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Spatial Variability of Playa Surface Types in Relation to Groundwater Depth and Salinity Regime: A Case Study from Haj Aligholi Playa, Damghan, Iran

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ABSTRACT

This study investigates the influence of salinity regime and groundwater conditions on surface morphology in the southern part of Haj Aligholi playa, Damghan, Iran. A multi-method approach integrating topographic and geological mapping, satellite image interpretation, and field investigations—including soil profile excavation and physicochemical analysis—was employed. Results reveal a systematic spatial transition in playa surfaces from the outer margins toward the center, with five distinct landform types identified: clay floor, soft puffy surfaces, plowed-like clay surfaces (Zardeh), wet zones, and patterned salt-clay surfaces. Groundwater depth decreased progressively from 400 cm in peripheral clay flats to 45 cm in the central wet zone, accompanied by substantial increases in electrical conductivity (EC: 4.6 to 174.8 ds/m) and sodium adsorption ratio (SAR: 5.3 to 191.7 meq/L). These findings demonstrate that surface morphology is primarily controlled by the interaction between groundwater depth (and associated capillary rise) and sediment texture, which jointly determine salt accumulation patterns. The study highlights playa surfaces as sensitive indicators of hydrological conditions and provides a framework for environmental monitoring and land management in arid closed-basin systems.

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1. Introduction

Extensive areas of arid regions are characterized by endorheic drainage, where waters collect in topographically low areas, forming lakes of varying sizes and origins (University of Nebraska Omaha, n.d. 1956). The playa represents the terminal discharge zone of a groundwater system where a groundwater basin and topographic basin coincide, a condition termed an 'undrained closed valley' (Snyder, 1962).

Playa settings are dynamic landforms presenting an active and interrelated set of sedimentary environments mainly controlled by the hydrological balance (Zanor *et al.*, 2012; Nield *et al.*, 2015). A playa is defined as an intercontinental basin with a negative water balance i.e. when evaporation exceeds rainfall, for more than half of the year (Rosen, 1994).

Wetlands including playas are among the most valuable and productive ecosystems on Earth, necessitating research to support informed development and protection (Ramsar Convention Secretariat, 2004).

Iran's arid regions contain more than 60 playas, with surface areas ranging from a few hectares to several hundred square kilometers (Figure 1). These environments are locally known as 'Kavir' (salt desert), 'Shagh', or 'Dagh' (clay pan). Based on groundwater depth, playas are generally classified into "wet" and "dry" types (Rosen, 1994; Reynolds *et al.*, 2007).

In wet playas, groundwater is shallow (<5 m depth), and capillary action allows for evaporation of the shallow groundwater, producing soft surfaces of loose sediment along with the formation of evaporate minerals (Reynolds *et al.*, 2007; Nield *et al.*, 2015). In such systems, geomorphological features, vegetation patterns, and soil properties are largely controlled by groundwater depth and hydrochemical composition (Zhu, 2016; Pourali *et al.*, 2023; Farpoor *et al.*, 2012). In contrast, the depth to groundwater is typically greater than 5 m in dry playas, precluding evaporation from the capillary fringe, and the surfaces are composed of dense, compact silt and clays (Bourrie, 2014). In these environments, geomorphology, vegetation distribution, and soil characteristics are predominantly influenced by surface hydrological processes and aeolian activity (Mabbutt, 1977; Reynolds *et al.*, 2007; Pi *et al.*, 2021).

The Haj Aligholi playa was selected due to its accessibility, the presence of diverse surface types within a relatively small area, and its representativeness of typical Iranian playa systems. Additionally, the site is under increasing anthropogenic pressure from groundwater extraction, making understanding its baseline conditions particularly urgent.

