Journal of Global Change Data & Discovery. 2025, 9(1): 1-13
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Global Change Research Data Publishing & Repository

Oases Distribution and Catalog of China

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Abstract: Oases, as azonal geographical units within arid regions, serve as distinct places for human survival, their livelihood and maintaining human-environment interactions. Despite their significant importance in arid zones, oases are confronting the critical challenges of unclear baseline statistics, uncertain boundaries, and inconsistent data that have been emerged under the rapid development of geospatial big data technologies. Notably, the absence of systematic cataloging has hindered the advancement of oasis science. To address these challenges, this study selected 2020 as the baseline year and employed high-resolution summer imagery from Google Earth as the primary data source, supplemented by Sentinel-2 imagery. Through a rigorous three-year process encompassing image calibration, visual interpretation, field surveys, and manual revisions, we successfully extracted foundational data on Chinese oases. Subsequently, each oasis was systematically cataloged based on administrative divisions, river, and area attributes. Our analysis confirms that China contains 1,466 oases with individual areas exceeding 0.01 km², collectively covering 277,375.56 km² (approximately 3.02% of the national territory). These oases are distributed between 74.04°E–101.21°E and 35.87°N–48.39°N, spanning five provinces, 22 geomorphic units, and 7 major river basins. In terms of size, super-large oases (>10,000 km²) are predominant, with only eight of such kind of oases covering 151,783.04 km², which constitutes 54.72% of the total oasis area. Xinjiang Uighur Autonomous Region has the largest oasis area (171,801.06 km²), representing 63.78% of China's total oasis area, primarily distributed at elevations of 700–2,600 m. Among geomorphic units, the Northern Tarim River lacustrine-alluvial plains small-region exhibits the most extensive oasis distribution (43,613.54 km²) and the highest concentration of large-sized oases, including the Tarim Mainstream Oasis, Weigan River Oasis, and Aksu Oasis, etc. The Tarim inflow region contains the largest oasis area (89,723.69 km², 30.80% of the national total), where oases form a ring along the periphery of the Taklimakan Desert, and interconnected by the Tarim River. In terms of quantity, 853 miniature oases (0.01–1 km²) account for 58.19%. Xinjiang has the largest number of oases (1,078), accounting for 73.53% of the total number of oases in China. This study not only clarifies the baseline statistics of Chinese oases in 2020 but also fills the critical gap in systematic oasis cataloging, providing a robust foundation for advancing oasis science and promoting global research on arid-region ecosystems.

Received: 24-10-2024; **Accepted:** 23-02-2025; **Published:** 25-03-2025

Foundations: Xinjiang Uygur Autonomous Region (2023TSYCLJ0049); National Natural Science Foundation of China (42361144792); Chinese Academy of Sciences (2023)

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Citation: Gui, D. W., Lin, J. W., Liu, Y. F., *et al*. Oases distribution and catalog of China [J]. *Journal of Global Change Data & Discovery*, 2025, 9(1): 1–13. https://doi.org/10.3974/geodp.2025.01.01.

Keywords: arid regions; oases; cataloging; China; river basins; geomorphic units

DOI: https://doi.org/10.3974/geodp.2025.01.01

1 Introduction

Oases are heterogeneous geographical units formed on desert substrates in arid regions, driven by stable water sources[1]. They serve as vital hubs for human livelihoods and biodiversity conservation in arid regions[2]. Therefore, the stability of oases holds significant importance for the ecological civilization and regional socio-economic development of arid regions[3,4]. Consequently, they consistently remain a key focus of research and are attracting increasing attention from scholars in these regions. Particularly after the systematic introduction of the concept of Oasis Studies by Huang[5], oasis research gradually became more systematic and turned into a distinctive discipline within the study of arid regions[6–8]. After 30 years of dedicated research, oasis studies in China have achieved a global prominence, focussing on land use changes in oasis[9], optimization of oasis water resource allocation[10], oasis evolution under climate change[11], and studies on suitable scales[12]. Several studies have focused on individual oases[13,14] or specific regions[15–17] from physical geography point of view. However, with the rapid development of geographic information and big data, there is still a lack of a complete and clear answer regarding the total number of spatially independent oases in China and their geographical attributes, such as location distribution, area boundaries, and regional affiliation.

The classification and cataloging of a geographical unit are fundamental tasks in geography and holds significant academic value in clearly understanding its distribution and evolutionary patterns. The lack of basic data on oasis distribution has hindered the progress of oasis cataloging. Compared to cataloging studies of other geographical units like glaciers[18,19], lakes[20], and wetlands[21], research on oasis cataloging remains generally underdeveloped and overlooked, resulting in an incomplete understanding of oasis science. Nonetheless, previous scholars in China have made considerable contributions to the zoning of oases. For example, Shen[22] conducted a comprehensive classification of China's oases based on human impact, the formation period and stages of oases, and their geomorphological location. Yang[23] systematically explored the principles and methods of oasis zoning and proposed a three-level zoning scheme for Chinese oases based on climate, geomorphology, and rivers. These studies about classification and zoning of oases provided a solid foundation for oasis cataloging and necessitate further development in this field to improve the oasis research.

