Patterns and Stability Analysis of Oasis Changes in the Heihe River Basin (Postprint)

Authors: Dong Jingru, Xie Yaowen, Duan Hanming, Wang Xiaoyun, Li Ruyan

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Abstract

This study aims to explore the spatiotemporal change patterns and stability of oases in the Heihe River Basin over the past 55 years. Based on 16 phases of multi-source remote sensing images from 1963 to 2017, we extracted the spatial distribution information of oases in the Heihe River Basin over the 55-year period, and employed overlay analysis, gridding, and other methods to analyze the spatiotemporal characteristics of oasis change patterns and stability. The results demonstrate that the oases in the Heihe River Basin are predominantly characterized by fluctuating change patterns; fluctuating oases are mainly distributed in areas with poor irrigation guarantee and soil salinization; expanding oases exhibit a pattern of inward filling in the early stage and outward expansion in the middle and late stages; and retreating oases are primarily distributed at the ecologically fragile edges of oases. Overall, the oases in the Heihe River Basin are gradually stabilizing, with the stability of downstream oases being lower than that of middle-stream oases. The fluctuations of Jinta and Dingxin oases in the middle and lower reaches occurred mainly in the early stage, whereas the fluctuations of the downstream Ejina Oasis occurred primarily in the middle stage.

Full Text

Pattern and Stability Analysis of Oasis Change in the Heihe River Basin

DONG Jing-ru[1], XIE Yao-wen[1,2]*, DUAN Han-ming[1,3], WANG Xiao-yun[1], LI Ru-yan[1] [1]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, Gansu, China
[2]Key Laboratory of Western China' s Environmental System (Ministry of Education), Lanzhou University, Lanzhou 730000, Gansu, China
[3]College of Land and Resources, China West Normal University, Nanchong 637002, Sichuan, China

Abstract: This study explores the spatiotemporal change patterns and stability of oases in the Heihe River Basin over the past 55 years. Based on 16 phases of multi-source remote sensing imagery from 1963 to 2017, we extracted the spatial distribution information of oases in the basin and analyzed their temporal and spatial characteristics using overlay analysis and grid-based methods. The results indicate that fluctuating change represents the dominant pattern, primarily distributed in areas with poor irrigation guarantee and soil salinization. Expanding oases exhibited an infilling pattern in early stages and outward expansion in middle-to-late periods, while shrinking oases were mainly located on the ecologically fragile margins. Overall, oases in the basin have gradually stabilized, though stability in the lower reaches remains lower than in the middle reaches. Fluctuations in the middle reaches and in the Jinta and Dingxin oases of the lower reaches occurred mainly in the early period, whereas fluctuations in the Ejina oasis of the lower reaches predominantly occurred in the middle period.

Keywords: oasis; change pattern; stability; remote sensing; GIS; Heihe River Basin

Oases represent a unique geographical landscape in arid regions formed by the uneven distribution of natural resources, particularly water resources. Due to the combined advantages of water, soil, topography, and climate, oases possess high carrying capacity for living systems and serve as crucial habitats for human survival and development in arid zones. The landscape matrix of oases is desert, and under the influence of natural environmental changes and human activities, the mutual transformation between oasis and desert constitutes two opposite yet interconnected geographical processes in arid regions—desertification and oasification. Oasis change is the product of the interplay between oasification and desertification in arid areas. Studying the spatiotemporal processes, characteristics, and patterns of oasis expansion and retreat helps deepen our understanding of the dynamics and mechanisms of these two fundamental ecological processes, while revealing oasis stability through their bidirectional transformation.

The Heihe River Basin has a long history of development, with its middle reaches forming an important grain base in western China and the lower Ejina region serving as a significant pastoral area. Located in arid and semi-arid regions, the middle and lower reaches face fragile ecosystems and severe ecological challenges including natural forest and grassland degradation, soil salinization, and lake desiccation under climate change and human activity, threatening oasis stability. Since oasis stability directly impacts regional social stability and ecological security, studying the spatiotemporal changes and stability of Heihe River Basin oases is crucial for ecological restoration and sustainable development. Extensive research has already been conducted on oasis changes and stability in this basin.

