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Oasis sustainability assessment in arid areas using GRACE satellite data

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Abstract An oasis is an important habitat for humans, plants, and wildlife in arid desert areas. The sustainability of an oasis is crucial for a smooth regional ecological functioning and healthy economic development. However, the overexploitation of groundwater will result in unsustainable oasis development. Due to the lack of long-term groundwater monitoring data, the impact of groundwater level changes on the sustainability of an oasis has not been studied extensively. In the present study, we used the ground water storage anomaly (GWSA) in combination with the Gravity Recovery and Climate Experiment (GRACE) and the Global Land Data Assimilation System (GLDAS) for the rapid identification of oasis sustainability, which has been tested and evaluated in Hotan and Qira oasis located in arid areas. The results showed that (1) the GWSA is a suitable and reliable indicator for trend change analysis in small-scale oasis and, (2) additionally, M–K test results for long-term trend change of GWSA showed a positive correlation with water resource carrying capacity (WRCC). These results suggest that GWSA can be used as a reliable index for the rapid assessment of oasis sustainability status in arid areas. Moreover, the potential applicability of GRACE satellite data in evaluating the groundwater sustainability in arid areas lacking proper data has also been proved in this study. These findings have provided a foundation to evaluate the sustainability status of an oasis and set a reference point to formulate future policies for the oasis.

Keywords Oasis · GRACE · GLDAS · Sustainability · WRCC · Arid area

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Introduction

An oasis is a unique natural geographical landscape in desert having stable water resources, vital for human survival and plant and animal growth and development (Luo et al., 2010; Song & Zhang, 2015; Wu et al., 2021). Being a special land type and important component of arid and semi-arid regions, the oasis landscape is widely distributed in Central Asia, the Middle East, and Northwest China (Guo et al., 2016; Hu et al., 2007). Plant diversity also varies with landscape heterogeneity or land use types (Zhou et al., 2020). Therefore, its sustainability is directly related to the stable development of regional economy and society (Yang et al., 2004). Water is the key factor to realize the sustainable development of the oasis, because the water volume and its spatial–temporal distribution significantly influences the stability and appropriate scale of the oasis (Liu et al., 2010; Luo et al., 2009; Yang et al., 2019; Zhang & Shao, 2017). Under specific climatic conditions, a certain amount of water can only nourish a particular oasis area. Therefore, in the long run, the decline of water resources means that the development of the oasis is unsustainable and under threat of deterioration (Lightfoot, 1996; Ma et al., 2009).

Currently, regional sustainability assessment is mainly carried out by the following methods: ecosystem health assessment (Xu et al., 2005), ecological footprint (Galli et al., 2012), wellbeing assessment (Breslow et al., 2016), and quality of life and natural resource availability (Graymore et al., 2008). Each of them has advantages and limitations. For example, ecological footprint can provide partial sustainability information of the system and highlights the existing sustainability problems. But this method is intermittent and unattractive for the policy makers due to the availability of data, the time involved, and the cost of evaluation. Meanwhile, oasis sustainability evaluation methods are more closely related to water resources, such as the oasis green index (Wang et al., 2002) and WRCC (Song et al., 2011). Although data required by these methods can accurately measure the sustainability of oasis development, it is a time-consuming process. Therefore, new indicators need to be evaluated, which can quickly identify the changes in oasis water resources to determine the sustainability of the oasis.

The launch of the Gravity Recovery and Climate Experiment (GRACE), which is a joint venture of the NASA and the German Space Center, has successfully performed space-based monitoring of large-scale terrestrial water storage (TWS) changes for the first time (Rodell et al., 2007; Swenson & Wahr, 2002). This TWS usually includes groundwater, surface water, soil water, and snow water. The Global Land Data Assimilation System (GLDAS) is traditionally used to estimate soil water and snow water. The GWSA has been derived from GRACE after removing the soil moisture anomaly and canopy water storage anomaly obtained from GLDAS. Areas such as deserts and oases lack the long time series groundwater monitoring data. Therefore, the GRACE may be the only option for groundwater assessment in these areas (Wang et al., 2020a, 2021). The method of estimating groundwater storage anomaly based on the GRACE is widely used to evaluate groundwater changes in major aquifer systems, e.g., Hexi Corridor in China (Liu et al., 2021) and the Lake Victoria (Khaki & Awange, 2021), the North Western Sahara (Mohamed & Goncalves, 2021), and Turkey (Khorrami & Gunduz, 2021). But GRACE satellite data have not been applied to monitor the oasis's sustainable development on a small scale.

To quickly understand the impact of the dynamic change of groundwater level on the sustainable development of the oasis, Hotan and Qira oasis, a typical oasis in the southern edge of Tarim Basin in the northwest arid land of China, is selected as a study area. The main objectives of this study are (1) to verify the accuracy of the GRACE satellite data in the change trend of groundwater storage at oasis scale; (2) to compare the relationship between GRACE satellite data and sustainable research methods; (3) to rapidly diagnose the sustainable development of the oasis in Central Asia and Northwest China based on objective 2.