Therefore, this study focuses on China's oases, selecting 2020 as the baseline year. Based on the definition of oases, the study uses multi-source remote sensing imagery and field surveys. The oases are first accurately interpreted through manual visual analysis, and then each spatially independent oasis is assigned a unique "academic ID" based on its geographical attributes. Ultimately, a comprehensive catalog of oases in China is created to present a panoramic view of oasis distribution. After three years of dedicated efforts, the research team completed the coding of all oases in China larger than 0.01 km^2. This coding effectively reflects the spatial distribution characteristics and natural attributes of the oases, providing a baseline for studies regarding land use changes in oasis, spatiotemporal variations, and so on. It holds significant implications for analyzing the causes and mechanisms behind the distribution of oases in China, advancing oasis research from qualitative to quantitative approaches, and establishing a strong foundation for the future quantitative study of oases in Central Asia and even on a global scale.

2 Data and Methods

2.1 Data Sources

The high-precision identification of oases is the foundation for oasis cataloging. The data used in this study primarily includes satellite remote sensing imagery, Digital Elevation Model (DEM) data, and basic geographic information of China. The remote sensing imagery is used to determine the presence of oases, extraction of oasis boundaries, and study oasis habitats. To ensure data uniformity, accuracy, and scientific reliability, high-precision imagery (from summer of 2020) of northwest China obtained from Google Earth (spatial resolution better than 1 m), was employed for identification and analysis. For areas where some images had not been updated in a timely manner or had quality issues such as excessive cloud cover, Sentinel-2 data[1] released by the European Space Agency (spatial resolution of 10 m), was used as a substitute. The DEM data were sourced from the 12.5m ALOS satellite product[2] from the Japan Aerospace Exploration Agency, which was used in conjunction with remote sensing data to assist visual interpretation and extract geometric parameters such as slope, aspect, and elevation of the oases. The basic geographic information of China was obtained from the National Geomatics Center of China[3], which included administrative divisions of provinces and the distribution of major rivers, providing data for oasis encoding and distribution analysis.

2.2 Methods

Repeated experimentation revealed that existing automatic oasis extraction methods[24,25], are time-saving and convenient, but they often use low-resolution remote sensing imagery for large-scale area extraction, resulting in poor extraction quality and accuracy. This leads to contrasting statistical results regarding oasis numbers and areas, lacking precise quantitative statistics on oasis numbers. Therefore, this study adopted a manual visual interpretation method, completing the extraction of oases over a period of three years. The sources of error in oasis extraction mainly fall into two categories: technical errors and human errors. To reduce technical errors, each remote sensing image was systematically radiometrically and geometrically corrected to make the features of image clearer and consistent with the geographic locations of the DEM data. Human errors mainly arose from differences in the judgment standards and practical experience of different operators when determining oasis boundaries. To minimize subjective errors, an expert group consisting of professionals in the field was established before the work began. The group discussed and formulated work guidelines for oasis data extraction (including the operating procedures of Google Earth software, selection criteria for remote sensing images and specifications for extracting oasis boundaries, etc.). Additionally, each staff member underwent expert guidance and skill training before conducting visual interpretation, and was tested on five experimental areas until they were proficient in identifying oases based on features such as the shape, size, and shadow of objects, as well as pixel texture and color. Only after achieving this level of proficiency could they begin formal oasis extraction work.

During the boundary extraction of oases, it was observed that the transition zone between oases and deserts shares similar features with the oasis itself in remote sensing images, which caused problems while classifying some areas[26,27], thus presenting difficulties in the extraction process. To accurately delineate the boundary between oases and deserts, we first performed land-use classification on the remote sensing images and then used the method of

[1] European Space Agency. https://scihub.copernicus.eu/.

[2] JAXA, Japan Aerospace Exploration Agency. https://search.asf.alaska.edu/.

[3] National Geomatics Center of China. http://www.ngcc.cn/.

calculating the Fractional Vegetation Cover (FVC) to make the distinction. The resulting FVC values ranged from 0 to 1. Pixels with FVC <0.2 (arid) or <0.3 (semi-arid) were classified as desert, while the rest were designated as oasis areas aligning with soil aridity indices and vegetation resilience thresholds[28].

In addition, for areas where land-use types were difficult to identify from the remote sensing imagery or where image quality was insufficient, detailed field surveys and GPS measurements were conducted to determine the land features and boundary ranges. This ensured that the extraction results for most areas of China's oases had an accuracy within 1 m, while the worst extraction precision being <10 m. The extracted oasis data for China were then imported into ArcGIS for spatial topology checks, removing patches smaller than the minimum identifiable area (0.01 km^2), and the data were projected using the Albers Equal-Area Conic projection (central meridian 91°E, standard parallels 35°N and 49°N, WGS84 coordinate system) for the purpose of oasis cataloging and area calculations.