Current oasis stability research has focused primarily on qualitative analysis and evaluation indicator systems. Previous scholars qualitatively analyzed the relationship between water resources and oasis stability, yielding relatively macroscopic and general conclusions. Others introduced indicators such as water-heat balance, landscape indices, vegetation NDVI, and oasis cool island effects to quantitatively evaluate stability, while some attempted to establish multi-indicator evaluation models. These indicator-based and model-based studies emphasized temporal variation characteristics but lacked spatial analysis. Although grid-based analysis methods have been developed to effectively detect spatial distribution features of oasis stability and have been widely applied in the Heihe and Shiyang River basins, they have not sufficiently analyzed temporal characteristics. This study employs both overlay analysis (capturing temporal change features) and grid-based methods to explore the spatiotemporal change patterns and stability of Heihe River Basin oases over the past 55 years.

1. Study Area Overview

The Heihe River originates from the Qilian Mountains, flows through the Hexi Corridor in Gansu Province, and finally empties into Juyan Lake in Ejina Banner, Inner Mongolia. As China' s second largest inland river basin, it is located between 96°04 -102°00 E and 37°41 -42°42 N. Most of the basin experiences a continental arid climate. The upper Qilian Mountains receive 300–500 mm annual precipitation with snow and ice meltwater recharge, forming the runoff generation zone. The middle Hexi Corridor receives 100–250 mm annually and constitutes the main oasis distribution area, concentrated in alluvial fans and plains. The lower reaches receive less than 50 mm annually, representing an extremely arid region where oases are mainly distributed along river courses and terminal deltas. Administratively, the basin involves Ganzhou District, Minle County, Linze County, Gaotai County, Shandan County, and Sunan County in Zhangye City; Jinta County and Suzhou District in Jiuquan City; Jiayuguan City; and Ejina Banner in Alxa League, Inner Mongolia. The Jinta, Dingxin, and Ejina oases are located in the lower reaches, while other oases are in the middle reaches [Figure 1: see original paper].

2.1 Data Sources and Oasis Information Extraction

Building upon an existing dataset, we replaced the 2013 data with better-timed 2014 imagery and added data from 2011 and 2017 to extend the temporal series. Image sources and resolutions for each year are detailed in Table 1. Prior to extraction, we performed systematic radiometric correction and atmospheric correction on the new data. We then calculated Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) and applied threshold segmentation to extract oasis information. Visual interpretation was used to refine automatically extracted oasis boundaries, yielding boundary data for each period.

The oasis extent in this study includes natural and artificial vegetation, water bodies, residential areas, industrial land, and small patches of wasteland or vacant land within oases. During extraction, non-oasis patches within oases exceeding 36 pixels were marked as desert, while isolated oases of $ $3 pixels were excluded.

2.2.1 Oasis Change Pattern Analysis

Based on conversion between oasis and desert and boundary change characteristics, we classified oasis change patterns into four categories: stable, expanding, shrinking, and fluctuating (Table 2). Patterns were identified through overlay analysis of oasis boundaries from different sample years. By overlaying data from two consecutive sample years, we detected unchanged areas; increase and decrease areas were identified by excluding unchanged portions from subsequent and previous data, respectively. Across the entire study period, the overlap of all unchanged areas from consecutive years represented stable oases, while the overlap of all increase and decrease areas represented fluctuating oases. Expanding oases comprised all increase areas excluding fluctuating areas, and shrinking oases were similarly derived. For expanding areas, we also identified specific expansion years to correspond with actual land use conditions. Shrinking changes, typically dispersed and fragmented, were not analyzed by specific year.

2.2.2 Oasis Spatial Stability Analysis

Oasis stability manifests as spatial and temporal stability—i.e., minimal change in spatial position and scope over time. Frequent mutual conversion between oasis and desert indicates disordered development. Therefore, we reveal spatial stability distribution based on bidirectional transformation intensity using time series data.

