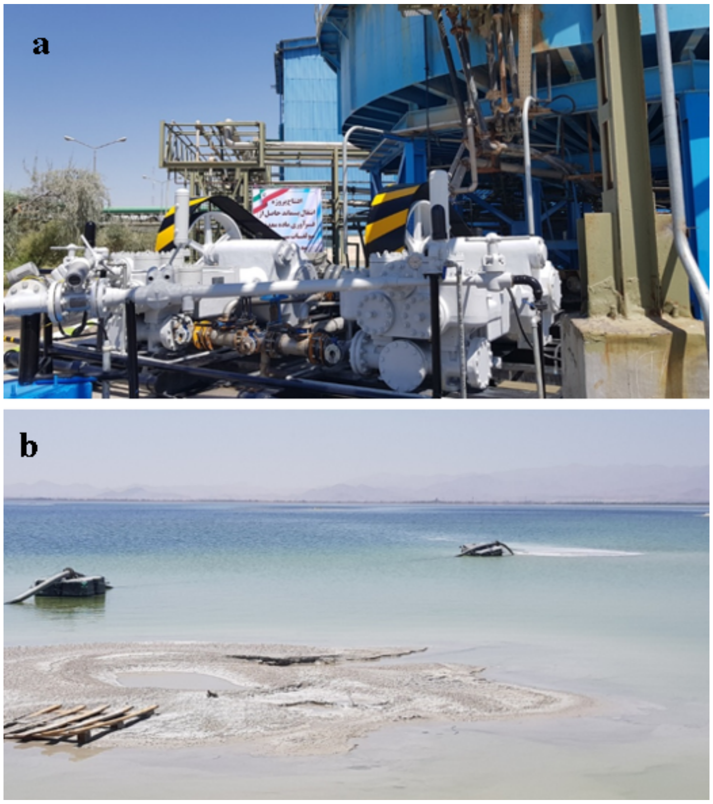


Figure 16. a) Pumping system (one working pump and one reserve pump) from the bottom of the washed mud thickener, b) Pumping output of tailings slurry in the old mined basins of Mighan Lake

5.5. Improving and rebuilding moisture line

Based on limited sampling conducted inside and outside the extraction area, the approximate moisture level line is shown in Figure 17, In order to reconstruct and prevent evaporation and correct the moisture level line, the waste from the sodium sulfate processing plant is returned to the extraction ponds and then leveled and reconstructed by machinery such as excavators, loaders or bulldozers if necessary. This has caused environmental brines to absorb, recrystallize, and absorb water within the clay as soon as possible after the mineral is extracted from the ponds, in addition to regenerating the extracted space. With the onset of the rainy season and the rise in water levels, the moisture line is gradually restored.

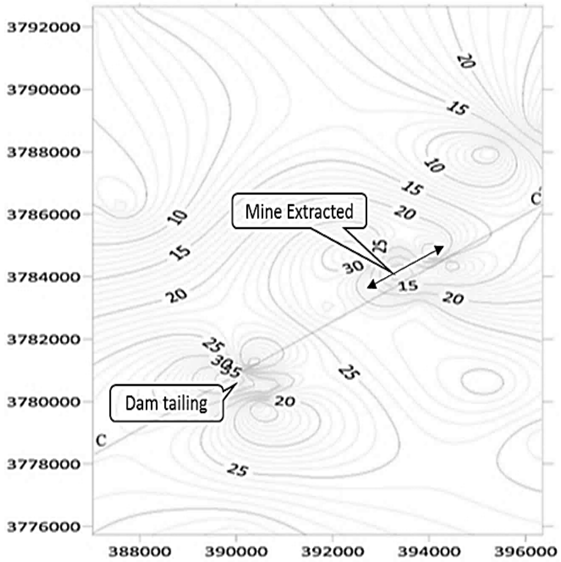


Figure 17. Humidity changes at different coordinate points inside and outside the sodium sulfate extraction area of Playa Mighan, Arak

6. Discussion

The extraction of evaporate minerals including sodium sulfate from lakes presents significant challenges [27]. In Iran, sodium sulfate is primarily extracted from soil deposits in lakes such as Namak Lake, Maharlu Lake, and Hoz Sultan Qom Lake [28]. In contrast, in other regions such as Canada, North America, South America, and China, sodium sulfate is commonly extracted from brine [20]. Brine extraction involves pumping brine from boreholes and transferring it to ponds, where evaporation and cooling during dry and wet seasons facilitate crystal accumulation [18, 19, and 29]. This method requires a substantial volume of high-concentration brine [30].

