Assessment of shape changes subsidence and risk map by remote sensing and GIS in hyper-arid lands, Iran

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Abstract: *Land subsidence is a global phenomenon characterized by the gradual or sudden sinking of the Earth's surface, occurring with minimal horizontal movement. In Iran, this issue has been exacerbated by climatic and hydrogeological droughts, primarily due to excessive groundwater extraction for agricultural purposes. This study focuses on a 20 square kilometer area in the playa geomorphological facies of eastern Iran, where significant groundwater withdrawal has resulted in pronounced subsidence of varying forms and densities. In addition to groundwater depletion, factors such as meteorological droughts and wind erosion have necessitated government initiatives, including extensive tree planting programs using resilient species known as "Haloxylon" to control fine dust that called Haloxylon Lands. By analyzing satellite images from Google Earth spanning 2012 to 2024, we documented the deformation of the earth's surface, identifying critical factors influencing subsidence, including land use, geology, lithology, Haloxylon Lands, and fluctuations in water levels. Using ArcGIS for spatial analysis, we created a subsidence sensitivity map, revealing that linear subsidence accumulations tend to occur 1 to 3 kilometers from agricultural wells, evolving from linear to polygonal shapes over the past decade. The findings revealed that sinkholes 1 to 2 meters deep are situated near Haloxylon and less than 0.5 meters away, expanding in lithological structures with over 70% clay content and more salt layers. To mitigate playas' subsidence, we recommend implementing quantitative and qualitative management of agricultural wells, utilizing alternative water sources such as treated wastewater, monitoring hydro halophyte harvesting in saline clay aquifers, and reconsidering Haloxylon planting initiatives. Given the global prevalence of subsidence in arid regions, the strategies developed in this research can be adapted to manage subsidence risks in similar regions.*

Keywords: Hyper-Arid Lands, Groundwater, Satellite Images, ArcGIS, Subsidence, Risk Map

Introduction

Subsidence is a concerning global issue marked by the slow or sudden sinking of the Earth's surface, typically with little horizontal displacement (Galloway et al., 2018). This environmental threat considerably impacts infrastructure and ecosystems, especially in arid and semi-arid regions where water resources are heavily exploited for agricultural and human activities (Bawden et al., 2019). This study centers on Playa geomorphological features, prevalent in hyper-arid environments. These flat, low-lying areas experience intermittent flooding, followed by rapid evaporation that leaves behind distinct geological formations (Chen et al., 2020). The study focuses on an area of approximately 20 km² of playa in eastern Iran, identified as having the highest subsidence concentration through satellite imagery and field surveys. The main aim of this research is to analyze subsidence patterns within the playa while also creating a detailed subsidence sensitivity map. This map is based on assessments of various factors, including land use, lithology, vegetation density, and aquifer characteristics, offering essential insights for policymakers and land management authorities. By presenting actionable recommendations that emphasize groundwater resource management, alternative agricultural practices, and ongoing monitoring initiatives, this research enriches the broader discussion on sustainable development in hyper-arid regions and may serve as a framework for similar areas worldwide.

Literature Review

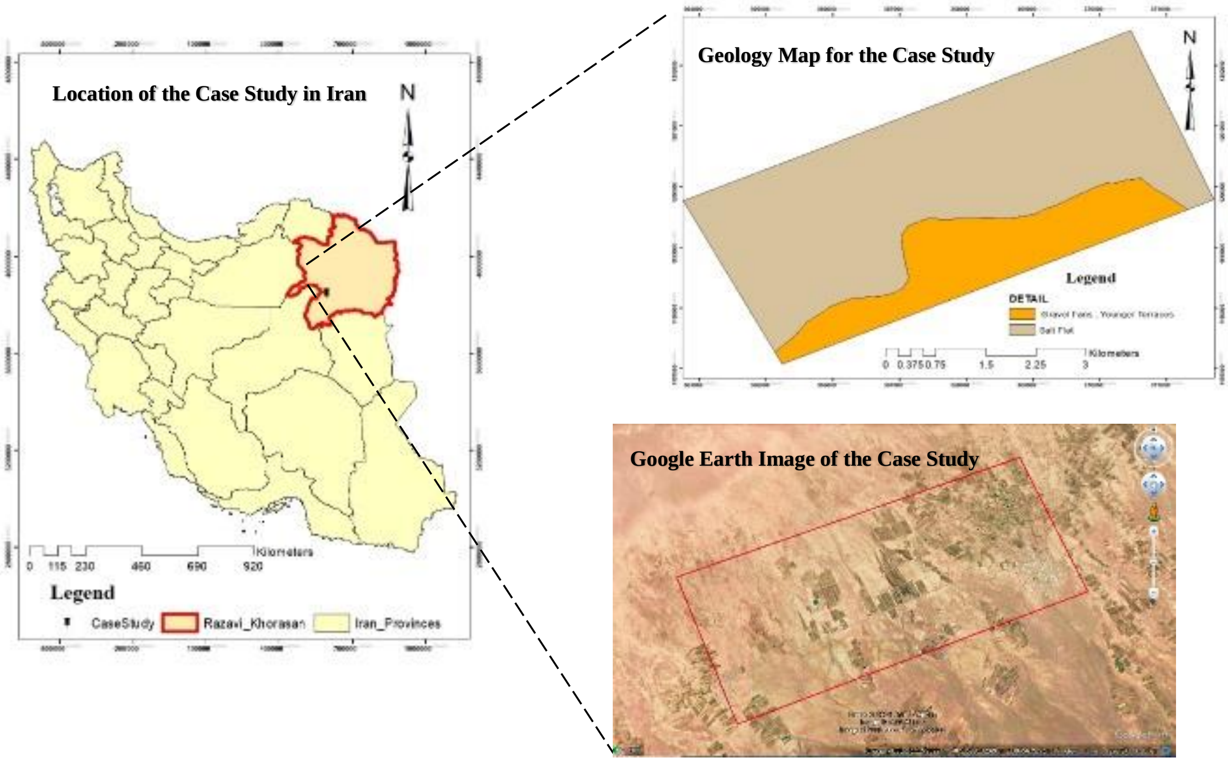
Subsidence is a critical geomorphological issue that poses a threat to both natural and human-made landscapes across the globe. It is characterized by the gradual or abrupt sinking of the Earth's surface, which can result from various factors, including geological processes, changes in hydrology, and human activities (Bishop et al., 2018). Additionally, the interplay between subsidence and meteorological factors is crucial. Climate variability, influenced by both natural phenomena and human actions, increases the vulnerability of hyper-arid regions to drought (Sadeghi et al., 2018). These droughts intensify subsidence by heightening the demand for groundwater while reducing its recharge potential (Akbari et al., 2019). Wind erosion also plays a significant role, particularly in the context of land-use changes, underscoring the need for vegetation cover strategies to combat soil degradation (Fathzadeh et al., 2020). Therefore, land use practices, especially those related to agriculture, are essential for understanding subsidence dynamics. Research indicates a direct relationship between proximity to agricultural wells and the rates of subsidence in hyper-arid areas (Shirvani et al., 2019). This finding calls for a reevaluation of water management approaches, stressing the need for sustainable groundwater extraction practices, alternative water sources, and thoughtful land use planning (D'Arcy & Reimann, 2018). The use of remote sensing technologies has made it possible for researchers to effectively analyze and monitor subsidence over vast regions. Recent advancements in these technologies have proven highly effective in pinpointing subsidence hot spots and examining their connections to groundwater dynamics (Zhou et al., 2019). This methodology is essential in hyper-arid zones, where resources for on-the-ground monitoring may be scarce (Chen et al., 2020).