2.3 Encoding Rules

Determining a reasonable coding scheme is the main pillar of the cataloging process. Based on the previous work of coding the fields of climate type, province, landform, river and area[29], in order to further reflect the simplicity and combine with the expert consultation, it was finally determined that China's oasis cataloging code consists of three attributes that best reflect the characteristics of the oasis, namely, province, river and area (Figure 1). Each oasis code comprises six characters, with two characters allocated to each of the three attributes. By defining and assigning these coding fields, each oasis is assigned a unique "academic ID". Beyond the coding system, additional geographic attributes such as latitude and longitude, perimeter, and elevation were included in the oasis attribute table (Table 1). The complete vector dataset of China's oases has been published in the Global Change Research Data Publishing & Repository[4].

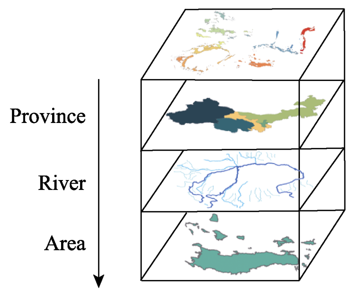


Figure 1 Composition of coding attributes for oases of China

3 Data Results

3.1 Overall Distribution and Scale of Oases of China

Based on the academic definition of oases, China's oases are distributed in the arid and semi-arid regions of Northwest China, spanning from 74.04°E to 101.21°E, 35.87°N to 48.39°N. These oases are located in northwestern Xinjiang, Gansu, and Qinghai, northern Ningxia, and central-western Inner Mongolia, extending westward to the Kashgar region and eastward to Baotou, bordered by the Altai Mountains to the north, and the Kunlun and Qilian Mountains to the south (Figure 2). This spatial delineation is generally consistent with the range defined in most literature sources[22,23]. However, some studies[30] have controversially classified areas east of Baotou as part of the oasis region. Since these areas are no longer within the semi-arid zone, they are not considered oases in this study.

According to statistical analysis, China has a total of 1,466 spatially independent oases, covering an area of 277,375.56 km^2, which accounts for 3.02% of China's total land area and approximately 8% of its arid region. Oases in China are distributed irregularly, with some oases forming continuous belts along river systems, while others are scattered as isolated patches in mountainous areas. This distribution pattern reflects the tendency of oases to spread along mountains, develop around water sources, and inhabit suitable soil environments.

[4] Global Change Research Data Publishing & Repository. http://www.geodoi.ac.cn.

Table 1 Attributes table of the China oases dataset (part)

OasisID	ProvinceID	RiverID	AreaID	Area (km^2)	Perimeter (m)	Longitude (°E)	Latitude (°N)	Mean_Elev (m)
XJ2401	XJ	24	1	33,498.30	5,380.39	86.91	44.45	576.50
QH1501	QH	15	1	30,647.27	441.84	95.08	36.97	1,067.54
IM0101	IM	01	1	19,956.77	2,810,556.99	108.14	40.55	1,008.51
XJ4201	XJ	42	1	19,847.57	1,700.63	84.91	40.86	1,259.98
XJ4601	XJ	46	1	14,136.35	3,003.74	78.03	38.95	2,206.44
XJ4301	XJ	43	1	10,777.39	64,004.84	76.57	39.28	1,997.92
NX0102	NX	01	2	7,757.03	809,678.51	106.88	38.63	1,091.11
GS1201	GS	12	1	7,677.37	4,232.61	102.82	37.79	1,550.95
GS0701	GS	07	1	6,736.80	1,989.15	100.47	38.89	1,523.81
XJ6201	XJ	62	1	3,311.27	1,845.63	88.34	39.12	1,564.58
XJ6101	XJ	61	1	3,263.30	2,247.24	86.59	38.74	1,733.57
GS0201	GS	02	1	2,439.29	37,639.23	96.52	40.40	1,917.41
NX0103	NX	01	3	2,329.93	579,639.79	105.48	37.58	1,281.51
NX0103	NX	01	3	2,323.19	579,639.79	105.48	37.58	1,281.51
GS1202	GS	12	2	2,198.81	3,670.20	103.35	38.78	1,357.35
GS0301	GS	03	1	1,830.21	160,134.99	94.71	40.35	1,440.23
XJ8302	XJ	83	2	1,688.97	12,531.04	81.75	41.77	1,857.40
QH7601	QH	76	1	1,649.45	989.08	90.68	39.61	2,104.10
NX0104	NX	01	4	887.36	321,164.73	105.07	37.02	1,666.08
QH1301	QH	13	1	841.89	1,189.96	94.19	38.93	746.73

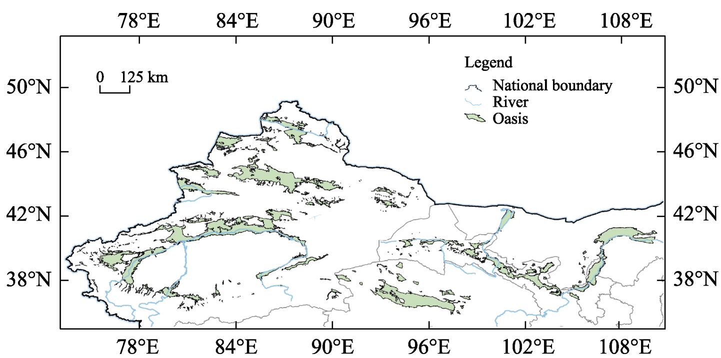


Figure 2 Spatial distribution of oases of China (2020)

Furthermore, the analysis also reveals that although small oases are numerous, they cover only a small fraction of the total oasis area. In contrast, large oases are less common but make up a substantial portion of the overall oasis coverage.