Materials and methods

Study area

The study area comprised of Hotan oasis (37°00′-37°30′N, 79°30′-80°30′E) and Qira oasis (36°54′-37°09′N, 80°37′-80°59′E), located in the Tarim Basin which is an arid area in Northwest China, and it is also the largest inland basin in the world. The above-mentioned oases are selected as representative oases to study the sustainable development of oases in the arid area, based on GRACE satellite data (Fig. 1). Hotan and Qira oases have an area of about 9730 km^2 and 157 km^2, respectively. Due to the relatively close oasis, the average annual temperature in the region is 12 °C; the precipitation is less than 40 mm, while the annual evaporation is as high as 2700 mm (Rumbaur et al., 2015). Karakash River and Qira

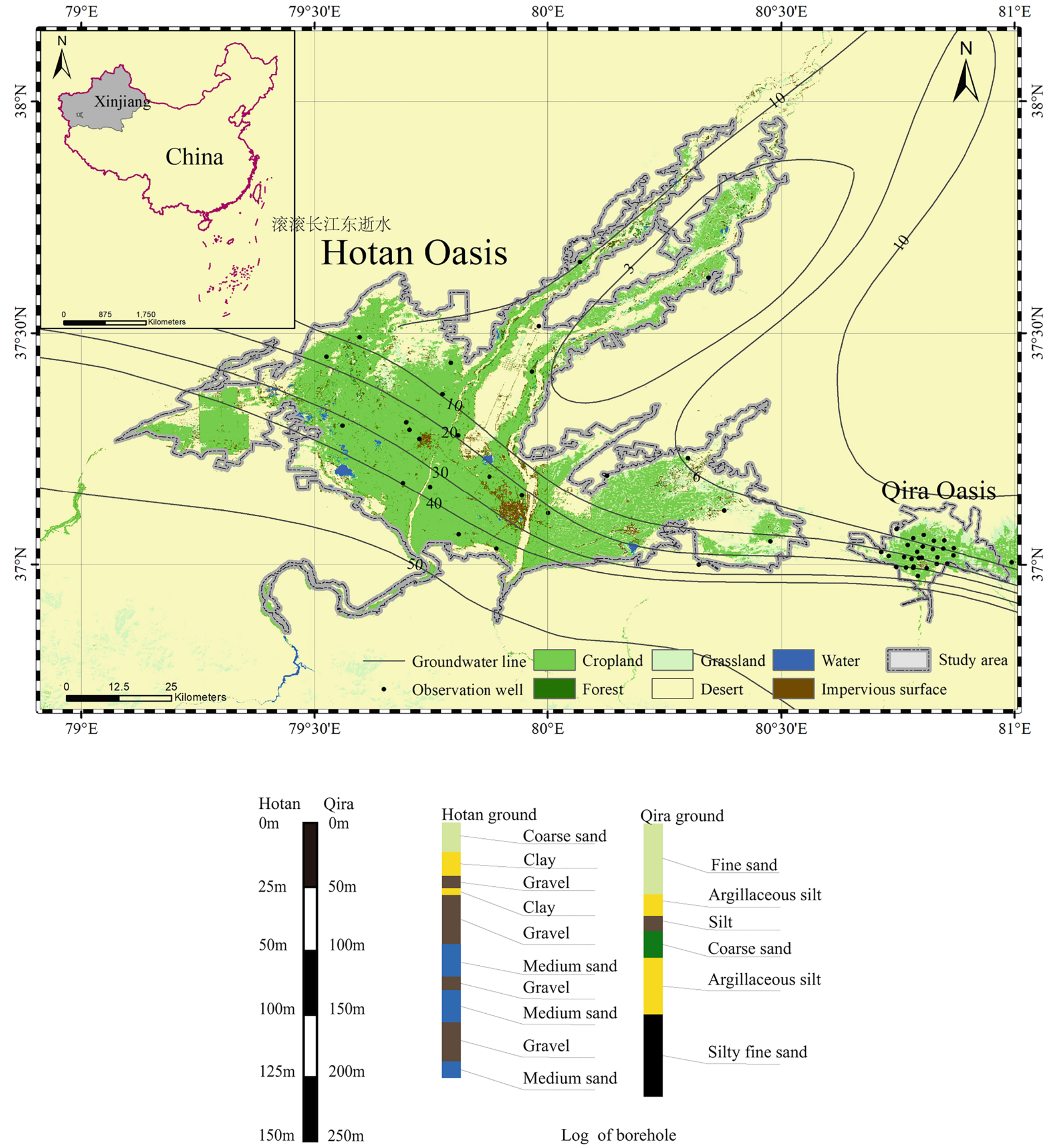

Fig. 1 Location map of the study area in the Hotan and Qira oasis

River, which originate from the high-altitude valley of Kunlun Mountain, are the main water sources for both oases. The average annual runoff is 22.25 × 108 m^3 and 1.27 × 108 m^3, respectively, finally flowing into the extremely arid Taklimakan Desert (Xu et al., 2016; Xue et al., 2017). The groundwater flow in the study area is characterized by a typical arid alluvial fan, and the groundwater flow is consistent with the surface water flow from south to north. The groundwater depth is less than 50 m, and the aquifer is characterized by Quaternary single-pore phreatic aquifer. In recent decades, as a consequence of climate change and human activities, the oasis has faced tremendous changes, causing severe development problems. Therefore, rapid diagnosis of groundwater changes in oasis is crucial for the formulation of relevant policies for sustainability.

Data sources

In the present study, we used the GRACE RL06 Mascon Solutions (version 02) data released by the University of Texas at Austin Center for Space Research (CSR). The spatial resolution is 0.25°×0.25°, and the period is from April 2002 to August 2020 (cubic interpolation is used for some missing months). The terrestrial equivalent water height, the soil water content, snow depth water equivalent, and plant canopy surface water from April 2002 to August 2020 in GLDAS were extracted by the python program. Surface water changes in arid areas can be ignored (Cao et al., 2015). Data are publicly available at https://disc.gsfc.nasa.gov/datasets?keywords=GLDAS. This continuous hydrometeorological data set is widely used in water resource research, especially in areas where data are lacking in time and space (Moghim, 2020). To verify the availability of GRACE/GLDAS data at oasis scale, the meteorological data from 2000 to 2020 were obtained from the Hotan and the Qira meteorological stations, while multi-year observation data about the groundwater level were taken from the Hotan and Qira hydrological stations. In this study, 67 observation wells were selected, evenly distributed in the oasis. However, the water level data were found missing for some years, and the MODFLOW model was used to simulate the missing year data. The social and economic data, including GDP and groundwater exploitation index, was acquired from the Hotan Statistical Yearbook (1990–2020), China Hydraulic Statistical Yearbook (1990–2020), and Xinjiang Water Resources Bulletin of corresponding years, respectively. These data were mainly used to calculate WRCC.

