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Groundwater Level Dynamic Impacted by Land-Cover Change in the Desert Regions of Tarim Basin, Central Asia

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Abstract: Groundwater is essential to residents, ecology, agriculture, and industry. The depletion of groundwater impacted by climatic variability and intense human activities could threaten water, food, and socioeconomic security in arid regions. A thorough understanding of groundwater level dynamics and its response to land-cover change is necessary for groundwater management and ecosystem improvement, which are poorly understood in arid desert regions due to a scarcity of field monitoring data. In our study, spatiotemporal characteristics of groundwater level impacted by land-cover change and its relationship with vegetation were examined using 3-years in-situ monitoring data of 30 wells in the desert regions of Tarim Basin during 2019–2021. The results showed that the depth to groundwater level (DGL) exhibited obvious spatial and seasonal variations, and the fluctuation of DGL differed significantly among the wells. The cultivated land area increased by 1174.6, 638.0, and 732.2 km^2 during 2000–2020 in the plains of Yarkand, Weigan-Kuqa, and Dina Rivers, respectively, mainly transferring from bare land and grassland. Annual average Normalized Difference Vegetation Index (NDVI) values increased with time during the period in the plains. DGL generally exhibited a weakly increasing trend from 2019 to 2021, mainly due to human activities. Land-cover change significantly affected the groundwater level dynamic. Generally, the groundwater system was in negative equilibrium near the oasis due to agricultural irrigation, was basically in dynamic equilibrium in the desert region, and was in positive equilibrium near the Tarim River Mainstream due to irrigation return water and streamflow. NDVI of natural desert vegetation was negatively correlated with DGL in the desert regions (R^2 = 0.78, $p < 0.05$). Large-scale land reclamation and groundwater overexploitation associated with water-saving irrigation agriculture development have caused groundwater level decline in arid oasis-desert regions. Hence, controlling groundwater extraction intensity, strengthening groundwater monitoring, and promoting water-saving technology would be viable methods to sustainably manage groundwater and maintain the ecological environment in arid areas.

Keywords: spatiotemporal variations; groundwater level; human activities; vegetation; groundwater resource management

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1. Introduction

Groundwater is essential to domestic, industrial, ecological, and agricultural water use in arid environments owing to low precipitation and insufficient surface water [1–3]. With climate change, agricultural development, and increasing population, the timing, locations, and amounts of groundwater recharge and discharge have been modified worldwide [4,5]. Groundwater depletion caused mainly by intense human activities could threaten water, food, and socioeconomic security in arid regions around the world in recent years, particularly with large irrigated agriculture [6–9]. Owing to groundwater over-extraction for agricultural irrigation in arid regions, the continuous decline of the groundwater level has affected regional hydrological and ecological processes in recent decades, especially in the oasis-desert region [10,11]. Groundwater level fluctuation could reflect the groundwater process within aquifers and thus could provide insight into the correlations between groundwater and the local environment [12]. Land-cover change has significantly influenced groundwater levels and thus, in turn, affected natural vegetation in desert regions, such as cultivated land expansion, which has led to groundwater level decreasing and vegetation degradation in oasis-desert regions over the past decades [5,11,13,14]. This has seriously threatened the security of water resources, economies, and ecosystems in arid areas [10]. Therefore, understanding groundwater level dynamics under the impact of land-cover change is of utmost significance to groundwater system management and ecosystem improvement in these arid regions [15,16].

The Tarim River Basin is the largest inland river basin in China, also the socioeconomically important region of the Silk Road Economic Belt, and is currently facing extremely large water scarcity stress and water use conflicts among ecology, economy, and agriculture owing to the development of agricultural areas [17–19]. Water demand is mainly concentrated in food production, and more than 90% of water use in the Tarim Basin is used for agricultural irrigation [10]. The cropland area has significantly expanded in the Tarim Basin in recent decades, owing to the rapid rise in population and land demand [20]. In the past 30 years, the uncontrolled exploitation of land and water resources associated with the growing population in the Tarim Basin has led to rapidly increased water consumption and a great change in the water regime, and the agriculture and desert vegetation relied on groundwater owing to scarce rainfall and limited surface water, resulting in regional groundwater overexploitation for irrigation and groundwater level decline [10,15,21]. The current decline and exploitation of groundwater is unsustainable, and human abstraction exceeds groundwater recharge, which has caused serious ecological issues in the lower reaches, such as soil desertification and natural vegetation degradation (e.g., desert riparian forests) [15,18]. Furthermore, groundwater near rivers supplied by stream water is an important water source of desert riparian forests in arid regions, and the dried-up river caused by the diversion of stream water in the upper reaches could lead to natural vegetation degradation in the desert area [3]. Therefore, with the oasis area expansion, water-saving irrigation promotion, and strict water resource constraints, a thorough study of groundwater level variation impacted by agricultural activities in the Tarim River Basin is urgently necessary for optimal utilization of groundwater resources and ecological environment protection, especially in desert regions [6,22,23].