3.2 Oasis Distribution Characteristics by Province

The number, area, and proportion of oases in each province are provided in Table 2. According to the Table 2, Xinjiang has the highest number and largest area of oases among all the five provinces, with 1,078 oases, accounting for 73.53% of the total number of oases in China. The total area is 171,801.06 km^2, accounting for 63.78% of the total oasis area in the country. Over the past 30 years, oasis area in Xinjiang has shown a significant increase and the proportion of oasis area to its administrative area has increased from about

5%–8%[31,32] to over 10% (reaching 10.32%). Oases in Xinjiang are divided into northern and southern parts by the Tianshan Mountains. The northern part of Xinjiang, contains the northern Tianshan oasis, formed by regions like Urumqi, Changji, and Shihezi, as well as the rapidly developing industrial and mining oasis of Karamay due to oil, and the scenic Ili oasis. The southern part of Xinjiang, comprises of many historically significant oases such as the Hotan, Aksu, and Kashgar oases.

Qinghai has a relatively small number of oases, with only 25 patches, covering a total area of 30,047.08 km^2, ranking second in China and accounting for 11.15% of the country's total oasis area. However, due to Qinghai's large administrative area, its oasis area proportion is only 4.16%. Qinghai's oases are predominantly natural, with extensive original vegetation, making them the least affected by human activities compared to other provinces.

Gansu ranks second in the number of oases (316 patches) and third in total oasis area (29,024.79 km^2), representing 10.77% of China's total oasis area and 8.81% of Gansu's administrative area. Notably, southeastern Gansu lies at the transition between semi-arid and semi-humid zones, where the boundary between oases and non-oases areas is difficult to define. Therefore, the actual oasis area in Gansu may be larger than reported.

Inner Mongolia and Ningxia have smaller oasis areas, with 25,201.61 km^2 and 13,301.02 km^2, accounting for 9.36% and 4.94% of the national total, respectively. However, due to the relatively small administrative areas of these provinces, their oasis area proportions are relatively high, at 21.30% and 20.03%, respectively. In Alxa, Inner Mongolia, the semi-arid climate has created a landscape with relatively dense herbaceous and shrub vegetation, which falls outside the academic definition of an oasis. Consequently, no natural oases exist in this region. However, increasing population and economic activities have led to extensive groundwater extraction for irrigation, resulting in the formation of numerous scattered artificial oases.

Table 2 Number, area, and percentage of oases in each province

Province	Number	Oasis area (km^2)	Administrative area (km^2)	Percentage of total oasis area (%)	Percentage of administrative area (%)
Xinjiang	1,078	171,801.06	1,664,900	63.78	10.32
Qinghai	25	30,047.08	722,300	11.15	4.16
Gansu	316	29,024.79	425,900	10.77	8.81
Inner Mongolia	37	25,201.61	118,300	9.36	21.30
Ningxia	10	13,301.02	66,400	4.94	20.03

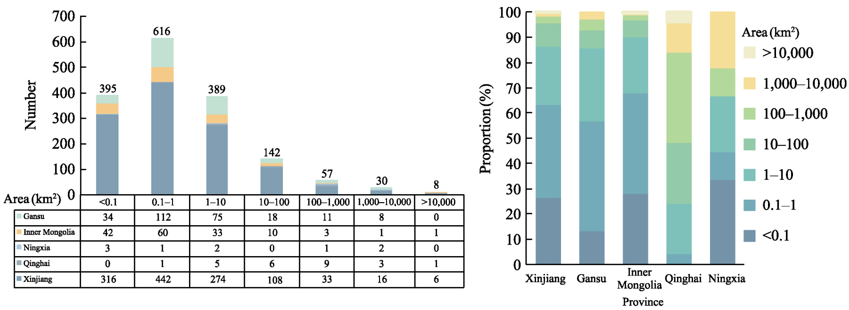
China's oases are classified into 5 categories based on size: micro oases (0.01–1 km^2), small oases (1–100 km^2), medium oases (100–1,000 km^2), large oases (1,000–10,000 km^2), and extra-large oases (>10,000 km^2)[33]. Statistical charts and percentage-stacked graphs of the number and area of oases at different scales in each province are presented in Figure 3 and 4. As shown in the figures, micro oases (0.01–1 km^2) are the most frequent in the four provinces of Xinjiang, Gansu, Inner Mongolia, and Ningxia, accounting for 59.65%, 59.81%, 43.24%, and 40.00% of the total number of oases in each province, respectively. Despite their large numbers, micro oases cover a small area, with a total of just 244.18 km^2. As the oasis size category increases, the number of oases decreases, while the total area occupied by these oases progressively increases, albeit at a diminishing rate.