We employed grid-based oasis spatial dynamic degree and cumulative dynamic degree models. The single dynamic degree of land use effectively represents quantitative changes in land use types but cannot reflect spatial distribution. Ma et al. proposed limiting single dynamic degree calculations to grid units to reflect spatial changes. However, Pontius et al. and Luo et al. noted that single dynamic degree only reflects net change, ignoring spatial distribution changes and underestimating total change. Integrating these perspectives, we developed a grid-based oasis spatial dynamic degree model using total change area instead of net change:

$$T_{grid}^{T_2-T_1} = \frac{\Delta U_{in} + \Delta U_{out}}{S_{grid}} \times 100\%$$

where ΔU_{in} and ΔU_{out} are oasis expansion and retreat areas within a grid unit during the study period; S_{grid} is the grid cell area; T_1 and T_2 are the initial and final periods; and T_{grid} is the dynamic degree of oasis change within the grid, theoretically ranging from 0 to 1.

To reflect stability over long time series, we calculated grid-based cumulative dynamic degree:

$$CT_{grid} = \sum T_{grid}^{T_{i+1}-T_i}$$

where n is the number of sample years. CT_{grid} is the cumulative dynamic degree, with a theoretical minimum of 0 and maximum equal to the number of sample intervals (15 in this study). Lower values indicate higher stability.

Considering that newly reclaimed farmland patches typically have edge lengths <1 km, we used 1 km$×$1 km grid cells to minimize impacts from individual farmer behavior and data quality issues, better reflecting overall oasis changes. We calculated grid-based dynamic degree and cumulative dynamic degree for each cell, using cumulative dynamic degree to represent fluctuation intensity and thus stability.

A decision tree determined the most volatile period for each grid to analyze temporal stability characteristics [Figure 2: see original paper]. The temporal series was divided into three roughly uniform periods (see Section 3.2). With uniform change, each period' s cumulative dynamic degree percentage would approach 33% with standard deviation near 0. We used a 5% standard deviation threshold to determine uniformity. When standard deviation exceeded 5%, we identified dominant periods based on cumulative percentage ranking and differences: if the difference between maximum and middle values was $ $10%, the maximum value' s period was dominant; if <10%, both maximum and middle periods were co-dominant.

3.1 Oasis Change Patterns

Figure 3 shows the spatial distribution of oasis change patterns, with area proportions in Table 3. Fluctuating change dominates, accounting for 54.47% of total oasis area (union of all annual extents). Stable, expanding, and shrinking oases comprise 26.42%, 17.78%, and 1.32%, respectively. Fluctuating oases are widely distributed in the lower reaches, while stable and expanding oases concentrate in the middle reaches. Shrinking oases are scattered throughout the basin.

Lower reach oases show greater fluctuation, with fluctuating areas comprising 75.16% of total lower reach oasis area and widespread distribution. Expanding areas account for 13.45%. Early-stage expansion (1963–1968) primarily involved infilling within existing oases as small patches, uniformly distributed within Jinta and Ejina terminal oases. Recent expansion mainly occurred at oasis margins, notably in Yangjingziwan Township southeast of Jinta Oasis and along the Jiu-Hang Highway between Jinta and Dingxin oases [Figure 4: see original paper]. The former began in the 1980s, the latter mainly after 2006. Stable areas comprise 9.58%, with larger patches near Jinta County seat and Ejina Banner government. Shrinking areas (1.81%) appear as small fragmented patches mostly at oasis edges.

Middle reach oases demonstrate higher overall stability. Fluctuating areas constitute 46.34% of middle reach oases, concentrated in most of Minle Oasis and central Linze Oasis, with additional distribution along rivers in Zhangye, Linze, and Gaotai oases and along northern margins of Jiuquan and Jiayuguan oases. Stable areas (33.05%) concentrate within Zhangye, Jiuquan, and Gaotai oases. Expanding areas (19.49%) are prominent in Jiayuguan Oasis, east-central Jiuquan Oasis (Minghua Township, Sunan County), western Gaotai Oasis (Luotuocheng Town), and the Zhangye-Minle Oasis junction [Figure 4: see original paper]. Expansion in Jiayuguan, Luotuocheng, and Minghua government areas began in the 1960s, 1970s, and 1990s, respectively, initially as "enclaves" distant from main oasis bodies before gradually connecting. Expansion in Minghua' s Qiantan Village and the Zhangye-Minle junction occurred mainly after 2006 as spread-type expansion. Shrinking areas (1.13%) are small and sporadically distributed at oasis margins.