Currently, studies of groundwater level dynamics are primarily based on two data sources, i.e., GRACE satellite data (Gravity Recovery and Climate Experiment) and in-situ monitoring data [22,24]. However, the GRACE data is suitable for monitoring groundwater storage at large scales, while in-situ groundwater observations are particularly at sub-basin and basin scales [9,25]. Previous studies on groundwater levels in arid areas primarily focused on the changing rate and trend of groundwater levels on an interannual or seasonal scale and its relationships with various driving factors, and thus, in turn, the groundwater cycling process and its interaction with surface water [3,6,22,26–28]. Generally, groundwater level fluctuation could be controlled by many factors in arid regions, including natural and anthropogenic pressures, such as stream water leakage, rainfall infiltration, irrigation return flow, evapotranspiration, groundwater extraction, land-cover pattern, and vegetation [12,22,29–32]. Recently, human activities (e.g., agricultural irrigation) have exerted greater effects on the natural groundwater cycle in arid regions [6]. Porhemmat et al. [29] found that water-saving irrigation systems could reduce phreatic water recharge. Ashraf et al. [9] reported that extensive human water withdrawals dominated the basin-scale groundwater depletions in Iran. Tang et al. [23] reported that the dynamic variations of groundwater level depth could largely control desert vegetation. Additionally, some studies have examined the characteristics of groundwater levels in the oases of Tarim Basin using multiple temporal scales [13,18,33]. Bai et al. [18] reported that groundwater overexploitation was the dominant factor of groundwater level decline in the Yarkand River irrigation districts in China. Furthermore, some researchers have simulated and analyzed the dynamic land-cover patterns in the Tarim Basin using the CA-Markov model, PLUS model, and remote sensing data [20]. Wang et al. [15] found that the cropland area and actual evapotranspiration were the dominant controlling factors for the groundwater level decline in the Weigan-Kuqa Oasis of Tarim Basin. However, the spatiotemporal dynamics of groundwater level and its response to land-cover change were not well understood in the arid regions due to scarce field monitoring data, which had imposed challenges on regional groundwater resources management and appropriate policy formulation [10].

Here, we analyzed the groundwater level dynamic and its response to land-cover change in the desert regions of northern Tarim Basin using 3-years in-situ groundwater monitoring data of 30 wells (2019–2021). The main objectives of this study were: (i) to analyze the variations of land-cover and vegetation in the plains, (ii) to examine the spatiotemporal characteristics of groundwater level on monthly scale and annual scale, (iii) to assess the relationship between groundwater level and vegetation, and (iv) to clarify the effect of land-cover change on groundwater level with the rapid irrigation agriculture development. The results would be expected to be helpful for a deeper understanding of groundwater processes in arid areas and be useful for groundwater resource management and vegetation restoration in desert regions.

2. Study Area

The Tarim Basin is located in the arid region of Northwest China (73.44–93.62° E, 34.84–43.36° N) and is characterized by temperate arid continental climate, with an area of 1.02×10^6 km^2. It is recharged by nine headwaters, including the Kaidu, Dina, Weigan-Kuqa, Aksu, Kashigeer, Yarkand, Hotan, Keriya, and Cherchen Rivers (Figure 1a). These headwaters were primarily supplied by precipitation and meltwater in the Tianshan Mountains and the Kunlun Mountains. Our study focused on the desert regions of three headwaters in the Tarim Basin: the Yarkand River, the Weigan-Kuqa River, and the Dina River. The three headwaters have different physical conditions, such as topography, climate, vegetation, and land-cover types. The elevation in the three headwaters ranged from 868 to 8354 m above sea level, mean annual precipitation was about 119–189 mm, and mean annual air temperature was from 1.8 to 7.5 °C (data from the Chinese National Meteorological Centre). Precipitation exhibited an obvious seasonal distribution, with 70% occurring between June and October [17].