Iran is characterized by a diverse array of climatic zones, with hyper-arid regions making up about 60% of its total land area. These areas experience extended dry spells with minimal rainfall, prompting a heavy dependence on groundwater for both agricultural and domestic needs (Farahmand et al., 2021). Groundwater serves as the main source of irrigation in these arid conditions, but its over-extraction has led to significant declines in the water table, which can result in various forms of land subsidence (Sudhakar et al., 2018). This subsidence issue is not limited to localized effects; it poses wider challenges for food security, water management, and rural economies (Zare et al., 2020). In Iran, where climatic and hydrogeological droughts are prevalent, subsidence has become an escalating concern, largely due to unsustainable groundwater extraction for agricultural uses (Javid et al., 2021). As urbanization picks up pace and water resources grow scarcer, understanding the mechanisms and effects of subsidence is increasingly important. In hyper-arid areas, particularly in eastern Iran, these problems are exacerbated by climatic extremes, such as prolonged droughts and the overuse of groundwater resources (Ghorbanalizadeh et al., 2020). Research has documented significant shifts in the patterns and densities of subsidence, incorporating analyses of contributing factors like land use, geology, lithology, vegetation, and aquifer structure through ArcGIS technology (Rezaei & Rahimi, 2021). Results show that linear subsidence typically occurs within 1 to 3 kilometers of agricultural wells, with a notable transformation from linear to polygonal subsidence shapes over the last decade (Nikkhah et al., 2022). The most significant sinkholes identified in the study area, reaching depths of 1 to 2 meters, are often located near Haloxylon trees, indicating a complex relationship between vegetation and subsidence processes (Zavareh et al., 2023). Additionally, the study revealed a link between the frequency of subsidence and lithological features predominantly composed of clay and salt layers—materials that are particularly susceptible to groundwater changes, thereby influencing subsidence dynamics (Sadeghi & Ranjbar, 2021). Based on these findings, this research seeks to create a subsidence sensitivity map to enhance the management and mitigation of subsidence risk in hyper-arid environments. The insights gained from this study could prove valuable for extending subsidence risk management strategies to similar regions globally, given the widespread occurrence of subsidence phenomena. This knowledge can also help shape adaptive policies to tackle pressing environmental and agricultural issues (Moghadam et al., 2020). However, any proposed interventions must be carefully evaluated for their potential effects on subsidence dynamics, especially in areas sensitive to climatic changes (Salimi & Khavari, 2021).

Methodology

1. Introduction to the Case Study

This case study investigates an ultra-arid region in eastern Iran, distinguished by its unique geomorphological features known as "playas." These playa environments, characterized by expansive low-lying flatlands and intermittent flooding, have been severely impacted by groundwater extraction, particularly for agricultural purposes. The focus of this study is a specific area encompassing approximately 20 Km^2 within the Bajestan Playa, the second-largest playa in Iran. This region was selected due to its notable concentration of subsidence phenomena, The Playa structure primarily consists of gravel fans and young terraces, with salt flats in the center (Figure.1.).



Source: Researchers' Analysis in ArcGIS 10.2 and Google Earth Pro

Fig1. Location of Case Study

The rapid depletion of groundwater resources, compounded by ongoing climatic drought conditions, has led to significant subsidence patterns, making this area an ideal subject for research utilizing remote sensing and Geographic Information System (GIS) technologies. An analysis of Google Earth imagery from 2012 to 2024 reveals an alarming spread of cracks around agricultural wells and Haloxylon fields. This expansion is primarily attributed to the over-extraction of groundwater and the agricultural practices associated with Haloxylon planting in the region, particularly along the playa. The figure included illustrates the location of the study area, which lies in the southeastern part of Iran within Razavi Khorasan Province. This research aims to enhance our understanding of the interplay between groundwater management practices and land subsidence in this vulnerable ecosystem.

2. Determination of the Period of Analysis

The analysis for this study covers the period from 2012 to 2024, aligning with the advent of the first satellite imagery for the targeted regions. We initiated our monitoring with satellite images from 2012, followed by evaluations in 2019 and 2024. In addition, we collected data on regional water level changes, which have been linked to a notable increase in agricultural activities since 2012. Importantly, the emergence of land deformation phenomena has occurred alongside significant water level fluctuations, alterations in land use, and the proliferation of Haloxylon plantations. Conversely, before 2012, agricultural practices and groundwater extraction were limited, with no significant growth in Haloxylon areas. To effectively monitor subsidence patterns throughout this 12-year period, we concentrated on land deformation changes as indicated by satellite data. This specific timeframe was chosen to support a thorough examination of long-term trends in land deformation and subsidence. We utilized high-resolution satellite imagery from Google Earth to observe changes throughout this period. By focusing on this particular duration, the study intends to capture not only the baseline conditions prior to major groundwater withdrawals but also the subsequent transformations driven by agricultural activities, droughts, and shifting land use patterns. The selected analysis periods will facilitate a comparative evaluation of land deformation trends over time, enhancing our understanding of the interplay between human activities and climatic factors in shaping the landscape.