3.2 Oasis Stability

Grid cumulative dynamic degree reflects oasis stability in each cell [Figure 4: see original paper]. Since actual changes typically occur as small patches <1 km$×$1 km, observed cumulative dynamic degrees are far below the theoretical maximum of 15, ranging from 0 to 7.5 in the study area. High values are rare, with 81.46% of grids having cumulative dynamic degree <2.5 and over half <1.04. High values indicate intense fluctuation.

Spatially, the lower reaches show higher overall dynamic degree. Concentrated high-value areas (>3) appear in Xiba Township and Dongba Town northwest and northeast of Jinta Oasis, along river courses and reservoirs near Dingxin Town, and along rivers and in terminal oases in Ejina Banner, indicating poor stability. The middle reaches have fewer high-value grids, concentrated in northern Minle Oasis and Yaning Town in central Linze Oasis, but with lower aggregation than downstream. Overall, most middle reach grids show low cumulative dynamic degree and relatively high stability, while the lower reaches have more high-value grids and intense fluctuation.

Xie et al. divided Heihe River Basin oasis development stages. Our added data post-2011 [Figure 5: see original paper] show consistent trends with their 2002–2009 period. We therefore adopt a similar periodization: 1963–1980, 1980–2002, and 2002–2017, designated as early, middle, and late periods. Based on dominant period analysis, we further classify temporal patterns into seven modes: early, early-middle, middle, middle-late, late, early-late, and entire period.

Most oasis fluctuations show temporal continuity, with the discontinuous early-late mode accounting for only 1.97%. Continuous modes (early-middle, middle-late, entire period) are also rare (14.12%, 5.35%, and 5.84%, respectively). Dominant periods are primarily single-period modes: early (26.83%), middle (23.27%), and late (22.62%).

In entire-period mode, 54.82% of grids have cumulative dynamic degree $ $1, primarily representing stable oases—most notably Zhangye Oasis. In late-dominant grids, the proportion with cumulative dynamic degree \$ \$1 is highest (75.72%), mainly representing expanding oases. The western Gaotai Oasis (Luotuocheng Town) shows middle-dominant fluctuation but also represents expansion. These areas show no actual fluctuation (dynamic degree = 0 or only expansion-related). Thus, although early, middle, and late-dominant grids are similarly numerous, early-dominant fluctuating oases far exceed those in middle and late periods, indicating a weakening fluctuation trend over time.

Middle reach oases and lower reach Jinta and Dingxin oases show early-dominant fluctuation. In Jinta Oasis, intensely fluctuating Xiba and Dongba Towns are early-dominant. In Dingxin Oasis, intense fluctuation occurred mainly in early-middle periods, with some riverine areas late-dominant. In Minle Oasis, northern fluctuation is early-middle dominant, while central Linze Oasis fluctuation is early-dominant with some middle and entire-period patterns. In contrast, Ejina' s riverine and terminal oases show middle-dominant fluctuation. Over time, oases have gradually stabilized, with early-dominant areas upstream of the Langxinshan hydrological station and middle-dominant areas downstream in Ejina Oasis.

4.1 Causes of Typical Expansion Patterns

Oasis expansion exhibits two spatial patterns: infilling within main oasis bodies and outward expansion. The former occurred mainly in early stages (especially 1963–1968), the latter in middle-late periods. Outward expansion occurs in two ways: gradual marginal spread, as seen in Yangjingziwan Township (Jinta County), Zhangye-Minle junction, and Minghua Township; and enclave formation at a distance from main oases that gradually expands, as along the Jiu-Hang Highway between Jinta and Dingxin oases, Jiayuguan City, and Luotuocheng Town.

Significant expansion in Minghua, Luotuocheng, and Yangjingziwan relates to resettlement programs. Minghua Township is a major ecological resettlement area for Sunan County, with nomads relocating and transitioning to farming since the early 1990s. Yangjingziwan and Luotuocheng were key resettlement bases under the "Two Wests" immigration program starting in 1983. Jiu-Hang Highway oases developed from 2006–2009, expanding significantly after 2009 following the highway' s 2005 completion, which enabled development in areas distant from towns. Zhangye-Minle junction expansion after 2006 features high-tech agricultural demonstration parks using water-saving technologies (drip and sprinkler irrigation) established by private enterprises. In Ganzhou District' s Qianjin Village, the Qianjin Pasture was established as a village-run shareholding enterprise under national agricultural support policies. Unlike agriculture-driven expansion elsewhere, Jiayuguan' s expansion mainly resulted from urbanization. Overall, Heihe River Basin oasis expansion primarily involves cropland and pastoral farms, with urbanization playing a smaller role, driven mainly by policy-guided resettlement and reclamation, transportation infrastructure, and collective farm development.