The hydrogeological conditions in the study area show large spatial heterogeneity, which influences the occurrence, flow, and distribution of groundwater [15]. The lithology of the geological strata at the location of the groundwater monitoring wells primarily consists of Quaternary unconsolidated sediments, with sandstone as the dominant rock type, and the soil particle size mainly comprises fine sand and medium-fine sand. The aquifer structure is loose, exhibiting strong hydraulic conductivity. The study area is relatively flat, with terrain slopes of less than 2 degrees. The dominant natural vegetation is *Populus euphratica*, *Tamarix* spp., *Alhagi pseudalhagi*, *Black spine*, *Phragmites communis*, and *Halostachys caspica* in the downstream of Yarkand, Weigan-Kuqa, and Dina River. Moreover, the economic structure is dominated by agricultural production in the three headwaters, and the main crops are corn, winter wheat, and cotton. In the past 40 years, the land use and cover of Tarim Basin have changed greatly, especially the expansion of cropland areas. The cropland area in Tarim Basin has increased from 251.64×10^4 hm^2 in 1980 to 371.78×10^4 hm^2 in 2015, with an increase of 47.74%.

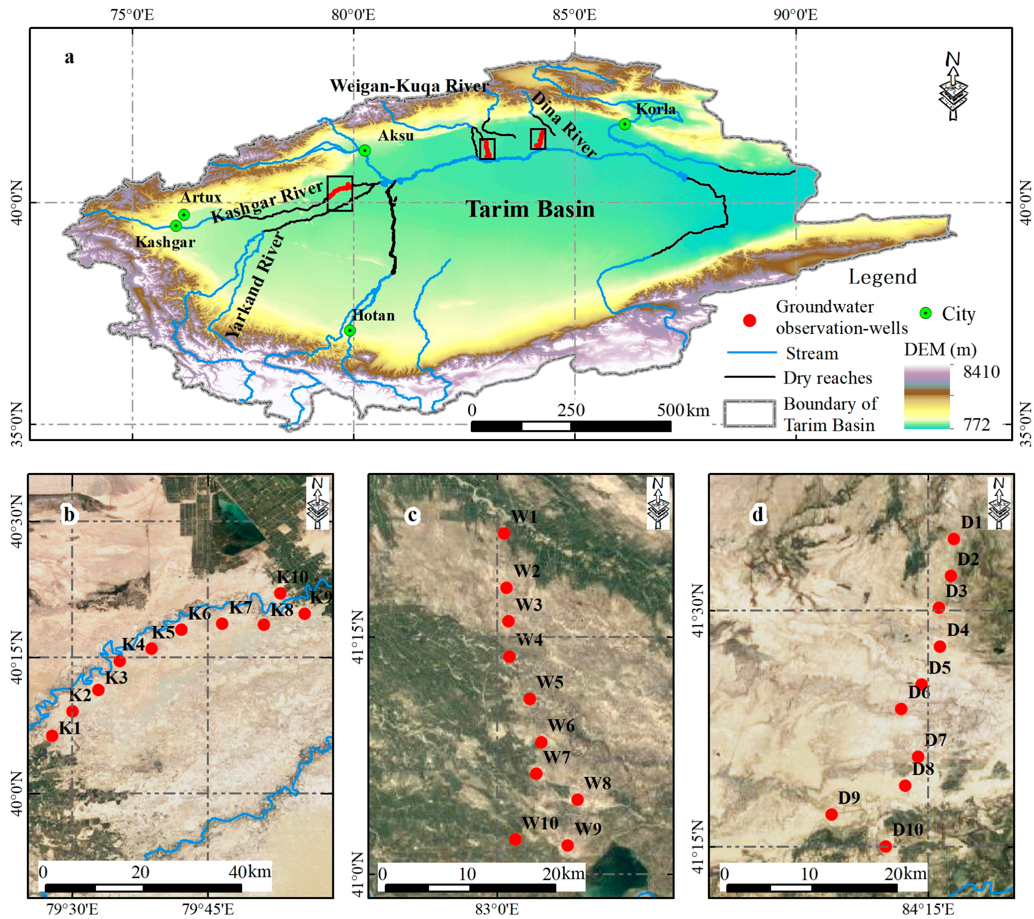

Figure 1. The location of the study area (**a**) and groundwater monitoring well sites in the Yarkand River (**b**), Weigan-Kuqa River (**c**), and Dina River (**d**) in the Tarim Basin of Northwest China.