Models

GWSA from GRACE and LSM

The gravity observations of the GRACE satellite can be used as a supplementary method to calculate the changes in groundwater storage. This method provides measurements of changes in terrestrial water storage on the earth's surface and underground water storage (Xiao et al., 2015). However, the GRACE satellite cannot directly separate TWS components, such as surface water, groundwater, and soil water. Similarly, the land surface model (LSM) only provides the water storage anomalies defined by the model, and it is difficult to obtain the total water storage anomalies. Therefore, GWSA usually introduce land assimilation model to separate groundwater components. Changes in water storage usually include groundwater storage (GWS), snow water equivalent (SWE), and soil moisture (SM) and can be written as (Rodell & Famiglietti, 2002)

$$\Delta TWS = \Delta GWS + \Delta SWE + \Delta SM \tag{1}$$

where all variables can be converted into equivalent water height, so it can be represented by distance units. Formally, groundwater storage anomalies can subtract the SM and SWE anomalies of the global land assimilation model from TWSA data, that is:

$$\Delta GWS = \Delta TWS - \Delta SWE - \Delta SM \tag{2}$$

MODFLOW simulation

MODFLOW is the most widely used numerical model for simulating regional groundwater (Furman, 2008). Based on the MODFLOW model, a visual operation software—Visual MODFLOW—is developed by combining MT3D and PEST, which is widely used worldwide because of its simple operation, friendly interface, and multi-functionality (Yifru et al., 2020). Hotan groundwater monitoring data was missing for more years and cannot meet the model validation requirements. There are few missing years of groundwater monitoring data in Qira oasis. Therefore, Visual MODFLOW only simulates Qira oasis to supplement the missing years, and Hotan oasis refers to relevant literature and official documents. According to the hydrogeological conditions of the study area, the groundwater flow system is generalized as a homogeneous, isotropic, two-dimensional, phreatic, and unstable groundwater flow system, and the following mathematical model is established and solved:

$$\begin{cases}\frac{\partial}{\partial x}\left[K(h-B)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(h-B)\frac{\partial h}{\partial y}\right]+\varepsilon_1(x,y,t)-\varepsilon_2(x,y,t)=\mu\frac{\partial h}{\partial t} & (x,y)\in D, t\geq 0\\ h(x,y,0)=h_0(x,y) & (x,y)\in D\\ K(h-B)\frac{\partial h}{\partial n}|\Gamma_1=q(x,y,t) & (x,y)\in\Gamma_1, t\geq 0\end{cases}\quad(3)$$

where:

h. B is the aquifer water level and floor elevation (m).

$\varepsilon_1(x,y,t), \varepsilon_2(x,y,t)$ represents aquifer recharge and discharge (m/d), respectively.

q(x,y,t) is the type II boundary single-width flow (m^2/d).

k is the coefficient of infiltration (m/d).

h_0 *(x,y)*is the initial water level (m).

μ is the storage coefficient.

The Visual MODFLOW software's numerical simulation area is 480 km^2 and divided into 1600 rectangular grids. The hydrogeological parameters including coefficient of infiltration (K) and storage coefficient are calibrated by the groundwater level observation data from June 2009 to June 2010. The calibrated hydrological model was then verified using the observation water level data in 2000, 2008–2009, and 2011. The root mean square (*RMS*), correlation coefficient (R^2), and residual mean (*RM*) were used to evaluate the groundwater model quantitatively. In order to be consistent with GRACE and model data on time scale, the water level data of 25 wells from 2002 to 2020 were finally calculated.

The height of the water column was obtained by subtracting the water level of each well from the elevation value of each well, and the height of the water column is converted to the water level anomaly according to Eq. (4). Finally, the calculated water level anomaly is converted to the water reserve anomaly by using Eq. (5):

$$\Delta h_{ano\to t} = h_t - \overline{h_{2002-2020}} \quad (4)$$

$$\Delta GWS_{ano\to t} = \Delta h_{ano\to t} \times Sy \quad (5)$$

where $\Delta h_{ano\to t}$ is the abnormal water level according to time variation, h_t is the water column height at different times, $\overline{h_{2002-2020}}$ is the average value of water column height from 2002 to 2020, and Sy is the storage coefficient of the aquifer in the study area, according to the experience value and reference related literature: $Sy=0.23$.

M–K test was proposed by Mann and developed by Kendall, which is a famous nonparametric test method (Nourani et al., 2015). This method is widely used to analyze the variation trend of hydrological climate variables over time (Jain et al., 2013). This method is used to verify the changing trend of groundwater storage (GWS) in the study area (Du et al., 2015).