3. Data Collection & Fieldworks

After establishing the analysis period, we utilized high-resolution images from Google Earth to pinpoint subsidence events and verify their locations, thereby reducing the potential for human error in detection. We recorded the coordinates of these identified subsidence zones using GPS and conducted field visits to confirm their on-site positions. In addition to the remote sensing data, we obtained crucial information on land use, lithology, Haloxylon distribution, agricultural wells, and piezometric wells from Iran's national hydrological database, which has been available since 2012, forming a solid foundation for our analysis. Moreover, we updated the land use, lithology, and Haloxylon maps for the years 2012, 2019, and 2024 using ArcMap 10.2.

4. Mapping Subsidence

In this study, we conducted a comprehensive assessment of subsidence shape changes and associated risks by utilizing Google Earth satellite images from three distinct analysis periods: 2012, 2019, and 2024. The data gathered during these periods enabled us to update and create several critical maps to visualize and analyze subsidence dynamics effectively. The maps in this study were categorized as follows:

4.1. Creation of Subsidence Shape Maps and Analysis: In the initial phase, comprehensive maps were created to illustrate the patterns of subsidence during all three analysis periods. These maps not only show regions of subsidence accumulation but also monitor the expansion process and changes in shape, evolving from linear to polygonal forms.

4.2. Land Use Change Maps and Agricultural Wells Location: During this phase, we generate precise maps that capture changes in land use throughout each analysis period, with a particular focus on trends in agriculture and urban development from 2012 to 2024. This visualization allows us to assess the relationship between land use changes and subsidence phenomena. Furthermore, the maps denote the locations of agricultural wells for which we have data, showcasing their substantial groundwater extraction during the analysis period. Importantly, most of these wells are located in or near agricultural zones, highlighting the connection between agricultural practices and groundwater depletion. This detailed mapping offers crucial insights into the interrelationship between land use and water resource management.

4.3. Haloxylon Lands Maps expansion and Analysis of Subsidence Locations: We created detailed maps to highlight the substantial transformations in Haloxylon lands during the specified analysis periods. These maps effectively demonstrate the growth of Haloxylon planting initiatives, which are strategically designed to address wind erosion, a problem that has worsened due to ongoing drought conditions. Additionally, the maps illustrate the development and expansion of new Haloxylon planting projects from 2012 to 2024, underscoring the dedicated efforts to restore and rehabilitate impacted areas. This expansion has not only enlarged the Haloxylon plantations but has also played a significant role in improving the ecological stability of the region.

4.4. Subsidence Risk Map: Our extensive mapping efforts have culminated in the development of a comprehensive subsidence risk map. This advanced map incorporates various thematic layers, such as lithology, geological formations, land use patterns, Haloxylon distribution, and areas of surface cracking documented in 2024. The main goal of this risk map is to accurately pinpoint regions most vulnerable to subsidence, facilitating the identification of critical areas that may need close monitoring and targeted interventions in the future. By integrating these diverse datasets, the map offers a complete perspective on the factors contributing to subsidence, empowering stakeholders to make informed decisions about land management and conservation strategies.

5. Statistical Analysis of Subsidences

5.1. Numerical Analysis of the Impact of Agricultural Wells and Haloxylon Lands on Subsidence

- **Buffer Maps around Agricultural Wells and Analysis:** We developed buffer maps with radii of one, three, five, seven, and ten kilometers around agricultural wells. These buffers allow us to explore the spatial relationship between subsidence and wells, enhancing our understanding of how the proximity to water extraction sites affects both the location and intensity of subsidence.

To quantitatively evaluate the effects of water level fluctuations and the expansion of Haloxylon vegetation on subsidence occurrence and progression, we analyzed data derived from the various buffers created in Arc Map 10.2. Our focus was on the influence of agricultural water extraction on subsidence formation, specifically by assessing the results from buffer zones set at distances of 1, 3, 5, 7, and 10 kilometers from subsidence sites. The outcomes were presented in graphical form to demonstrate the relationship between agricultural water usage and subsidence events.

- **Buffer Maps around Haloxylon Lands and Analysis:** To further understand the relationship between Haloxylon lands and subsidence, we analyzed the results derived from smaller buffer zones, with intervals of 0.1, 0.2, 0.5, 1, and 3 meters around Haloxylon areas. Similarly, these results were presented graphically to depict the proximity effects that Haloxylon plantations may have on subsidence development.

We also developed buffer maps with intervals of 0.1, 0.5, 1, 3, and 5 meters around Haloxylon lands. Our field observations indicated that many instances of subsidence are closely associated with these areas (Fig.2), prompting the consideration of smaller buffer distances to accurately assess this relationship.

Source: Researchers' Fieldwork Findings

Fig.2. Subsidence around the Haloxylon

5.2. Numerical Analysis of the Relationship between Lithology and Subsidence Density

In this section, we developed density maps that integrate occurrences of subsidence with lithological characteristics. These visualizations clarify the interactions between various geological structures, primarily composed of young alluvial terraces, clay formations, and salt deposits, while also depicting their correlation with the frequency of subsidence events. This approach enhances our understanding of how lithological factors influence subsidence patterns within the region. We quantified the occurrence ratio of subsidence across various lithology's and illustrated these relationships through frequency graphs, enabling a clearer visual representation of the data. The primary objective of this section is to elucidate how diverse lithological and geological structures contribute to subsidence accumulation. Additionally, we aimed to highlight the underlying geological factors that may drive subsidence processes in the study area. Through these analyses, we aspire to provide a comprehensive understanding of the interplay between agricultural practices and geological features, particularly in the context of ultra-arid regions of Iran.