3. Materials and Methods

3.1. Data

Daily groundwater level data from January 2019 to December 2021 in the downstream of the Yarkand, Weigan-Kuqa, and Dina Rivers were obtained from the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. For each groundwater monitoring well (Figure 1b–d), the groundwater level was continuously automatically monitored and recorded every 4 h using the Telemetering Stage Recorder (XH17-S1, Xinhe Puhua Technology Co. Ltd., Beijing, China) with an analytical precision of 1 mm. More detailed information on the 30 groundwater monitoring wells on the Yarkand River (K1–K10), Weigan-Kuqa River (W1–W10), and Dina River (D1–D10) can be found in Table 1.

Precipitation and air temperature data were obtained from the Chinese National Meteorological Information Center (http://cdc.cma.gov.cn, accessed on 1 January 2022), which was a monthly precipitation and air temperature of China from 1961 to the present with a 0.5° spatial resolution. The above precipitation and air temperature grid data in the study area from 2019 to 2021 were used in our study. Furthermore, normalized difference vegetation index (NDVI) was used to describe vegetation cover. NDVI data in the study area from 2000 to 2020 were derived from the MODIS NDVI product (MOD13Q1) provided by the National Aeronautics and Space Administration (NASA), with a 250 m and 16-day spatial resolution and temporal resolution, respectively. Moreover, the annual land use and land cover (LULC) data in the study area were derived from the GLC (Global Land Cover) data products (GlobeLand30) at 30 m spatial resolution for the years 2000, 2010, and 2020, which were developed by the National Geomatics Center of China (http://www.globallandcover.com, accessed on 25 February 2023). The GlobeLand30 data was produced using a pixel-object-knowledge-based (POK) classification approach, with 10 first-level classes (wetland, water bodies, grassland, artificial surfaces, forest, cultivated land, bareland, permanent snow/ice, shrubland, and tundra) [34].

Table 1. Basic information on the 30 groundwater monitoring wells in the Yarkand River, Weigan-Kuqa River, and Dina River.

Location	Well ID	Longitude (°E)	Latitude (°N)	Altitude (m)	DGL (m)	LULC	NDVI
Yarkand River	K1	79.463	40.107	1048	9.12	Grassland	0.15
	K2	79.501	40.151	1050	9.79	Grassland	0.09
	K3	79.548	40.191	1045	8.23	Bare land	0.08
	K4	79.588	40.244	1041	7.59	Bare land	0.08
	K5	79.647	40.267	1041	7.71	Bare land	0.10
	K6	79.701	40.301	1041	6.95	Bare land	0.09
	K7	79.777	40.312	1057	6.24	Bare land	0.09
	K8	79.853	40.310	1051	7.30	Bare land	0.12
	K9	79.929	40.331	1063	5.46	Bare land	0.13
	K10	79.884	40.369	1060	5.44	Cultivated land	0.75
Weigan-Kuqa River	W1	83.011	41.361	966	5.10	Cultivated land	0.63
	W2	83.013	41.304	953	4.52	Grassland	0.14
	W3	83.016	41.268	955	4.97	Grassland	0.15
	W4	83.016	41.231	952	4.62	Cultivated land	0.72
	W5	83.038	41.187	953	7.71	Grassland	0.46
	W6	83.050	41.141	948	8.17	Grassland	0.47
	W7	83.045	41.107	951	9.86	Grassland	0.37
	W8	83.089	41.080	942	2.89	Bare land	0.29
	W9	83.078	41.031	945	4.18	Bare land	0.22
	W10	83.023	41.038	945	2.68	Cultivated land	0.53
Dina River	D1	84.278	41.576	925	5.31	Bare land	0.19
	D2	84.263	41.462	919	12.14	Grassland	0.19
	D3	84.244	41.422	917	8.89	Bare land	0.12
	D4	84.222	41.396	918	6.04	Bare land	0.08
	D5	84.240	41.345	913	9.11	Grassland	0.09
	D6	84.226	41.315	910	5.12	Grassland	0.12
	D7	84.205	41.251	911	4.78	Grassland	0.12
	D8	84.274	41.537	911	4.53	Bare land	0.13
	D9	84.262	41.503	914	6.01	Bare land	0.10
	D10	84.148	41.284	919	6.74	Grassland	0.22

Notes: DGL: depth to groundwater leve; LULC: land use and land cover; NDVI: normalized difference vegetation index.

3.2. Statistical Analysis

In this study, data statistical analyses were processed using Microsoft Excel (version 2016), and the figures were prepared using MATLAB (version R2018a), ArcGIS (version 10.6), and Origin (version 2021). The Mann-Kendal test method was used to detect the significant trends of vegetation dynamics, which has been widely used to analyze the time series data of resource and environmental factors [35,36].