Water resource carrying capacity

In this paper, the fuzzy linear transformation principle and maximum membership principle are used to evaluate the water resource carrying capacity of the area. Fuzzy comprehensive evaluation model fully considers the multiple factors related to the evaluated things and the correlation between the various factors, which can make up for the lack of excessive consideration of a single factor and make a reasonable comprehensive evaluation. A judgment factor dataset $U=\{u_1, u_2, u_3, \ldots, u_m\}$ and a remark set of $V=\{u_1, u_2, u_3, \ldots, u_n\}$. U represents the sum of comprehensive evaluation factors and V represents the sum of all comment grades. The single-factor judgment evaluation of factor U_i is carried out to determine its membership grade of the judgment grade V_j (represented by R_{ij}). Therefore, the judgment matrix R of the entire judgment factor set (number of m) is as follows (Wang et al., 2005):

$$R=\begin{bmatrix}R_1\\R_2\\\cdots\\R_m\end{bmatrix}=\begin{bmatrix}r_{11} & r_{12} & \cdots & r_{1n}\\ r_{21} & r_{22} & \cdots & r_{2n}\\ \cdots & \cdots & \cdots & \cdots\\ r_{m1} & r_{m2} & \cdots & r_{mn}\end{bmatrix} \quad (6)$$

where R is a fuzzy link between U and V and the weight of each evaluation factor is $W=[a_1, a_2, \ldots, a_m]$ (W is a fuzzy subclass of clustering U, $0\leq W_i\leq 1$). According to the comprehensive operation of fuzzy transformation, the fuzzy subclass of clustering V is calculated, that is, the comprehensive evaluation results:

$$B = W \cdot R = \left[b_1, b_2, \ldots, b_3\right] \quad (7)$$

where B is a fuzzy set of V. Fuzzy transformation $W * R$ can be transformed into general matrix calculation, which is affected by many factors and is suitable for multi-factor sequences. The calculation process is as follows:

$$b_j = \min\left\{1, \sum_{i=1}^{m} a_i r_{ij}\right\} \quad (8)$$

Results and analysis

After carefully adjusting the parameters and fitting the flow field, the Visual MODFLOW model has achieved good results. The parameter identification results and the water level fitting are shown in Fig. 2. The calculated flow field is the same as the measured flow field. Since there may be a certain deviation in the layout of the mining amount in the fitting process, the abovementioned water level fitting error is understandable. The flow field fitting results also preliminarily show that the established hydrogeological conceptual and mathematical models are correct.

Applicability of GWSA data in arid oasis

GWSA-AA (based on the annual average) and GWSA-Sum (based on the annual average of June to August) in Qira oasis retrieved from GRACE satellite data and the GLDAS showed moderate linear correlation having the correlation coefficient of 0.48 (Fig. 3). The long time series data also revealed that the inter-annual variation trend is the same in both cases. Since the observed groundwater data are mostly concentrated in June to August each year, therefore, to minimize the error caused by MODFLOW simulation, we also calculated the variation trend of the average equivalent water height of groundwater storage in Qira oasis from June to August each year. The results showed a consistent inter-annual variation characteristic among GWSA-AA, GWSA-Sum, and GWSA-well (based on observation well data). Due to the lack of measured Hotan groundwater level data, in previous studies, Sun (Sun & Baidourela, 2018) and Zhu (Zhu et al., 2018) used GRACE and GLDAS to establish the Hotan groundwater level estimation model, the results showed that GWSA is consistent with the change trend of groundwater storage, and the Hotan groundwater storage reflected a significant downward trend.

In the arid oasis, shallow groundwater plays a vital role in the scale and stability of the oasis, and the observation data of groundwater level in the long time scale are very scarce in the arid oasis area. The consistency of GWSA and well observation proves that GRACE satellite data has specific applicability in studying the groundwater level fluctuations in the long time scale of the oasis.

Change trend test of GWSA

Based on the calculation results of GWSA data, the M–K trend test was used to analyze the variation

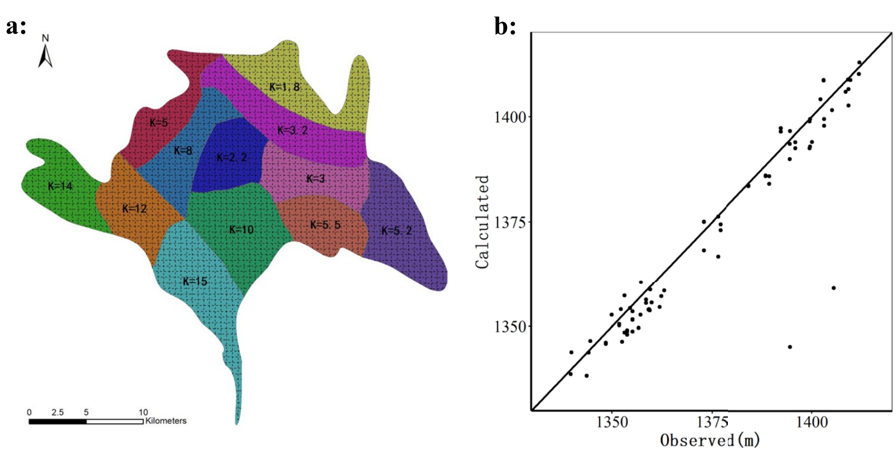

Fig. 2 **a** The coefficient of infiltration values (K) of different regions from Pumping test (unit: m/d) and **b** model identification period water level fitting diagram $RMS = 2.1$, $R^2 = 0.95$, $RM = 0.27$