While previous studies have examined playa morphology in various global contexts, the specific relationships between salinity regime and surface type distribution in Iranian playas remain poorly quantified. The objectives of this study are to: (1) identify and map playa surface types in the southern Haj Aligholi playa; (2) determine the physicochemical properties (EC, SAR, and texture) associated with each surface type; (3) establish relationships between groundwater depth and surface morphology; and (4) evaluate the relative importance of hydrological versus sedimentological controls on playa surface development. The main objective of this study is to characterize and interpret the playa environment through integrated analysis of geomorphological, geological, vegetation, water table, and groundwater chemistry data, supported by detailed field observations.

2. Materials and methods

2.1. Description of the study area

The study area is located at the southern margin of the Haj Aligholi Playa, south of Damghan County. The area spans the geographical coordinates 54°32' to 54°33' E longitude and 35°50' to 35°51' N latitude (Figure 2). The Damghan watershed covers approximately 239,000 ha, of

which 46,600 ha comprises the playa. The elevation ranges from 1,051 to 1,350 m above sea level, with a mean elevation of 1,150 m. The region experiences an arid climate with an average annual rainfall of 148 mm.

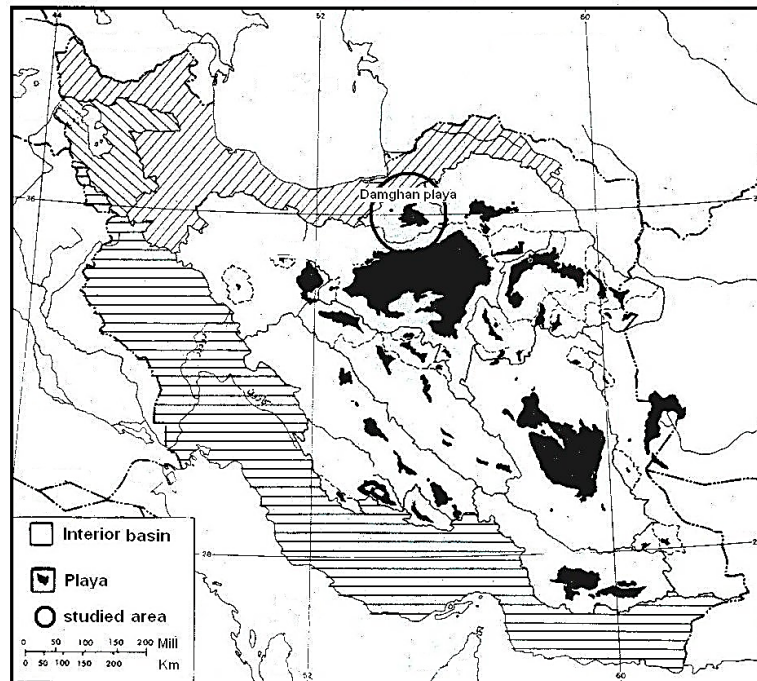


Figure 1. Interior basins and playas of Iran (Krinsley, 1970)