Percentage variation of individual LULC was calculated to evaluate the LULC variation extent between two time points, which can be calculated by Equation (1) [37]:

$$\text{Percent variation}(\%) = \left(\frac{A_2 - A_1}{A_1}\right) \times 100 \quad (1)$$

where, A_1 and A_2 are the area of a given LULC type in time 1 and time 2, respectively.

The Sen's slope method was applied to calculate the variation amplitudes and trends of vegetation cover, which has been widely used to evaluate the spatial and temporal variations of long-term time series data [15,38]. The formula is given as Equation (2):

$$Sen_{ij} = MEDIAN\frac{(X_j - X_i)}{(j - i)} \quad (2)$$

where, Sen_{ij} is the Sen's slope; X_i and X_j are the sequential values corresponding to times i and j, respectively, $1 < i < j < n$, n is the length of the time series. $Sen < 0$ shows that the time series displays a decreasing trend, while $Sen > 0$ shows that the time series displays an increasing trend.

4. Results

4.1. Variations of Land-Cover and Vegetation

Figure 2 shows the distributions of LULC in the plains of Yarkand, Weigan-Kuqa, and Dina Rivers from 2000 to 2020. In the plain of Yarkand River, bare land was the dominant land-cover type (43.2% in 2020), and cultivated land was second in dominance (30.1% in 2020), followed by grassland (16.7% in 2020; Figure 2a–c). In the plain of the Weigan-Kuqa River, cultivated land was the dominant land-cover type (65.6% in 2020), followed by grassland (16.4% in 2020) and bare land (10.0% in 2020; Figure 2d–f). In the plain of Dina River, bare land was the dominant land-cover type (62.8% in 2020), followed by grassland (18.8% in 2020) and cultivated land (17.2% in 2020; (Figure 2g–i). Compared to other land-cover types, the area of bare land, grassland, and cultivated land varied significantly over the last 20 years. Over the period, cultivated land area increased by 1174.6, 638.0 and 732.2 km^2 in the plains of Yarkand, Weigan-Kuqa and Dina Rivers, respectively, while grassland area and bare land area decreased by 1703.9 and 1336.6 km^2 in the plain of Yarkand River, 544.0 and 267.0 km^2 in the plain of Weigan-Kuqa River, 303.1 and 472.5 km^2 in the plain of Dina River. Obviously, the decreased bare land and grassland were mainly transferred to cultivated land. Furthermore, the area coverage of wetlands, water bodies, and artificial surfaces continuously increased from 2000 to 2020; the forest area gradually decreased in the Weigan-Kuqa River but increased in the Yarkand and Dina Rivers. As shown in Figure 2, bare land was mainly distributed on the periphery of cultivated land and grassland. In the plain of the Yarkand River, cultivated land was mainly in the southwest and middle, and grassland was mainly in the middle and northeast. In the plain of the Weigan-Kuqa River, cultivated land was mainly in the north and southwest, and grassland was mainly in the southeast. In the plain of the Dina River, grassland and cultivated land were mainly in the middle and southwest.

The annual average NDVI in the plains of Yarkand, Weigan-Kuqa, and Dina Rivers exhibited an increasing trend from 2000 to 2020 (Figures 3 and 4). During this period, the average increasing rate of NDVI was the smallest in the Dina River (0.003/year), followed by the Yarkand River (0.004/year), while the largest in the Weigan-Kuqa River (0.009/year). As shown in Figure 3, NDVI across the plains exhibited noticeable spatial distributions. Overall, vegetation cover was highest in the Weigan-Kuqa River, followed by the Yarkand River, while it was lowest in the Dina River. In terms of spatial distribution, NDVI values were relatively low in the edge and northeast of the Yarkand River plain, while they were high in the central part of the Dina River plain. Similarly, the sparse vegetation cover area was located at the edge and the southeast of the Weigan-Kuqa River plain.