The number of small oases (1–100 km^2) is 523, covering an area of 6,264.85 km^2, mainly distributed in Xinjiang, Inner Mongolia, and Gansu. Compared to micro oases, their number decreased by 15.10%, but their total area was increased by 24.66 times. The number of medium oases (100–1,000 km^2) is 53, accounting for 3.62% of the total number of oases in China, with a combined area of 16,734.13 km^2, representing 6.03% of the total oasis area.

Among them, Qinghai has the highest proportion of small and medium-sized oases, reaching 25.71%.

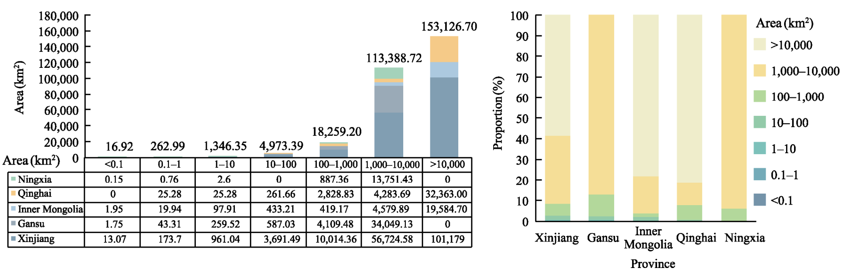
The number of large oases (1,000–10,000 km^2) is 29, accounting for 1.98% of the total number of oases in China, with a total area of 100,517.68 km^2, representing 36.23% of the total oasis area. Among these, the proportion of large oasis areas was the highest in Ningxia (85.99%) and Gansu (93.30%). Compared to medium oases, the number of large oases decreased by 45.28%, but their total area increased by 5.01 times. The number of extra-large oases (>10,000 km^2) are extremely rare, with only 8 in total, out of which 6 are located in Xinjiang, and one each in Qinghai and Inner Mongolia. These extra-large oases account for just 0.54% of the total number of oases in China but cover a vast area of 151,783.04 km^2, making up 54.72% of the total oasis area. Compared to large oases, the number of extra-large oases decreased by 72.41%, while their total area increased by 0.51 times.

Based on the spatially contiguous oasis areas, the ten largest oases in China are: the middle and lower reaches of the Tarim River Oasis (51,900.52 km^2), the northern slope of the Tianshan Mountains Oasis (33,498.30 km^2), the Qaidam Basin Oasis (30,647.27 km^2), the Hetao Plain Oasis (30,043.73 km^2), the Kashgar-Yarkand River Oasis (24,960.17 km^2), the Shiyang River Oasis (10,851.67 km^2), the Irtysh River Oasis (10,774.94 km^2), the Ili Oasis (9,080.27 km^2), the middle reaches of the Heihe River Oasis (6,736.80 km^2), the Emin River Oasis (6,248.26 km^2).



Area (km²)	<0.1	0.1–1	1–10	10–100	100–1,000	1,000–10,000	>10,000
Gansu	34	112	75	18	11	8	0
Inner Mongolia	42	60	33	10	3	1	1
Ningxia	3	1	2	0	1	2	0
Qinghai	0	1	5	6	9	3	1
Xinjiang	316	442	274	108	33	16	6

Figure 3 Number and percentage of oases by different scales in 5 provinces of China



Area (km²)	<0.1	0.1–1	1–10	10–100	100–1,000	1,000–10,000	>10,000
Ningxia	0.15	0.76	2.6	0	887.36	13,751.43	0
Qinghai	0	25.28	25.28	261.66	2,828.83	4,283.69	32,363.00
Inner Mongolia	1.95	19.94	97.91	433.21	419.17	4,579.89	19,584.70
Gansu	1.75	43.31	259.52	587.03	4,109.48	34,049.13	0
Xinjiang	13.07	173.7	961.04	3,691.49	10,014.36	56,724.58	101,179

Figure 4 Area and percentage of oases by different scales in 5 provinces of China

From the ridge plot of the average elevation distribution of oases in each province (Figure 5), it can be observed that the elevation range of oases in Xinjiang is the widest, forming multiple ridges. The lowest point is below sea level, while the highest point approaches 4,000 m. The majority of oases are concentrated between 700 m and 2,600 m. The elevation distribution of oases in Qinghai is relatively balanced, with a smaller range of variation, as all oases are located in high-altitude regions. The lowest point is approximately 2,600 m, while the highest exceeds 3,100 m, forming a distinct bimodal structure. The peak values, indicating areas with concentrated oasis distribution, are around 2,800 m and 3,000 m.

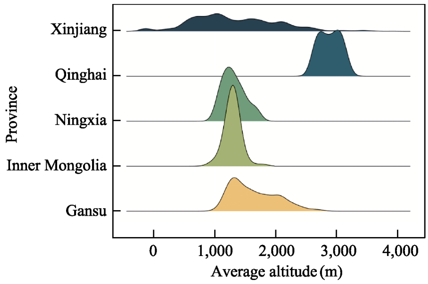


Figure 5 Ridge map of average elevation distribution of oases by province of China

The elevation distribution characteristics of oases in Ningxia and Inner Mongolia are similar, with relatively lower overall elevations compared to other regions. The lowest elevations in both provinces are around 900 m, and the ridge plots exhibit a unimodal structure, with peak values at approximately 1,300 m in Ningxia and 1,400 m in Inner Mongolia. The elevation distribution of oases in Gansu is wider, ranging from a minimum of approximately 1,000 m to a maximum exceeding 2,700 m. The distribution forms two peaks, one major and one minor. Around the main peak at 1,300 m, 49.22% of the oases are distributed, while around the secondary peak at 2,200 m, 10.85% of the oases are found.