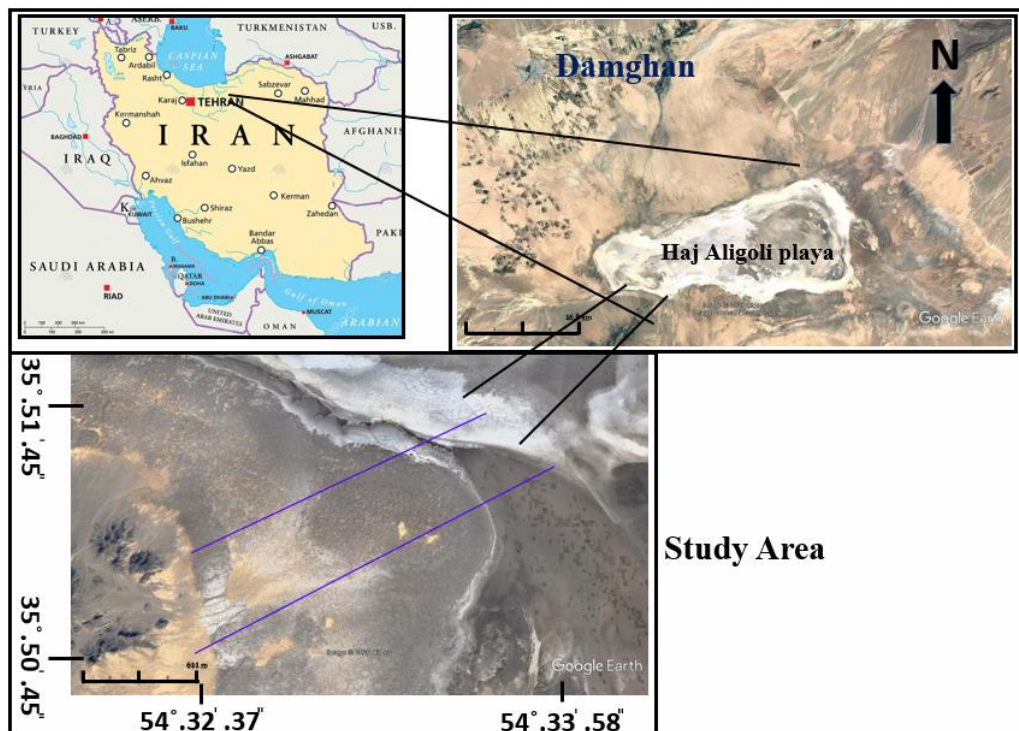


Figure 2. Location of the study area

2.2. Materials

This study utilized a combination of topographic maps at scales of 1:50,000 and 1:250,000, a geological map at a scale of 1:100,000, aerial photographs at a scale of 1:55,000, and satellite images.

2.3. Methods

The following procedures were carried out using these materials:

- Interpretation of aerial photographs and satellite images

Aerial photographs and satellite imagery were interpreted to identify surface features and spatial patterns. The analytical approach for interpretation was visually validated by ground control.

- Tectonic and lithological analysis

Tectonic setting and lithological characteristics were examined using available geological maps and image interpretation.

- Geomorphological analysis and preliminary landform mapping

Geomorphological features were studied, and a preliminary map of landform units was prepared using aerial photograph interpretation, satellite imagery, topographic maps, and the geological map.

- Field survey and ground verification

Field investigations were conducted to verify interpreted features and complete the geomorphological assessment. "During fieldwork, soil profiles were excavated and samples were collected for analysis. The study evaluation was conducted based on 4 soil profiles.

Groundwater depth in the drilled profiles was measured at the end of the flooding period in June using well drilling. Given seasonal variations in playa groundwater levels, future studies should incorporate multi-temporal measurements.

Soil samples were collected from each horizon of four excavated profiles. EC and pH were measured in a 1:5 soil: water suspension using saturation extract of mud. Cation concentrations (Na, Ca, and Mg) were determined using Flame photometer method. SAR was calculated as $SAR = Na^+ \sqrt{Ca^{2+} Mg^{2+}}$, with all concentrations expressed in meq/L. Soil texture was determined using the hydrometer method following. All analyses were conducted in triplicate and mean values reported.

- Integration of geomorphological and soil

Finally, geomorphological and soil chemistry data were integrated to support interpretation of the playa environment. Due to small sample size, statistical inference is limited and only descriptive patterns are presented.

3. Results

3.1. Lithology

Geological mapping (Geological Survey of Iran, 1991) indicates that sediments in the study area are of Quaternary age. These deposits comprise two distinct units: clay Flats (QC) and Kavir sediments (Qka), with a composition of fine-grained sediments ranging from fine sand to clay, as illustrated in Figure 3.

3.2. Geomorphology

The study area, part of a playa system, is influenced by three principal regimes: hydrological, sedimentary, and salinity regimes. Each regime exerts distinct controls on playa surface formation and evolution, collectively influencing vegetation, soil properties, groundwater

dynamics, and salt deposition.