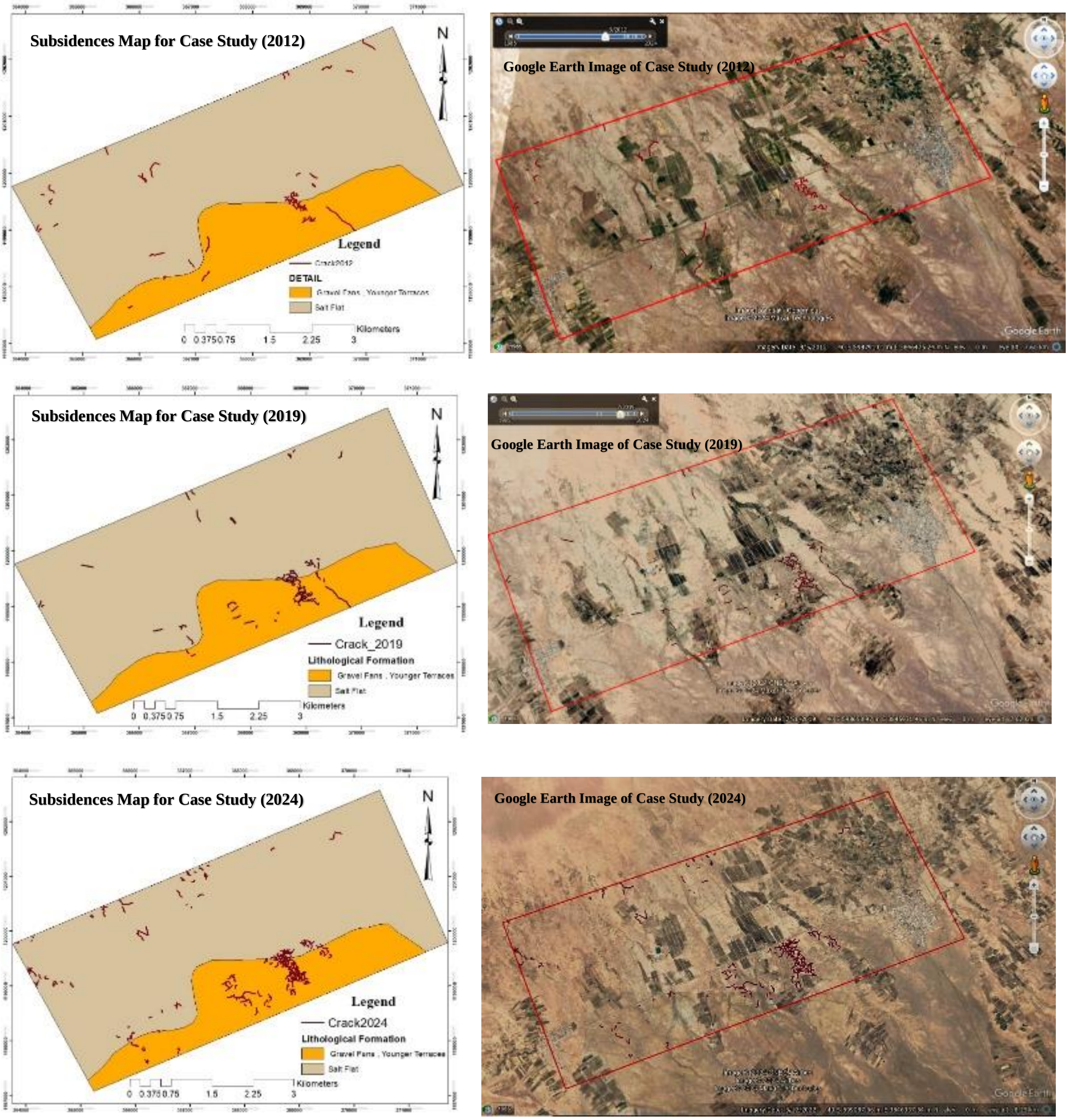
Results and Discussion

1. Overview of the Case Study: Analysis Period and Methodology

The study area, situated in the southern region of Razavi Khorasan province, represents one of the most arid locations in Iran, facing a significant decline in groundwater levels in recent years. Groundwater sources are the primary supply of water in these regions, making their sustainable management critical. Since 2012, there has been a notable increase in groundwater extraction, which has coincided with a substantial expansion of agricultural land, particularly in the cultivation of Haloxylon species, aimed at mitigating wind erosion effects. Our examination of the various segments of the plain revealed that the most pronounced subsidence, manifesting in both polygonal and linear patterns, occurs along the periphery of the playa. This area, composed primarily of fine-grained sediments interspersed with salt layers, has experienced considerable deformation and subsidence of its surface. Consequently, we focused our analysis on a 20 square kilometer section characterized by the highest subsidence density. To understand the impact of agricultural practices on groundwater resources, we collected data from 24 authorized agricultural exploitation wells, which have recorded the highest levels of extraction from 2012 to 2024. Notably, satellite imagery indicates that, despite persistent drought conditions and declining groundwater levels during the same period, the extent of agricultural cultivation has not only persisted but increased, alongside the cultivation of Haloxylon lands. This 12-year study demonstrated significant changes in land deformation, revealing a strong correlation between the increase in land use and Haloxylon lands, as evidenced by numerical analysis and supported by Google Earth images from the same period.

2. Mapping Subsidence

2.1. Creation of Subsidence Shape Maps and Analysis: As illustrated in graphs a, b, and c in Figure 3, there has been a significant increase in both the level and frequency of agricultural activities and farmlands from 2012 to 2024. Our analysis reveals that the areas most impacted by subsidence are frequently located in densely populated regions, where the effects on housing and agricultural land are particularly pronounced. This correlation underscores the critical need for effective land management strategies to mitigate the adverse consequences of subsidence in these vulnerable areas.