Evaporate deposits are composed of various minerals including sodium sulfate, magnesium sulfate, calcium sulfate, calcium carbonate, iron sulfate, and sodium chloride [31]. The specific minerals deposited at the pond's bottom are determined by the brine concentration and the rock source [32]. The water sources for most lakes include surface water, groundwater, and direct precipitation [33, 34]. Extracting sodium sulfate from sediment is significantly more expensive than brine extraction. Evaporate minerals in sediments are typically crystalline, thinly interbedded with mud, or mixed with it, necessitating the use of processing plants for separation [17]. These plants often employ specialized systems to separate evaporate minerals and may also produce other valuable minerals through conversion technologies. Arak Mighan Lake, a significant source of sodium sulfate in Iran, faces numerous environmental and operational challenges due to its proximity to Arak city. Key issues include:

- **Environmental and hydrological concerns:**
  - Seasonal drying of the lake [35].
  - Rapid water leakage into extraction ponds and stagnant water ponds [36, 37].
  - Imbalance in water levels to the islands.
- **Operational constraints:**
  - Non-utilization of brine resources by the sodium sulfate plant.
  - High moisture content (up to 40%) in the extracted deposits, requiring additional drying time near the plant.
- **Biodiversity and tourism impacts:**
  - The presence of migratory birds during wet seasons and the tourism potential of Mighan Lake.
  - Interactions with NGO institutions advocating for environmental conservation.

Despite these challenges, the most critical issue is the drainage of gravitational water from the lake's walls to the extraction site, which complicates mining operations and transportation. Water from the Arak treatment plant is channeled to the lake’s southern edge, and subsequently into extraction ponds, where depths exceed three meters in most cases. Extracted deposits, with high moisture content, are stored near the plant to undergo natural evaporation and gravity-driven leachate outflow before processing. In conclusion, optimizing water management, enhancing brine utilization, and addressing environmental challenges are critical for sustainable sodium sulfate extraction from Mighan Lake.

7. Conclusions

Preliminary borehole explorations have uncovered an impure Glauberite layer beneath the dark clay at the bottom of the mining area, situated approximately 2 to 3 meters above the current groundwater level. This mineral layer extends as sodium sulfate salt along the walls of all extraction spaces. The accumulation of sodium sulfate occurs at varying rates as gravity-driven water, including wastewater, precipitation, river water, and dissolved brine, drains into the extraction spaces. This presents a potential opportunity to recover sodium sulfate from the brine, although further investigations are necessary to assess the feasibility and extent of this resource.

The existing method for extracting sodium sulfate salt at Mighan Lake involves open-field mining within a semi-aquatic environment, operated by the sodium sulfate plant. However, the presence of water in the extraction spaces complicates the mining process, and decreases efficiency. In light of these challenges, there is a pressing need to redesign the extraction method to better align with the semi-aquatic nature of the environment and improve overall extraction efficiency, particularly by incorporating the use of brine. To address the challenges posed by the current method, a comprehensive reconstruction of the mining process is recommended. Key solutions include the creation of a winter deposit for Glauberite extraction and the establishment of a brine winter reserve to enhance sodium sulfate recovery while improving environmental management.

(a) Winter deposit for Glauberite extraction: A key proposal is the construction of a winter deposit for Glauberite extraction near the plant. This deposit would help manage the operational challenges associated with water interference during the extraction process. By utilizing the winter months, when water levels may be more stable and manageable, the deposit would enable more efficient mineral extraction and allow for the accumulation of sodium sulfate in a controlled environment. This strategy would facilitate the reconstruction of the mining process, pending approval from relevant government institutions.