3.3 Oasis Distribution and Scale across Different Geomorphological Units

Geomorphological units, as the primary receptors and media for light, thermal energy, and water, directly influence the regional environment and distribution of surface water and thermal energy. They also affect the conversion processes of land, vegetation, and their products, as well as the succession and evolution of ecosystems indirectly. The formation and development of oases are closely related to specific geomorphological locations, and the type of landform is strongly correlated with the geometric configuration and spatial distribution under these conditions of oases. In China, oases are predominantly distributed in plains and basins, covering a total area of 255,476.68 km^2, accounting for 92.10% of the total oasis area. The number of oases is 1,181, making up 80.56% of the total number of oases.

According to the Chinese geomorphological classification system[34], the regions where China's oases are located are divided into 22 geomorphological units (Table 3). The top three geomorphological units with the largest oasis areas are the Northern Tarim River lacustrine-alluvial plains small-region (43,613.54 km^2), the Qaidam Basin small-region (38,315.63 km^2), and the Southern margin of Junggar Basin diluvial-alluvial plains small-region (34,396.02 km^2), which account for 15.52%, 13.81%, and 12.40% of the total oasis area in China, respectively. The Northern Tarim River lacustrine-alluvial plains small-region, located in the Tarim River Basin, is formed by river erosion and lake deposition. The terrain is flat, and the water and soil conditions are favorable for human settlements, supporting large oases such as the Tarim River main stream oasis, the Weigan River oasis, and the Aksu oasis. The Qaidam Basin small-region, surrounded by a series of northwest-southeast parallel mountain ranges and wide valleys, has favorable heat conditions in the center, allowing the deposition of material carried from the surrounding mountains. This leads to fewer oases (27 in total), but a very large oasis (30,647.27 km^2) exists in the center of the basin. The Southern margin of Junggar Basin diluvial-alluvial plains small-region relies mostly on natural precipitation for vegetation development, with relatively uniform seasonal water distribution. This is the only region in China's desert areas where vegetation is distributed in a non-contracted pattern.

The top three geomorphological units in terms of oasis quantity are the Hexi Corridor alluvial-diluvial plains small-region (235 oases), the Turpan-Hami alluvial-diluvial plains small-region (211 oases), and the Southern margin of Tarim River alluvial-diluvial plains small-region (140 oases), which account for 16.03%, 14.39%, and 9.55% of China's total oases, respectively. The Hexi Corridor alluvial-diluvial plains small-region consists of the Anxi-Dunhuang Basin, the Jiuquan-Zhangye Basin, and the Wuwei Basin. Due to its unique geographical location and favorable terrain, this area has long been a major communication route in central and western China, with a long history of development. The Hexi Corridor has not only many oases but also contains considerable oasis areas (25,482.18 km^2). The Turpan-Hami alluvial-diluvial plains small-region is the driest and hottest region in Xinjiang, making it difficult to form perennial rivers. Historically, people used qanat systems to channel water into oases, leading to a high degree of fragmentation, but also many oases. The Southern margin of Tarim River alluvial-diluvial plains small-region includes five medium-sized oases in areas such as Cele, Yutian, Minfeng, Ruoqiang, and Qiemo. Each oasis is linked to the river that provides water and soil, but the rivers are relatively short, and their outlets lead into the desert, which makes the oases scattered and loosely connected in this area. Additionally, the western segment of central Kunlun Mt. high mountains and lake basins small-region, with its high altitude and barren soil, belongs to a plateau temperate climate. Under such conditions, the oasis formation is very difficult resulting in a few and small size oases. Therefore, the only oasis in the Altyn-Tagh Mountain area, which is abundant in lakes, is located here.

Table 3 Statistics of oases in different geomorphological units

Geomorphological Units	Area (km^2)	Number
Northern Tarim River lacustrine-alluvial plains small-region	43,613.54	125
Qaidam Basin small-region	38,315.63	27
Southern margin of Junggar Basin diluvial-alluvial plains small-region	34,396.02	41
Hetao alluvial plains small-region	27,714.43	9
Hexi Corridor alluvial-diluvial plains small-region	25,482.18	235
Southern margin of Tarim River alluvial-diluvial plains small-region	24,084.52	140
Ulungur and Ertix rivers alluvial plains small-region	12,331.79	41
Kashgar diluvial-alluvial plains small-region	11,173.14	59
Central Tianshan Mt high mountains and basins small-region	9,100.20	6
Yanqi Basin small-region	8,855.34	57
Western Junggar middle mountains and hills small-region	7,769.56	102
Southeastern margin of Tarim River alluvial-diluvial platforms and plains small-region	6,628.62	12
Liupan Mt middle and low mountains, hills and valleys small-region	5,543.84	6
Mazong Mt middle mountains and hills small-region	4,653.37	4
Tianshan Mt north piedmont low mountains, hills and plains small-region	4,344.45	108
Turpan-Hami alluvial-diluvial plains small-region	4,340.83	211
Alxa plateaus, hills, aeolian plains small-region	4,133.59	109
Eastern Tianshan Mt. high mountains small-region	1,563.85	67
Gurbantunggut Desert small-region	1,475.91	21
Western segment of central Kunlun Mt high mountains and lake basins small-region	962.40	1
Western Kunlun Mt high and extremely high mountains small-region	485.20	13
Southern Tianshan Mt high mountains small-region	407.13	72