Among these, the hydrological regime - specifically surface and underground drainage, and especially groundwater discharge - and the salinity regime exerts the most significant influence on playa surface morphology.

Playa Surface Types

The floor of Haj Aligholi playa consists of several surface types, distributed according to hydrologic and related controls (Figure 4).

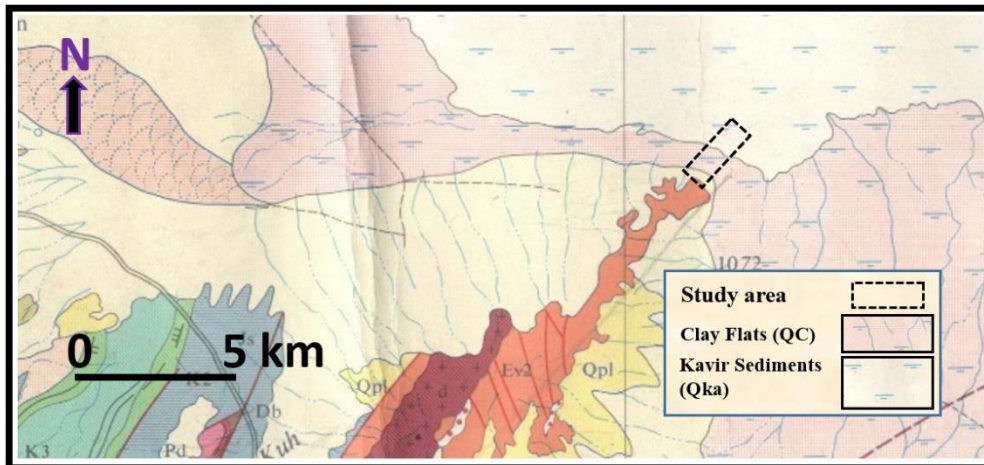


Figure 3. Geologic map

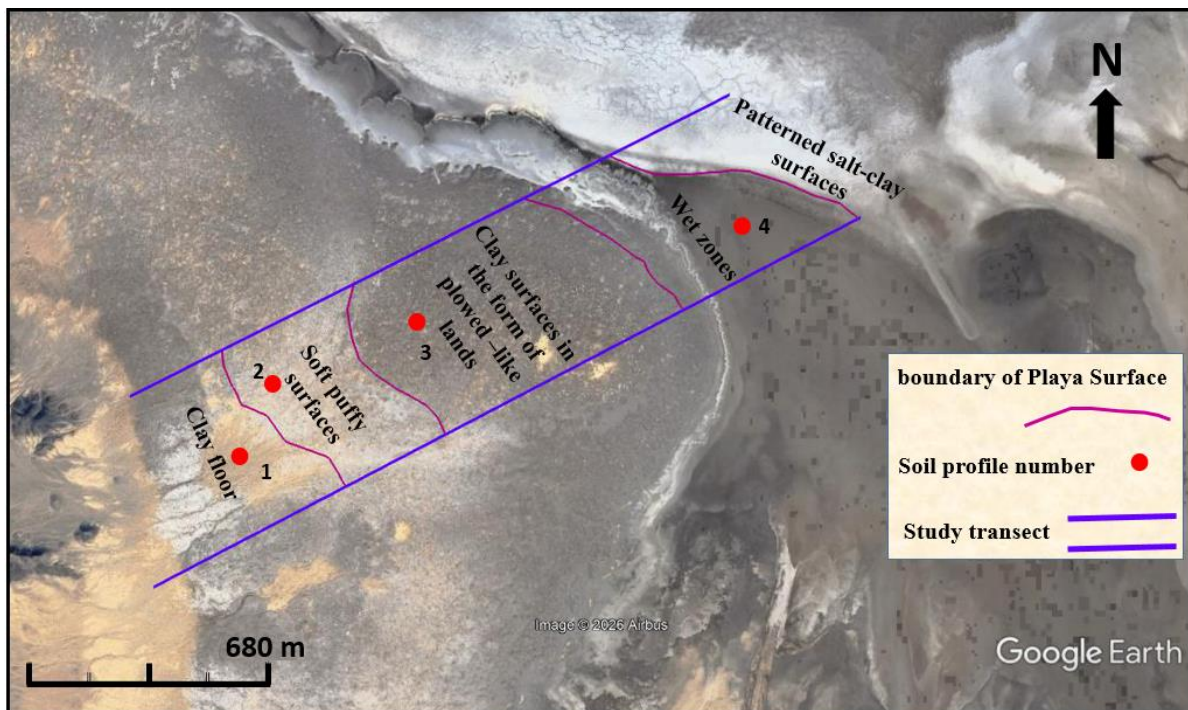


Figure 4. Types of playa surfaces and their transformation from the outside to the center of the playa based on decreasing water table depth, salt composition, and degree of salt solubility.

3.2.1. *Clay floor*

These surfaces are remarkably flat and consist predominantly of clay and silt. They are found in the outer part of the playa, which not subject to groundwater discharge, or above the capillary fringe of the groundwater table. This playa surface has a vegetation cover of the type of *salsola*. Soil profile 1 was excavated at this surface.

3.2.2. *Soft puffy surfaces*

In the region, this landform occurs as a "self-rising ground", forming a friable blistery surface of loose granular texture, typically after clay floors and where it is subject to strong groundwater drainage to the lowest part of the playa. This landform typically occurs as a crust with a suitable texture within 1 to 3 meters of the groundwater table and is hence within the capillary fringe.

3.2.3. *Clay surfaces in the form of plowed -like lands (Zardeh)*

The third landform consists of fine-textured sediments where seasonal seepage brings groundwater to the surface. In this case, the playa surface appears as plowed -like lands (Zardeh).

3.2.4. *Wet zones*