Source: Researchers' Analysis in ArcGIS 10.2 and Google Earth Pro

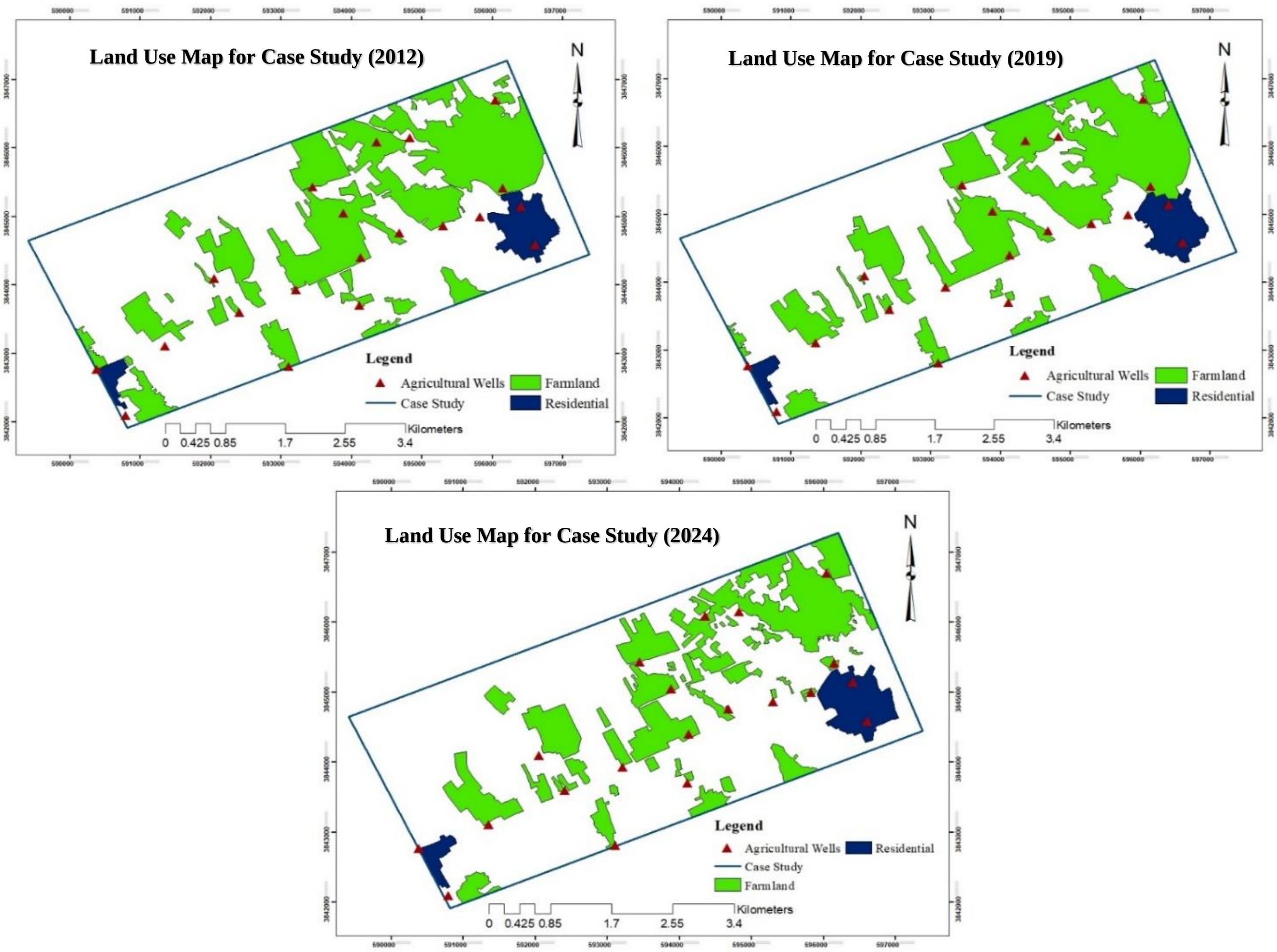
Fig.3. Subsidence Frequency During in Period of Analysis (2012-2019-2024)

Additionally, as illustrated in Figure 3, the trend of subsidence from 2012 to 2024 exhibits an initial linear pattern followed by a polygonal form. This shift not only underscores the severity of land degradation but also highlights the alarming nature of the subsidence phenomenon. The transition from a linear to a polygonal trend reflects complex changes in the subsurface conditions and external factors affecting the land.

Source: Researchers' Analysis in Google Earth Pro

Figure 4: The pattern of subsidence shapes transitioning from linear to polygonal during Period of Analysis

2.2. Land Use Change Maps and analysis of expansion on Subsidence: As illustrated in Figure 5, the period from 2012 to 2024 has been marked by significant land use changes within the study area. Notably, there was a pronounced expansion of agricultural cultivation from 2012 to 2019, accompanied by a more modest increase in residential areas. These transformations have played a crucial role in the occurrence and exacerbation of land subsidence in the region, highlighting the interconnectedness of land use practices and geological stability. However, the trend observed from 2019 to 2024 reveals a notable decline in agricultural land use.



Source: Researchers' Analysis in ArcGIS 10.2 and Google Earth Pro

Figure 5: Location of Agricultural Wells and Land Use Changes during the Analysis Period