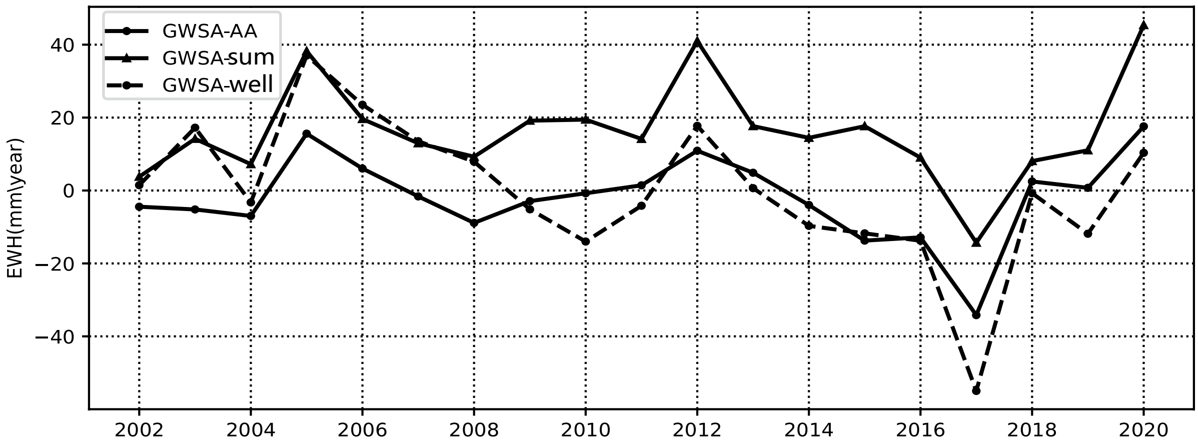

Fig. 3 Comparison of three value kinds of groundwater storage anomalies

trend of groundwater storage in the study area in the past 18 years (Fig. 4). The Z value of Hotan oasis was 2.2, and the *P* value was 0.02. Through the 95% significance test, the UF and UH values intersected in 2008. The intersection was between the critical lines, indicating that the groundwater storage in Hotan oasis began to decline in 2008. However, the *Z* value of Qira oasis was 0.2, and the *P* value of 0.8 did not pass the 95% significance test, that is, GWSA did not decrease significantly from 2002 to 2020. The M–K test is consistent with the calculated water resource carrying capacity results. Therefore, the future study on the sustainable development of arid oasis can be quickly diagnosed by the GWSA index and M–K test.

Water resource carrying capacity in oasis areas, 1990–2020

The WRCC plays a fundamental role in the sustainable development of the oases. Based on the index system described by the national water resource supply and demand analysis, the differences in the natural occurrence of water resources in the oasis region and the different development and utilization methods are fully considered. Based on the water resource evaluation criteria, the following corresponding evaluation indexes (Table 1) are selected to calculate the WRCC and further judge the relationship between GWSA and the sustainable development of the oasis.

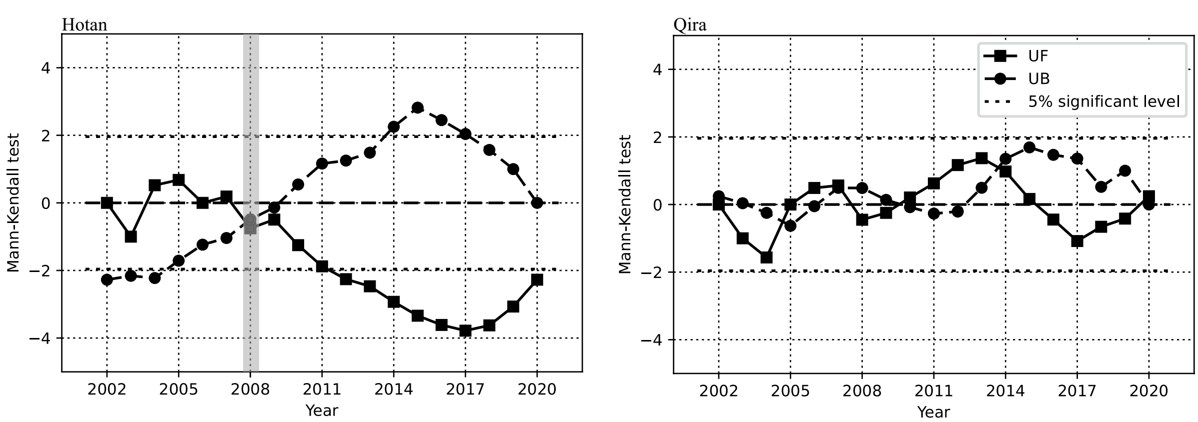

Fig. 4 M–K trend test chart of GWSA index in Hotan and Qira oasis from 2002 to 2020

Table 1 Evaluation factor classification index

Evaluation factors	V_1	V_2	V_3
U_1 water use efficiency %	> 80%	80–50%	< 50%
U_2 water resources utilization %	< 30%	30–75%	> 75%
U_3 water supply modulus (m^3/km^2)	< 1	1–15	> 15
U_4 water requirement modulus ($10000m^3/km^2$)	< 1	1–15	> 15
U_5 agricultural water use rate %	< 30	30–70	> 70
U_6 eco-environmental water use rate %	> 25	25–10	< 10
U_7 per capita water resources (m^3/person)	> 4000	4000–2500	< 2500
U_8 per capita water supply (m^3/person)	> 3000	3000–2000	< 2000

According to the actual value of each evaluation factor, the membership function of the evaluation matrix is calculated by comparing the grading index. The membership function is constructed by fuzzy processing, so that the values are smoothly transitioned between all levels. The V_1 level indicates that the WRCC is well, meaning that water resources still have great potential, while the V_3 level is the opposite. For the V_2 level, the intermediate interval, the membership degree of the midpoint of the interval is 1, the membership degree of the edge points on both sides is 0.5, and the intermediate point decreases linearly to both sides. For the intervals on both sides of V_1 and V_3, the farther away from the critical value, the greater the membership degree on both sides. The membership degrees on both sides of the critical value are 0.5, respectively. The calculation formula of the membership function of each evaluation grade is constructed according to the above assumptions. The calculation results are shown in Tables 2 and 3.