The hydrological regime results in the formation of a moist marginal zone, extending up to several meters in width along the playa boundary. This zone experiences seasonal fluctuations in groundwater levels, with higher water tables during the wet period and lower levels during the dry period. Table 1 presents the landforms of the study area.

3.2.5. *Patterned salt-clay surface*

This landform occurs in the interior of the playa, immediately adjacent to salt crust zones. It has been shaped by the influence of clay and salt, forming patterned clay salt flats. It results from volume changes in fine-textured sediments and contained salts on wetting and drying, with associated salt crystallisation, and from thermal expansion and contraction reinforced by changes in the degree of hydration of the salts.

Geomorphological analysis reveals a systematic spatial transition in landforms from the outer margins toward the playa interior. This transition is characterized by a progression from fine-grained sediments with either firm or puffy (soft, porous) surfaces to salt-impregnated deposits, and ultimately to zones dominated by salt crust.

3.3. *Pedology*

Soil identification was based on profile excavation, horizon description, and laboratory analysis of samples from each landform (Table 1; Figure 4).

3.4. *Groundwater Level*

A longitudinal transect was established extending from south to north (i.e., from the playa margin toward the interior). Along this transect, soil profiles were dug to investigate groundwater depth as well as soil and sediment properties.

Groundwater depth decreases progressively from the outer margin toward the playa interior. Specifically, groundwater depth decreases from approximately 4 m in the peripheral zone (outside) to about 1 cm in the central₂ of playa (Table 1).