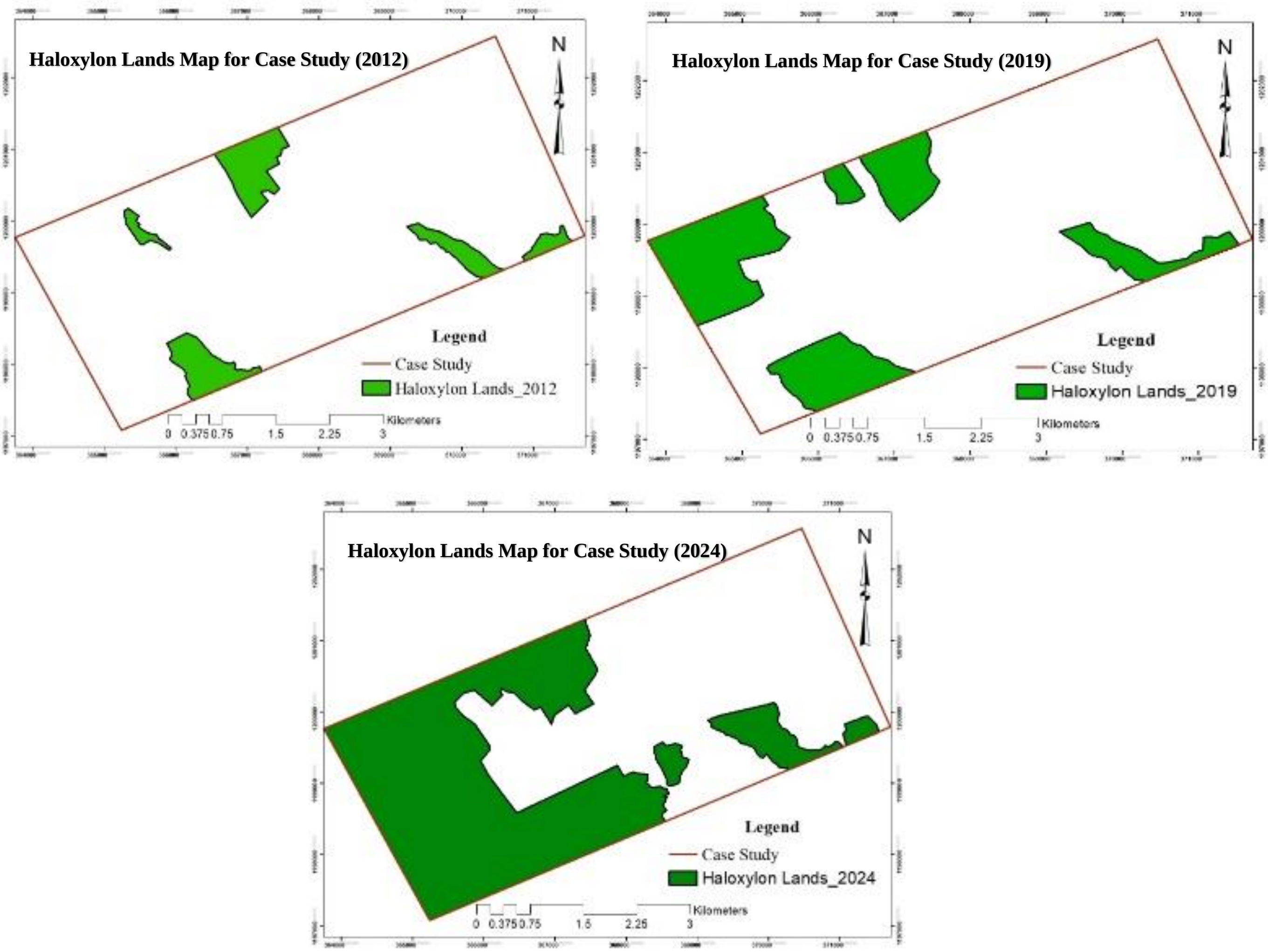
As illustrated in Figure 5, the level of agricultural activity in 2024 has declined compared to 2012 and 2019. Our field observations indicate that this reduction can be attributed to the salinization of agricultural lands (Figure 6) and the expansion of subsidence, which have rendered portions of farmland increasingly inaccessible to farmers.

Source: Researchers' Fieldwork Findings

Figure 6: Salinization of agricultural lands from extracting saline groundwater

The rising salinity of groundwater resources has made it increasingly challenging for farmers to maintain sustainable crop production, while concurrently contributing to a higher incidence of subsidence. Consequently, these factors have prompted a significant shift away from traditional agricultural practices.

2.3. Haloxylon Lands Maps expansion and Analysis of Subsidence Locations: Since 2010, Haloxylon Lands projects have been initiated in the study area. Beginning in the second year after planting, these Haloxylon trees require irrigation, which has gradually contributed to the emergence of land subsidence issues in the region. Figure 7 illustrates the development process of Haloxylon species at the beginning, during, and at the end of the analysis period.

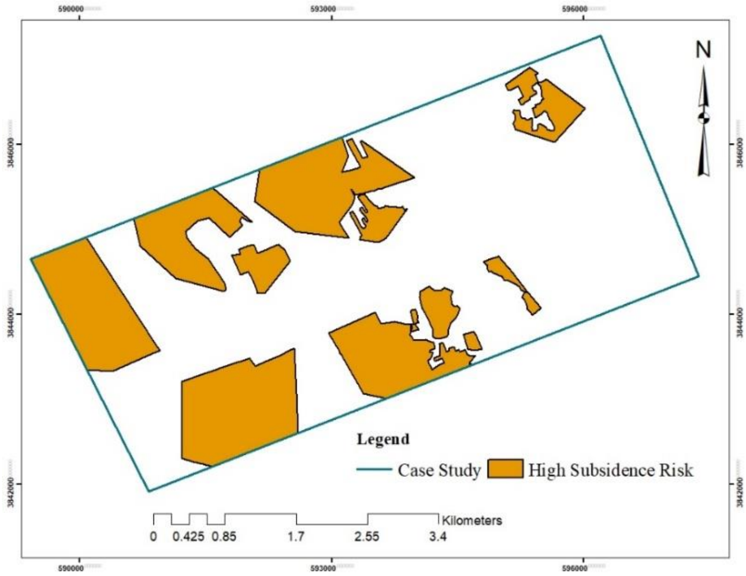


Source: Researchers' Analysis in ArcGIS 10.2 and Google Earth Pro

Figure 7: Expansion of Haloxylon Lands during Period of Analysis

2.4. Subsidence Risk Map:

After thoroughly examining the various factors influencing subsidence—specifically, type of land use, lithology, geological structure, and the expansion of Haloxylon lands—we proceeded to develop a subsidence risk map. This map is intended to illustrate areas with a heightened potential for subsidence or its further expansion in the years following 2024. The creation of the subsidence risk map involved overlaying several critical layers of information: the crack density observed in 2024, lithological and geological characteristics, current land use, and the distribution of Haloxylon lands. Figure 8 clearly displays the regions most prone to subsidence in the coming years, particularly highlighting areas where salt-laden lithological structures coincide with Haloxylon and agricultural lands. These locations demonstrate a concerning propensity for subsidence due to both geological and anthropogenic influences.