According to the membership function of comprehensive evaluation indexes, the membership matrix of each index factor with respect to V_1, V_2, and V_3 in different years is obtained. Then, combined with the above weight matrix (Ge et al., 2021), the evaluation result matrix B of water resources carrying capacity is calculated according to Eq. (7). The evaluation grade set is $a_i = \{0.95, 0.5, 0.05\}$. Finally, the comprehensive evaluation table of WRCC of Hotan and Qira oasis in different years is obtained. Combined with the natural ecological environment and socio-economic development of oasis, the evaluation index classification standard is determined, and the WRCC is divided into three types: overload (0–0.4), bearable (0.4–0.6), and full carrying (0.6–1).

The development and utilization of water resources in Hotan oasis have reached an overload scale in 1990 (Table 4). The membership degree of b_j to V_2 is relatively high, but the membership degree to V_1 and V_3 is relatively low. Under the economic and technological conditions at that time, the carrying potential of water resources is relatively small, and the difference between the supply and demand of water resources becomes obvious. Due to the overexploitation of groundwater and the destruction of the water environment in recent years, the development and utilization potential of water resources in Hotan oasis have been decreased. With the increase in population, the total water demand is also increasing. The water resources in Hotan oasis are not enough

Table 2 Hotan oasis evaluation matrix table

evaluation factors	weight	1990			2000			2010			2020		
U_1	0.1	0.000	0.286	0.714	0.000	0.863	0.137	0.000	0.755	0.245	0.453	0.547	0.000
U_2	0.14	0.572	0.428	0.000	0.164	0.836	0.000	0.000	0.865	0.135	0.000	0.384	0.616
U_3	0.18	0.000	0.750	0.250	0.000	0.683	0.317	0.000	0.550	0.450	0.000	0.469	0.531
U_4	0.16	0.025	0.975	0.000	0.000	0.796	0.204	0.000	0.618	0.382	0.000	0.291	0.709
U_5	0.15	0.000	0.415	0.585	0.000	0.371	0.629	0.000	0.363	0.637	0.000	0.349	0.651
U_6	0.13	0.766	0.234	0.000	0.734	0.266	0.000	0.646	0.354	0.000	0.000	0.824	0.176
U_7	0.14	0.000	0.413	0.587	0.000	0.650	0.350	0.000	0.930	0.070	0.000	0.630	0.370

Table 3 Qira oasis evaluation matrix table

evaluation factors	weight	1990			2000			2010			2020		
U1	0.1	0.000	0.300	0.700	0.000	0.692	0.308	0.000	0.755	0.245	0.453	0.547	0.000
U2	0.14	0.641	0.359	0.000	0.288	0.712	0.000	0.000	0.905	0.095	0.000	0.461	0.539
U3	0.18	0.000	0.667	0.333	0.000	0.567	0.433	0.000	0.429	0.571	0.000	0.385	0.615
U4	0.16	0.000	0.832	0.168	0.000	0.981	0.019	0.000	0.868	0.132	0.000	0.491	0.509
U5	0.15	0.000	0.456	0.544	0.000	0.384	0.616	0.000	0.361	0.639	0.000	0.414	0.586
U6	0.13	0.924	0.076	0.000	0.919	0.081	0.000	0.927	0.073	0.000	0.929	0.071	0.000
U7	0.14	0.844	0.156	0.000	0.864	0.136	0.000	0.846	0.154	0.000	0.832	0.168	0.000

to meet the existing water demand for social development. The WRCC is decreasing year by year, and the membership degree of V_1 level has decreased from 0.1836 in 1990 to 0.0453 in 2020, while the membership degree of V_3 has increased from 0.2863 to 0.4676 in 2020. The comprehensive score of carrying capacity has also decreased from 0.4538 to 0.31 in 2020, becoming overloaded (Table 4). In this situation, water resources will seriously restrict the development of Hotan oasis. The WRCC score of Qira oasis has decreased from 0.54 to 0.46, which is still in the range of carrying capacity. The main reason is that the population is relatively small, the economic development is slow, and the Qira River flowing through the oasis, supplies a lot of water every year. These findings indicate that the Qira oasis has significant development potential. Based on WRCC calculations, it can be inferred that Hotan oasis is in a state of unsustainable development, whereas Qira oasis development is relatively stable.

Evaluation of sustainable development of typical oasis in Central Asia

The Aksu-Weigan River oasis, the northern foot of Tianshan oasis (Xinjiang), Ashkhabad oasis (Turkmenistan), Dasoguz-Urganch oasis (Turkmenistan-Uzbekistan), and Margilon oasis (Uzbekistan) typical oasis (Fig. 5) were selected for sustainable development evaluation. It is evident from Fig. 6 that except for Ashkhabad oasis, the water storage in the rest of the oasis decreased to different degrees, which has resulted in the unsustainable development of the oasis. Among them, the water storage of the Aksu-Weigan River oasis and the oasis at the north foot of Tianshan Mountain in Xinjiang decreased more significantly, and similar is the case with annual water storage losses. This might have happened because both oasis areas are dominated by urbanization, agricultural development, and large industrial and agricultural water consumption, resulting in a greater risk of oasis degradation. The Z value of Dasoguz-Urganch oasis and Margilon oasis is less than 0, indicating that the development of these two oases is unsustainable due to excessive water use. Regional managers should change the. This unsustainable trend of oasis development can be prevented by employing different strategies such as promoting water-saving agriculture, improving planting structure, and reducing industrial water consumption. Ashkhabad oasis showed a stable development, and its water storage did not decrease significantly. The main reasons behind this development are that the oasis has sufficient surface water supply due to river flow and less dispersed urban population, slow economic development, and less competition for industrial and agricultural water.