Table 1. Physicochemical properties of soil and water table in landform units

Land form	Profile number.	Depth (cm)	Ec (ds/m)	pH	SAR (meq/L)	Ca ₂ +Mg (meq/L)	Texture	salinity	Water-table (cm)
Clay floor	1	0-5	4.6	7.7	5.3	30	Loamy sand	Non-saline and non-sodic soils	400
		5-30	3.7	7.7	1.9	28	Sandy clay loam	Non-saline and non-sodic soils	
		>30	6.1	7.9	10.1	33	Sandy	Non-saline and non-sodic soils	
Soft puffy surf aces	2	0-5	192.0	8.0	573.1	78	Sandy loam	Saline and sodic soils	170
		>5	102.3	8.1	180.9	100	Sandy loam	Saline and sodic soils	
Clay surfaces in the form of plowed -like lands	3	0-5	200.0	7.7	583.1	94	Sandy loam	Saline and sodic soils	77
		>5	130.6	7.6	193.5	152	clay	Saline and sodic soils	
Wet zones	4	0-20	174.8	7.1	191.7	368	clay	Saline and sodic soils	45

4. Discussion

Results indicate that the salinity regime is a primary control on playa surface characteristics in arid regions. The clear differentiation among playa surfaces suggests that surface morphology is closely related to groundwater availability, soil or sediment texture, composition and solubility, and ultimately evaporation intensity (Neal 1965). As shown in Table 1, the water table depth decreases from the outer part of the playa, namely the clayey flatland land form (4 m), toward the inner part of the playa, namely the wet zone (45 cm). At the same time, EC and SAR increase toward the center of the playa (EC, from an average of 7.4 in the clayey flatland land form to 174.8 in the wet zone; SAR, from an average of 8.6 in the clayey flatland land form to 191.7 in the wet zone).

The trends observed in this study are consistent with findings from other Iranian playas. For example, Abtahi *et al.* (2016) reported a similar surface zonation in the Kashan playa, with the highest EC of the saturated soil extract being 174 and the lowest being 6.6, and the minimum and maximum EC of the water being 4 and 128 dS/m. In general, with distance from the lake, the depth of the water surface increases and the EC decreases, indicating differences in brine composition and evaporative mineralogy.

These results suggest: (1) a positive correlation between EC and SAR, and (2) the role of water table fluctuations and capillary rise in controlling salt distribution. In the clayey flat landform, the water table lies at 4 m depth, beyond the capillary fringe. Consequently, salts are not accumulated at the surface by upward movement, resulting in relatively low EC (average 4.8 ds/m) and SAR (average 6.6 meq/L) values. In contrast, from the soft puffy surfaces toward the playa interior, the water table falls within the capillary fringe; consequently, salts move upward through evaporation-driven capillary rise and form salt-enriched sedimentary land

form. The soil texture and salinity data in Table 1 also support this interpretation.

The development of puffy surfaces in the 1-3 m capillary fringe zone likely reflects salt accumulation at the surface due to evaporation-driven upward transport. The observed high SAR values (180.9-573.1 meq/L) in these zones suggest sodium-dominant brines, which promote clay dispersion and the formation of the loose, friable surface texture observed. This mechanism has been previously described by Bourrie (2014) in similar playa settings.

These findings are consistent with previous studies that emphasized the role of groundwater fluctuations and salinity in playa evolution (Rosen, 1994; Arndt *et al.*, 1993; Duffy *et al.*, 1988). Earlier research has shown that playas function as dynamic sedimentary basins where hydrological inputs and evaporative losses determine surface zoning and salt redistribution. The observed pattern in Haj Aligholi playa also agrees with the general model proposed for arid closed-basin systems (Fookes *et al.*, 2018), in which shallow groundwater supports wet playa surfaces, whereas deeper groundwater levels and greater evaporative stress promote dry, salt-encrusted surfaces.

The lithological findings are consistent with this interpretation. Quaternary clayey floor and Quaternary Kavir deposits dominate the study area and provide the parent material for playa-surface development. Quaternary Kavir deposits, which are predominantly fine-grained, have greater moisture retention capacity and facilitate capillary rise of saline groundwater, whereas Quaternary clayey floor deposits are coarser-grained and have a lower capacity to maintain moist conditions. This textural contrast explains the observed spatial variability and coexistence of wet and dry microenvironments.