Source: Researchers' Analysis in ArcGIS 10.2

Figure 8: Subsidence Risk Map of Case Study

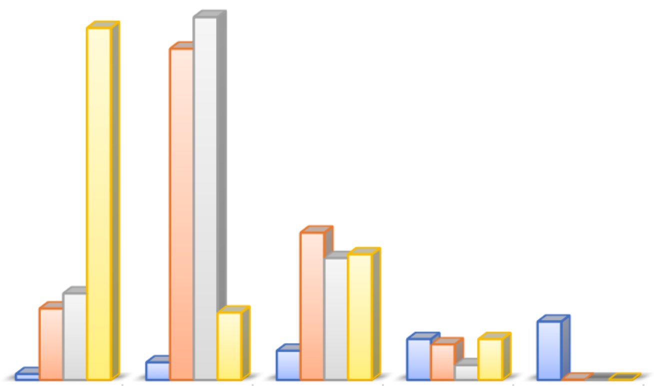
Additionally, our findings indicate the proliferation of Haloxylon vegetation and its escalating demand for groundwater, particularly as these plants enter their growth phases. This increasing water demand poses a considerable risk to the local aquifers, exacerbating the challenges posed by subsidence. The deteriorating water table levels and rising salinity from 2012 to 2024 further elevate the intensity and frequency of subsidence events, creating a feedback loop that threatens the sustainability of both agricultural practices and natural ecosystems.

3. Statistical Analysis of Subsidences

3.1. Results of Numerical Analysis of the Impact of Agricultural Wells and Haloxylon Lands on Subsidence

- **Results of Buffer Maps around Agricultural Wells and Analysis:**

The analysis of buffers at varying distances of 1, 3, 5, 7, and 10 kilometers around agricultural wells yielded significant insights (Figure 9). In 2012, wells located within a 1-kilometer radius exhibited the highest potential for subsidence frequency. This indicates that subsidence initially occurred in close proximity to the wells. However, over time, particularly by 2019 and continuing into 2024, increased groundwater extraction and prolonged drought conditions resulted in a noticeable decline in the groundwater level. Consequently, there was a marked accumulation of subsidence at greater distances, specifically extending to 3 kilometers. This trend suggests that the impact radius of groundwater extraction and the drop in aquifer levels has expanded, resulting in a greater spread of subsidence events and an increase in their density over time. The findings emphasize the need to consider not only the immediate vicinity of agricultural wells but also the broader impacts that groundwater extraction has on subsidence across the surrounding landscape.



	1	2	3	4	5
Distance(km)	1	3	5	7	10
Effectiveness Rate(%)2024	12.24	56.37	25.22	6.09	0.05
Effectiveness Rate(%)2019	14.83	61.72	20.9	2.53	0
Effectiveness Rate(%)2012	59.89	11.54	21.55	7	0

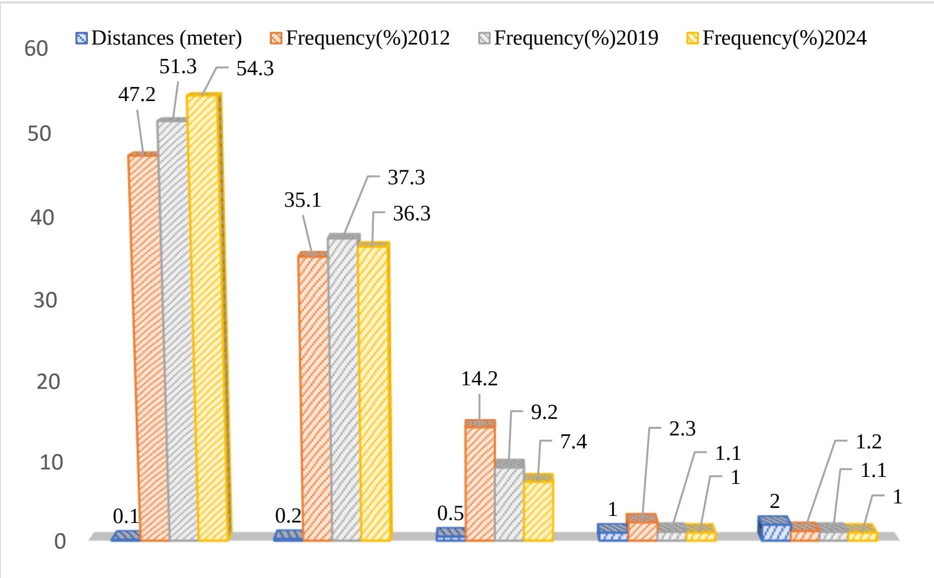
Source: Researchers' Analysis in ArcGIS 10.2

Figure 9: Numerical Analysis of the Impact of Agricultural Wells on Subsidence

- **Buffer Maps around Haloxylon Lands and Analysis:**

The analysis of buffer zones at varying distances of 0.1, 0.2, 0.5, 1, and 2 meters around Haloxylon lands over the years 2012, 2019, and 2024 revealed significant patterns in the occurrence and frequency of subsidence (Figure 10).

The results indicated that the highest number and frequency of subsidence events were observed at a distance of 0.1 meters from the Haloxylon plants. This finding suggests that subsidence primarily occurs around the roots of these plants, likely due to their significant demand for water and moisture in the immediate vicinity. As groundwater levels decline, Haloxylon roots tend to extend further outward in search of moisture. Consequently, subsidence begins to manifest beyond the initial 0.1-meter radius, with notable occurrences at distances of 0.2 meters and 0.5 meters. Notably, the highest density of subsidence around Haloxylon lands was recorded consistently in 2012, 2019, and 2024 within these extended distance increments. Overall, these findings underscore the critical relationship between Haloxylon plant physiology, groundwater extraction, and subsidence dynamics, highlighting the importance of monitoring subsidence patterns in areas dominated by this vegetation.