3.4 Oasis Distribution and Scale across River Basins

Rivers originating from mountainous areas are the main driving factors responsible for oasis formation[35]. Spatial variation in river directly governs the spatial distribution of oases[36]. Water is essential for an oasis, and its absence leads to desertification. The amount of river runoff directly impacts the existence, development scale, and disappearance of oases, while the number of rivers also determines the number of oases. As shown in Figure 6, oases in China are distributed across the Yellow River mainstream basin, the Hexi Corridor-the Alxa inflow zone, the Qaidam inflow zone, the Junggar inflow zone, the Tarim inflow zone, the Irtysh River basin, and the Ili-Emin River basin. The area and proportion of oases in each river basin are shown in Figure 7.

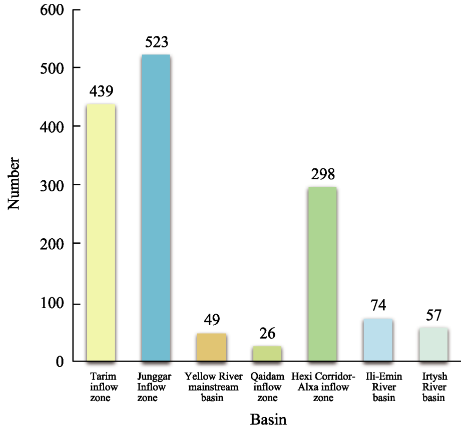


Figure 6 Number of oases in each basin

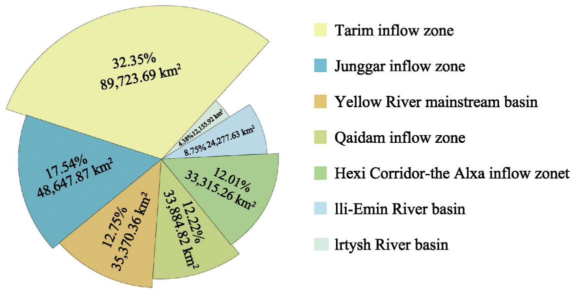


Figure 7 Area and percentage of oases in each basin

Among these, the Tarim inflow zone has the largest oasis area (89,723.69 km^2), accounting for 32.35% of the total oasis area in China. Located in southern Xinjiang, between the Tianshan and Kunlun Mountains ranges, this is the world's largest inland river basin. The water sources of the Tarim River mainly come from the Aksu, Hotan, and Yarkand rivers, which irrigate and form a massive ring of oases surrounding the Taklamakan Desert.

The Junggar inflow zone has a dense and complex river network. While its oasis area (48,647.87 km^2) is smaller than the Tarim inland basin, it contains a greater number of oases (523 oases), which account for 35.68% of the total number of oases in China. The oasis economy here is also more developed than the Tarim River inland basin. Notably, the northern foothills of the Tianshan Mountains are rich in rivers, such as the Manas and Kuitun rivers, which provide abundant water for the formation of oases along the northern Tianshan slopes.

In the Qaidam inflow zone, all rivers originate from the surrounding high mountains, and the basin almost does not generate runoff. Furthermore, the runoff is extremely unevenly distributed throughout the year. As a result, although the oasis area is large (35,370.36 km^2), the closed terrain and limited basin area dictate the inland nature of the Qaidam water system and the shortness of its rivers. These features create a radial distribution of oases, with fewer oases (26 in total), which are concentrated in the lower-altitude central parts of the basin.

The Yellow River mainstream basin has a large oasis area (33,884.82 km^2), but fewer oases (49 oases), accounting for 12.22% and 1.09% of China's total oasis area and quantity, respectively. The Yellow River, often known as the "Mother River of the Chinese nation", provides abundant water and fertile silt to the regions it flows through. It forms three major exogenous oasis areas in the Hetao Plain: the Ningwei Plain, the Yinchuan Plain, and the Houtao Plain. Particularly, the Houtao Plain oasis area, located at the "S" shaped bend of the Yellow River, is China's largest ancient irrigation area, historically known as an area of strategic importance and a vital grain production base and ecological protection barrier.

In the Hexi Corridor-the Alxa inflow zone, the oasis area is not very large (33,315.26 km^2), but the number of oases is relatively high (298 oases). Similar to the northern Tianshan foothills, the Hexi Corridor features many rivers, including the Heihe, Shiyang, and Shule rivers, forming the Hexi Corridor oasis group. Among them, the Heihe River basin has the largest oasis area (16,147.52 km^2) and the most oases (132 oases), with many oases concentrated along riverbanks and delta regions.