In addition, geomorphological mapping shows that playa landforms have an overall organized pattern (Krinsley, 1970) and are not randomly distributed; rather, they are structured by the interaction among topographic gradient, drainage slope, and salinity regime (Table 1). Low-lying depressions tend to accumulate water and salt, whereas slightly elevated areas remain drier and experience stronger evaporative stress. Such spatial organization has also been reported in other playa systems, where small differences in elevation and groundwater depth can lead to significant changes in soil salinity and surface type.

From a broader perspective, this study confirms that playa landscapes serve as sensitive indicators of hydrological and climatic variability in desert environments (Born *et al.*, 1979). Any change in groundwater extraction, precipitation regime, or surface runoff can modify the balance between wet and dry conditions and alter the long-term geomorphic evolution of the playa (Jiménez *et al.*, 2018). The sensitivity of playa surfaces to groundwater depth highlights the vulnerability of these systems to groundwater over-extraction. Given the shallow groundwater depths (45-170 cm) in the inner playa zones, even modest declines in water table could substantially alter surface characteristics, potentially increasing aeolian sediment mobilization and dust emission. This is particularly relevant given recent land-use changes and increased groundwater exploitation in the Damghan region. Thus, Haj Aligholi playa functions as a dynamic environmental system where salinity regime, sedimentology, and groundwater dynamics jointly determine surface distribution patterns.

Our studies showed that among the factors examined, groundwater depth appears to be the primary control on surface type distribution of playa, with sediment texture playing a secondary modulatory role. This is evidenced by the data in Table 1.

Several limitations should be acknowledged: (1) the study was based on only four soil profiles, which limits statistical inference; (2) field measurements were conducted during a single season, precluding assessment of temporal dynamics; (3) mineralogical analysis of salts was not performed; and (4) the spatial distribution of sampling points may not capture the full

variability of playa surfaces.

5. Conclusion

The playa surfaces in the southern Haj Aligholi Playa represent the terminal stage of evaporite deposition under hyperarid conditions. This study demonstrates that playa surface types in the southern Haj Aligholi playa exhibit a systematic spatial distribution controlled by groundwater depth and associated salinity regime. Five distinct landforms were identified, transitioning from clay floor at the periphery (groundwater >4 m depth, low EC and SAR) to wet zones in the interior (groundwater <45 cm depth, high EC and SAR).

The findings confirm that the capillary rise of saline groundwater is the primary mechanism driving surface salt accumulation and landform differentiation. Sediment texture plays a critical role in mediating these processes by influencing the capillary rise of saline groundwater. The critical threshold depth (~170 cm) at which surfaces transition from non-saline to saline-sodic conditions has important implications for understanding playa sensitivity to environmental change.

Comparison with other Iranian playa systems reveals similar patterns but with site-specific thresholds, suggesting that local sediment texture mediates the relationship between groundwater depth and surface morphology.

From a management perspective, the documented sensitivity of playa surfaces to groundwater depth indicates that groundwater extraction in the Damghan region should be carefully monitored to prevent surface degradation and associated dust emissions. Future research should incorporate multi-temporal monitoring, mineralogical analysis, and assessment of anthropogenic impacts to better predict playa responses to environmental change.

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Authors Contribution

Author Contributions Naser Mashhadi contributed to all aspects of the study, including conceptualization, methodology, validation, analysis, investigation, data curation, visualization, manuscript preparation, review and editing, supervision, project administration, and funding acquisition. The author has read and approved the final version of the manuscript.

Ethics approval and Consent to participate

The study used publicly available remote sensing datasets and soil and water samples and did not involve human participants or laboratory animals. Therefore, ethical approval was not required.

Competing Interests

The author declares no conflict of interest.

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Consent for Publication

The author consent to the publication of identifiable details, which may include in-text details, which will be published in the journal and the above article.

Data Availability

Data available on request from the author.

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