Table 4 Comprehensive evaluation of water resource carrying capacity in Hotan and Qira oasis, 1990–2020

	Hotan				Qira			
Year	V_1	V_2	V_3	Value	V_1	V_2	V_3	Value
1990	0.1836	0.5301	0.2863	0.4538	0.3280	0.4336	0.2385	0.5403
2000	0.1551	0.6174	0.2275	0.4674	0.2808	0.5150	0.2042	0.5345
2010	0.0840	0.6252	0.2908	0.4069	0.2389	0.5036	0.2576	0.4916
2020	0.0453	0.4871	0.4676	0.3100	0.2826	0.3618	0.3556	0.4672

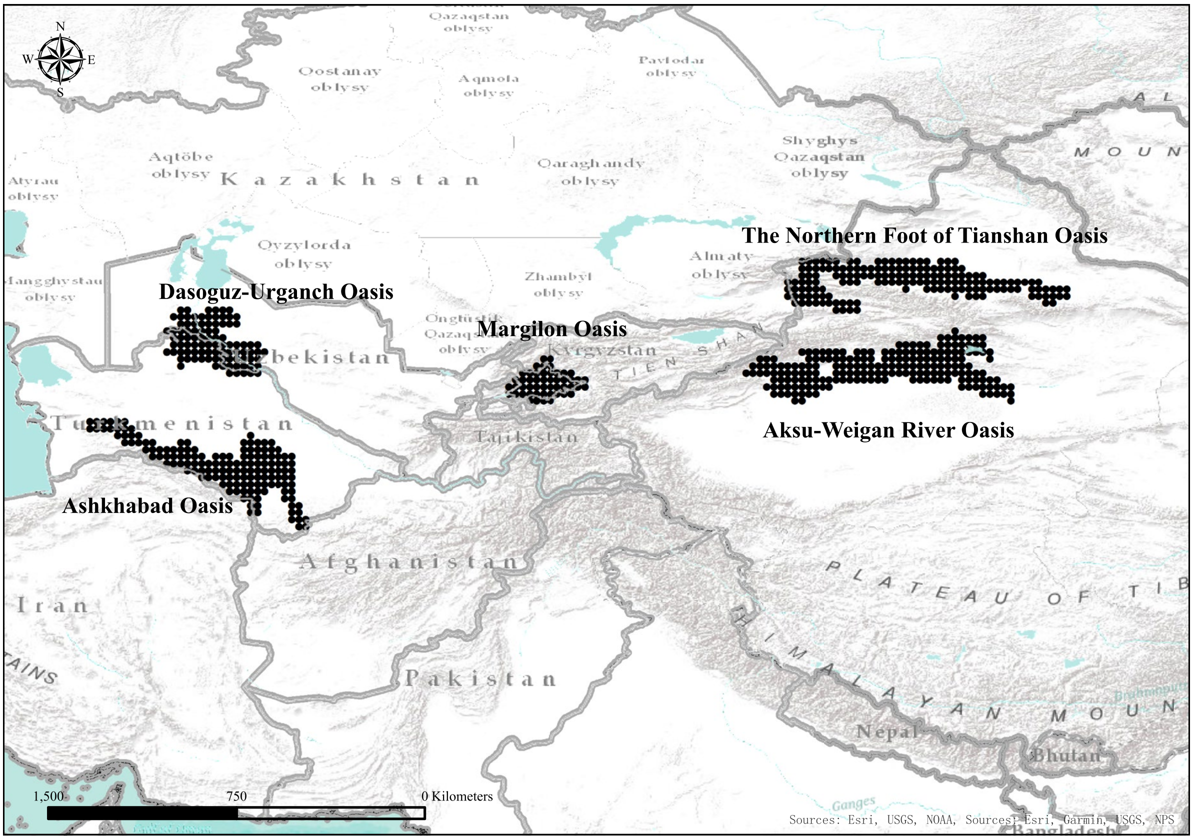

Fig. 5 Spatial distribution of typical oasis in Central Asia

By using the GRACE satellite data, we can quickly identify the development of arid oasis, which could also be helpful to prevent the excessive development of the oasis under scarce water resources that otherwise may lead to desertification. This study has provided a basis for the suitable assessment of the current status of the oasis development.

Discussion

Water resources are one of the critical factors for the sustainable development of oasis. Water supports the rapid development of the oasis economy, increasing the willingness to demand water, but the availability of water sets an implicit limit to the development of oasis. Due to the various internal factors (crop type, land use) and external factors (policy, economy), the sustainable development of the oasis may indeed have problems. Therefore, we assumed that the state of oasis development can be evaluated by calculating the water storage change.

The use of satellite data in arid or extreme arid areas in evaluating oasis sustainable development has been scarce. This paper determines that GRACE data can be used as an index in the rapid monitoring of oasis scale sustainable development. The application of GRACE data quickly inverses the changes of oasis groundwater storage and judges the status of sustainable development of the oasis through the M–K test. In this study, the temporal variation trend of GRACE data is consistent with the measured groundwater storage anomaly. The calculation of WRCC in Hotan and Qira oasis is consistent with the previous findings (Meng et al., 2009). Li et al. (Li et al., 2020) calculated the sustainable development level of the oasis at the north foot of Tianshan Mountain. They found that the overall ecological environment of the oasis is in an unsustainable development situation. Chang et al. (Chang