The Ili-Emin River basin has an oasis area of 24,277.63 km^2, which accounts for 8.75% of China's total oasis area. The Ili River basin, located near the highest peak of the Tianshan Mountains, has a climate that differs significantly from other arid regions, with some areas receiving over 400 mm of rainfall and being less affected by sandstorms and droughts. Most of the oases are river valley oases irrigated by the Ili River, offering fertile land and abundant pasture, thereby the region is called as “wet island” of Central Asia’s arid zone.

The Irtysh River basin, which originates from China’s Altai Mountains, is an exogenous river with the second-largest flow among rivers in Xinjiang. However, due to its location in the northernmost part of Xinjiang and its poor thermal conditions (with an average annual temperature ranging from 2 ℃ to 4 ℃), the oasis area here (12,155.92 km^2) is the smallest among the seven basins, accounting for only 4.38% of the total oasis area in China. The number of oases (57 oases) is also relatively low.

4 Conclusion and Outlook

The first comprehensive cataloging of China’s oases has been completed, using 2020 as the baseline year. This effort has resulted in a detailed understanding of the current state of oases across various geomorphological units and river basins throughout the country. This study advances oasis research and provides a foundation for understanding future oasis dynamics. It addresses discrepancies in research data and establishes a robust baseline for the continuity of oasis cataloging in the future. Based on this cataloging, the general distribution of oases in China can be summarized as follows.

In 2020, the total area of oases in China was 277,375.56 km^2, with 1,466 oases distributed across the northern regions of Xinjiang, Gansu, Qinghai, Ningxia, and the western part of Inner Mongolia. These oases are distributed either as continuous oasis belts along the same river or as isolated blocks spread across mountainous areas.

In terms of oasis distribution across different provinces, Xinjiang emerges as the predominant region, comprising 63.78% of the China’s total oasis area, while Ningxia has the smallest oasis area. Xinjiang also has the highest number of oases, while Gansu, Inner Mongolia, Qinghai, and Ningxia have relatively fewer oases. The altitudes of oases also vary across provinces, with Xinjiang having the widest range of elevations, oases in Qinghai are at the highest overall altitudes, while the altitudes of oases in Ningxia and Inner Mongolia are similar.

The 22 geomorphological units comprising of oases, flat plains and basin areas account for 92.10% of the total oasis area and 80.56% of the total number of oases in China. In terms of area, the largest oasis areas are in the Northern Tarim River lacustrine-alluvial plains small-region, followed by the Qaidam Basin small-region and the Southern margin of Junggar Basin diluvial-alluvial plains small-region. In terms of numbers, the Hexi Corridor alluvial-diluvial plains small-region has the greatest number of oases, followed by the Turpan-Hami alluvial-diluvial plains small-region and Southern margin of Tarim River alluvial-diluvial plains small-region.

In terms of oasis distribution across different river basins, most oases are in inland river basins. The Tarim inflow zone has the largest oasis area, accounting for 32.35% of the total oasis area in China. The Junggar inflow zone has the most oases, accounting for 35.68% of the total number of oases in the country. Oases in exogenous basins are mainly distributed along the Yellow River mainstream basin, but these oases are fewer in number and smaller in size.

While significant strides have been made in the systematic documentation of China’s oases, this represents merely the initial step in the current era of geographic information big data. There is still much work that remains to be done in expanding and advancing oasis research. First, it is necessary to expand this research beyond China by conducting thorough and precise identification and cataloging of global oases using 2020 as the baseline. This initiative would represent a significant advancement in the field. Second, the limitations of current oasis identification methods must be recognized. Although high-precision oasis identification has been achieved, manual visual interpretation methods are time-consuming and costly, and cannot effectively meet the need for catalog updates. Therefore, it is crucial to integrate rapidly developing artificial intelligence image recognition technologies to address the technical challenges of high-resolution oasis identification. This will allow a rapid updating of oasis cataloging. Third, many detailed studies require further refinement, such as distinguishing between oases in hot and cold deserts, the accurate identification and evolutionary mechanisms of natural versus artificial oases, and strategies for the sustainable development and adaptation under future climate change. These efforts require the involvement of more scholars, open sharing of data, and the development of geographically relevant technologies aligned with current advancements.

Author Contributions

Gui, D. W. and Liu, C. were responsible for the formulation of the technical specifications and the overall design of the paper framework; Lin, J. W. collected and processed the data; Zhang, S. Y. conducted data validation; Gui, D. W. and Lin, J. W. wrote the data paper; Liu, Q. and Liu. Y. F. provided guidance and revised the paper.

Acknowledgements

We would like to express our sincere gratitude to Professor Yang, Faxiang and Professor Lei, Jiaqiang from the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, for their encouragement and strong support throughout this work. Our heartfelt thanks also go to Professor Chunxi from Inner Mongolia Normal University for the professional advice provided in the oasis identification work in semi-arid regions.

Conflicts of Interest

The authors declare no conflicts of interest.

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