4.2 Stability and Influencing Factors of Typical Fluctuation Patterns

Over the past 55 years, Heihe River Basin oases have fluctuated significantly, with fluctuating areas accounting for 54.47% of total oasis area. Low irrigation guarantee and soil salinization are the most important causes. Jinta and Ejina oases, located at the terminals of the Beida River and Heihe River mainstem, are vulnerable to water shortage and high salinity. Central Linze Oasis (Xinhua and Yaning towns) lies at the edge of alluvial fans with low-lying topography and shallow groundwater—these three regions are high-incidence salinization areas. Salinization reduces soil productivity and crop yields, prompting abandonment of original farmland and reclamation of new land, leading to frequent fluctuations.

River channel migration and water level changes are another important cause. Minle Oasis lies on alluvial fans at the northern Qilian Mountains foothills, with numerous longitudinal tributaries and channels, fragmented cropland, and lack of large water storage, diversion, and irrigation systems, causing large interannual fluctuations. Fluctuations in Dingxin and Ejina riverine oases relate more to water level fluctuations—in low-flow years, low water levels expose riverbanks identified as "desert," causing identification differences.

Fluctuations have weakened over time. Middle reach oases and lower reach Jinta and Dingxin oases show early-dominant fluctuation, related to extensive early-stage agriculture and imperfect irrigation systems. In middle-late periods, improved irrigation conditions and intensive production stabilized original oases, with change dominated by expansion. Middle-dominant fluctuation in Ejina's riverine and terminal oases relates to Heihe River mainstem water conservancy projects. In the 1990s, the Caotanzhuang and Dadunmen water diversion projects reduced downstream flow, causing terminal lake desiccation and severe vegetation degradation, making irrigation unsustainable and causing frequent fluctuations. Since 2000, unified water scheduling has secured downstream flows, curbed vegetation degradation, improved irrigation guarantee, reduced fluctuations, and enhanced stability—consistent with previous research.

It should be noted that 1973 and 1977 Landsat MSS imagery had low resolution and poor timing, reducing extraction accuracy and introducing error into early-stage stability analysis.

This study extracted oasis boundary information at relatively high temporal frequency (1963-2017) and identified four basic change patterns through overlay analysis: stable, expanding, shrinking, and fluctuating. Grid-based cumulative dynamic degree analysis further examined stability and dominant periods. Main conclusions are: (1) Fluctuating change dominated Heihe River Basin oases, accounting for ~50% of total area, followed by stable and expanding areas, with shrinking areas being smallest. (2) Stability is weaker in lower reaches than middle reaches, strengthening from early to middle-late periods. Specifically, lower reach stability is weaker than middle reaches; middle reach and lower reach Jinta and Dingxin oases fluctuated mainly in early periods, while Ejina's riverine and terminal oases fluctuated mainly in middle period. (3) Causes vary: resettlement and agricultural technological innovation drove expansion; salinization, river migration, and water level changes caused fluctuation; water conservancy development, policy implementation, and water-saving irrigation technology improved stability and enabled orderly expansion.

Compared with previous studies, this work simultaneously detected temporal and spatial characteristics of oasis changes at grid scale, enabling more effective change localization and cause analysis. However, it only qualitatively analyzed stability influencing factors; future research should conduct quantitative analysis from socio-economic and technological perspectives.

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Pattern and stability analysis of oasis change in Heihe River Basin

DONG Jing-ru[1], XIE Yao-wen[1,2*], DUAN Han-ming[1,3], WANG Xiao-yun[1], LI Ru-yan[1] [1]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, Gansu, China
[2]Key Laboratory of Western China’ s Environmental System (Ministry of Education), Lanzhou University, Lanzhou 730000, Gansu, China
[3]College of Land and Resources, China West Normal University, Nanchong 637002, Sichuan, China

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Note: Figure translations are in progress. See original paper for figures.