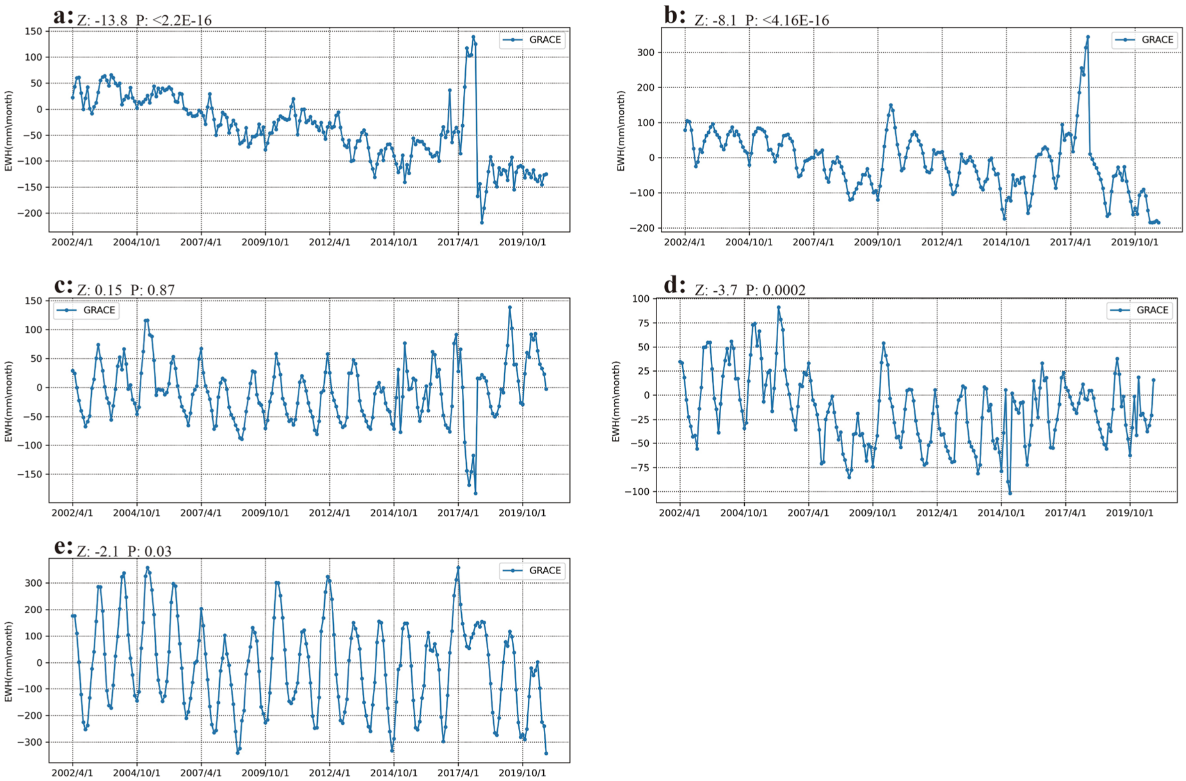

Fig. 6 The trend of GWSA in typical oasis of Central Asia based on GRACE data

et al., 2018) analyzed the sustainable development of Hotan oasis based on emergency and decision analysis; the results showed that the environmental pressure on Hotan oasis continues to increase, which means the unsustainable development of Hotan oasis in the long-term. Wang et al. (Wang et al., 2020b) have studied the utilization of water resources and water security in Central Asia; the research showed that Turkmenistan and other countries are at the security level in the water supply and demand security. Uzbekistan is confronting great pressure on water resources which means that the development of oases is unsustainable. These studies further proved that the application of GRACE satellite data can quickly and effectively diagnose the state of oasis development in the oasis area lacking proper long-term series data.

The GRACE satellite data and GLDAS model provided an important method to study the sustainable development of the oasis. However, this method has some limitations. Despite having variable size of the oasis, the GWSA and the GWSA-well exhibited a strong correlation at the small scale of the oasis. But the influence of large-scale irrigation water on the soil moisture (SM) is not considered during the model assimilation and only simulated SM data is used. But the SM sensor based on the ground can provide more reliable data to improve the GWA change estimation obtained by GRACE. In addition, GWSA is only used for rapid evaluation of the regional development status of oasis in arid areas that lack data, so it cannot be used in humid areas to assess the regional development status.

The Chinese government has launched ecological protection policies, such as the ecological red line and reforestation. Central Asian governments have also started to pay attention to regional sustainable development and initiated relevant measures. These policies and measures have promoted the sustainable development of oases in Northwest China and arid areas of Central Asia. However, due to the increase of population and the influence of climate factors, it is challenging to balance between the oasis's ecological sustainability and economic development. At present, policies regarding the oasis development in Central Asia and Northwest China lack strong measures to protect oasis groundwater resources, ecological environment, and reclamation of wasteland. Therefore, future research should focus on different methods which can improve the accuracy of GRACE satellite data in estimating the accurate fluctuation trend of water storage, so that development status of oases can be quantified accurately. This would certainly help policymakers to formulate site specific policies for the sustainable development of the oases.

Conclusions

Based on the GRACE satellite data and the GLDAS model data, the water storage fluctuations in the oasis and its impact on the sustainable development of the oasis were studied.

The results showed that the GWSA is correlated with the measured groundwater storage anomalies on the time scale, and the correlation coefficient is 0.48, indicating that GRACE satellite data can be used to analyze the fluctuation trend of small-scale water storage anomalies. The WRCC of the Hotan oasis changed from bearable to non-bearable from 1990 to 2020, while the water resources of Qira oasis were still within the range of tolerable capacity in the same period. Through the M–K test of the change trend of GWSA in Hotan and Qira oasis from 2002 to 2020, it was found that GWSA in the Hotan oasis showed a downward trend from 2009, but GWSA in Qira oasis did not show a decreasing trend. The result is consistent with the calculation result of WRCC. To sum up, we can take GWSA as an index for the rapid diagnosis of oasis sustainable development. These findings will help the policymakers to put forward some effective solutions for sustainable management of groundwater resources keeping in view the current development status of the oasis. Moreover, future research should focus on improving the accuracy of small-scale regional water storage changes by downscaling the GRACE satellite data.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent for publication Not applicable.

Competing interests The authors declare competing interests.

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