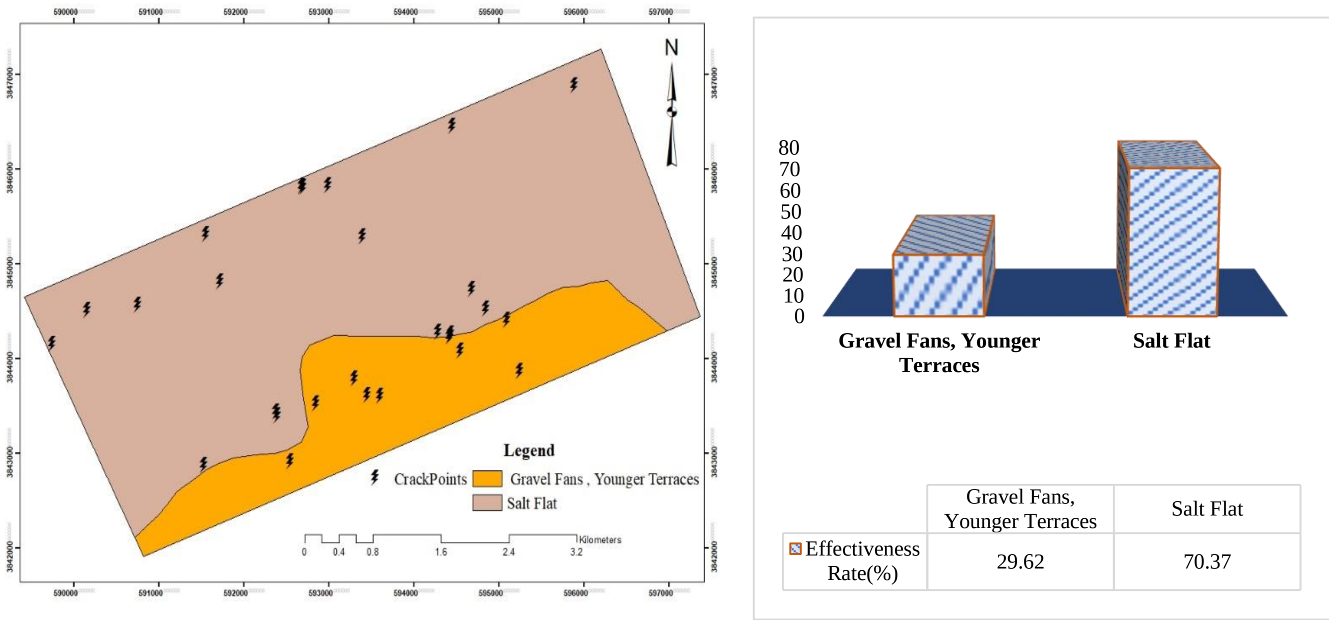


Source: Researchers' Analysis in ArcGIS 10.2

Figure 10: Numerical Analysis of the Impact of Haloxylon Lands on Subsidence

3.2. Numerical Analysis of the Relationship between Lithology and Subsidence Density

As illustrated in Figure 11, over 70% of sediment accumulation occurs within the lithological and geological structures of salt flats, specifically within fine-grained areas characterized by salt layers. This significant finding indicates that soils with higher salinity levels tend to accumulate and concentrate sediments. While sediment deposition is not exclusively limited to plains and gravel fans, it is predominantly observed in formations containing salt layers.



	Gravel Fans, Younger Terraces	Salt Flat
Effectiveness Rate(%)	29.62	70.37

Source: Researchers' Analysis in ArcGIS 10.2 and Google Earth Pro

Figure 11: Schematic occurrence of subsidence in different lithological structures

This correlation highlights the urgent need for farmers and policymakers to reconsider groundwater extraction practices in areas featuring clay-rich and fine-grained lithology, such as playa environments. By addressing these concerns, stakeholders can work towards more sustainable management of groundwater resources, thus mitigating further sediment accumulation and potential land degradation.

Conclusion and Recommendation

This research presents a thorough evaluation of subsidence trends in the hyper-arid regions of eastern Iran, with a particular emphasis on playa geomorphological features. By combining remote sensing technologies, GIS analysis, and extensive field investigations, we have garnered important insights into the mechanisms of ground deformation. Notably, a significant reduction in groundwater levels—intensified by agricultural expansion, particularly through Haloxylon cultivation—has resulted in increased subsidence throughout the area. Our findings indicate a concerning phenomenon where subsidence is predominantly found in regions with particular geological traits, especially those featuring fine-grained sediments and high salinity. The primary driver of subsidence in the area is the over extraction of groundwater for agricultural activities, further aggravated by geological conditions, including soils rich in clay and salt (Fathian et al., 2020; Mohammadi et al., 2019). We have developed a subsidence risk map that highlights critical areas vulnerable to subsidence, serving as a guide for future land management and agricultural practices. Moreover, the research emphasizes the urgent need for sustainable water-use strategies to alleviate negative impacts on local aquifers and agricultural sustainability. Our findings align with those of previous studies, such as Ranjan et al. (2019) and Wu et al. (2020), which identified strong correlations between intensive agricultural practices and land subsidence, worsened by unsustainable groundwater extraction. Additionally, Martin et al. (2018) underscored the significance of understanding the hydrological impacts of vegetation growth, paralleling our investigation into Haloxylon species. The creation of the subsidence risk map has proven to be a useful resource for stakeholders, pinpointing high-risk areas and guiding sustainable land management efforts. The recommendations from this study stress the importance of an equitable approach to groundwater management, advocating for the exploration of alternative water sources and careful vegetation management practices. In summary, the knowledge acquired from this study not only enhances our comprehension of subsidence in hyper-arid landscapes but also provides actionable solutions to mitigate the risks associated with this issue.

This study underscores the importance of implementing sustainable land and water management practices due to rising subsidence and groundwater depletion. Key recommendations involve establishing stringent regulations on groundwater extraction in vulnerable areas, potentially through a quota system and water use permits, with the support of ArcGIS for spatial analysis. Farmers are encouraged to embrace sustainable techniques such as drip irrigation and cultivating drought-resistant crops to minimize water dependency, assisted by satellite technology for crop monitoring. Additionally, rehabilitating saline lands through soil amendments is crucial, along with ongoing monitoring of groundwater levels and soil salinity. Public awareness initiatives and training programs can inform communities about sustainable practices and the consequences of excessive extraction. Collaborative efforts among stakeholders will strengthen integrated water resource management, while adaptive management approaches provide the necessary flexibility to address evolving conditions. By implementing these strategies, we can alleviate negative impacts on the environment and agriculture.

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