(b) Brine winter reserve: In addition to the winter deposit, the construction of a brine winter reserve is proposed to support the extraction process. This reserve would increase the supply of aqueous sodium sulfate salt, enabling more efficient extraction. Furthermore, the reserve would facilitate the redistribution of water from the extraction pond to surrounding areas, thereby improving the local hydrological balance. This approach would also address environmental concerns by managing water flow and minimizing disruptions to the surrounding ecosystem.

The current method of sodium sulfate extraction at Mighan Lake faces significant challenges due to water interference during the mining process. However, the proposed solutions, including the construction of a winter deposit for Glauberite extraction, the establishment of a brine winter reserve, offer promising strategies to optimize mineral extraction and improve environmental management. By adopting these strategies, the extraction process can be better aligned with the semi-aquatic environment, increasing efficiency and sustainability while minimizing environmental impact. Further investigations and regulatory approvals will be necessary to proceed with these plans, but these initiatives hold potential for enhancing both the operational efficiency and ecological stability of the area.

Based on the studies conducted, it is necessary that in mining operations, in addition to the appropriate efficiency of extracting the target mineral and economic issues, issues related to compliance with environmental indicator standards and the broad consequences of sustainable resource management and its protection begin at the time of activity and continue continuously until the end of mining and even years after that, and appropriate reconstruction be carried out.

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دریاچه شور میقان اراک

چکیده

در این مقاله استخراج سدیم سولفات (Na_2SO_4) از دریاچه میقان اراک در استان مرکزی بررسی شده است. به تعداد ۱۶۳ حلقه گمانه تا عمق ۲۰ متر حفاری و رسوبات ناهمگن آن غالباً شامل کانی های گلوبریت ($Na_2Ca(SO_4)_2$) و میرا بیلیت ($Na_2SO_4\cdot10H2O$) بوده که غلظت‌های متوسط سولفات سدیم ۲۵ درصد (که در بازه ۲تا ۳۲ درصد متغیر است و در نواحی خاصی در جنوب غربی به ۵۵ درصد می‌رسد) است. سطح دریاچه عمدتاً با خاک رس پوشیده شده (۹۴ درصد) و در لایه‌های آن تناوب رخساره های تبخیری (گچ، هالیت و کانی‌های کربناته) وجود دارند. ورودی‌های فصلی آب به میزان ۸۰۰-۲۰۰ لیتر در ثانیه از تصفیه‌خانه فاضلاب اراک، به همراه گودال‌های استخراج به عمق ۳/۵ متر و زهکشی گرانشی، منجر به تجمع آب در برکه‌ها در بیش از ۲۵درصد از ناحیه جنوبی دریاچه شده و افت سالانه آب ۱۰-۵ درصد است. لایه‌های گلوبریت خالص (به ضخامت ۱-۰/۵متر) در عمق‌های ۱۶۵۳–۱۶۵۶ متر دیده می شوند که در تضاد با توالی‌های گلوبریت- میرا بیلیت ناخالص (تا ۹ متر) در عمق‌های ۱۶۴۹–۱۶۵۹ متر قرار دارند. برای کاهش این چالش‌ها، رویکرد مهندسی یکپارچه شامل پمپاژ شورابه‌ها به استخرهای تبخیر خورشیدی، استفاده از سیستم‌های پمپ دوقلوی مداوم برای مدیریت ته‌مانده‌ها، و پیاده‌سازی تعادل هیدرولیکی از طریق دیوارهای نگهدارنده و ذخایر شورابه‌های زمستانی پیشنهاد می شود. اقدامات اخیر کارایی استخراج را در نواحی با غلظت بالا به میزان ۴۲-۳۰ درصد افزایش می‌دهند. چنین شیوه‌های استخراج تطبیقی، که شامل شستشوی شوراب در محل و تصفیه پیشرفته فاضلاب است. به منظور تأمین ۷۰درصد از تقاضای سالانه سدیم سولفات در ایران از یک منطقه عملیاتی به مساحت ۸ کیلومتر مربع طراحی صورت گرفته و کاهش تخریب زیست‌محیطی را نیز به همراه دارند.

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