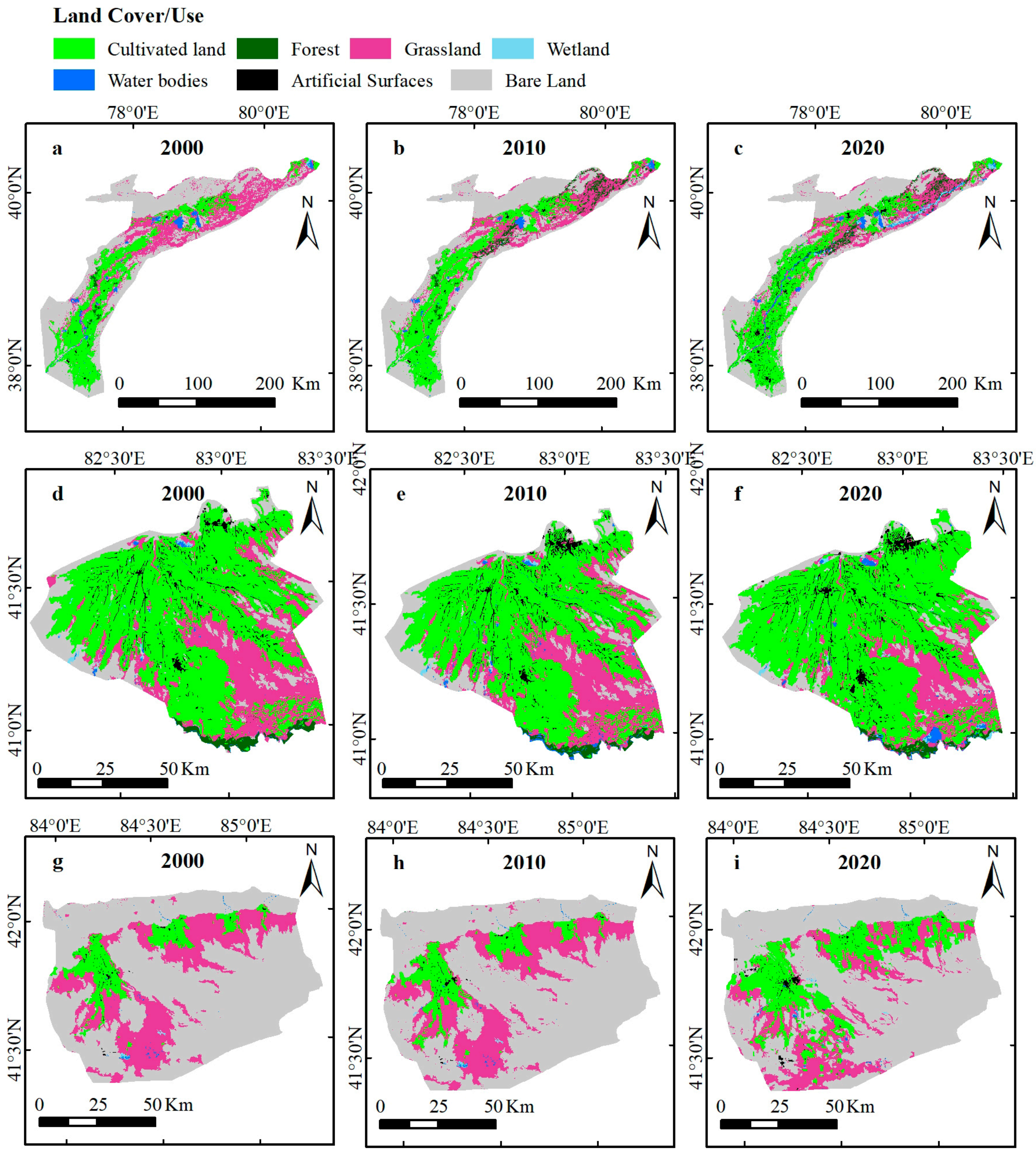

Figure 2. Distributions of land cover types in the plains of Yarkand River (**a**–**c**), Weigan-Kuqa River (**d**–**f**), and Dina River (**g**–**i**) for 2000 (**a**,**d**,**g**), 2010 (**b**,**e**,**h**), and 2020 (**c**,**f**,**i**), respectively.

Moreover, Figure 4 used color gradients to present the details of NDVI variation in spatial distribution over the plains from 2000 to 2020. Generally, NDVI decreased significantly in sporadic areas of the plains of Yarkand, Weigan-Kuqa, and Dina Rivers while increasing noticeably in most parts of the study area. Overall, the increasing trend of NDVI was concentrated in the cultivated land and forest of the oasis region (Figures 2 and 3). In the plain of the Yarkand River, vegetation cover in the central part changed more noticeably than that in the other part from 2000 to 2020. In the plain of the Weigan-Kuqa River, vegetation cover in the southeastern part changed less obviously than that in the other part over the last 20 years. In the plain of Dina River, vegetation cover in certain localized areas of the central part changed more noticeably from 2000 to 2020.

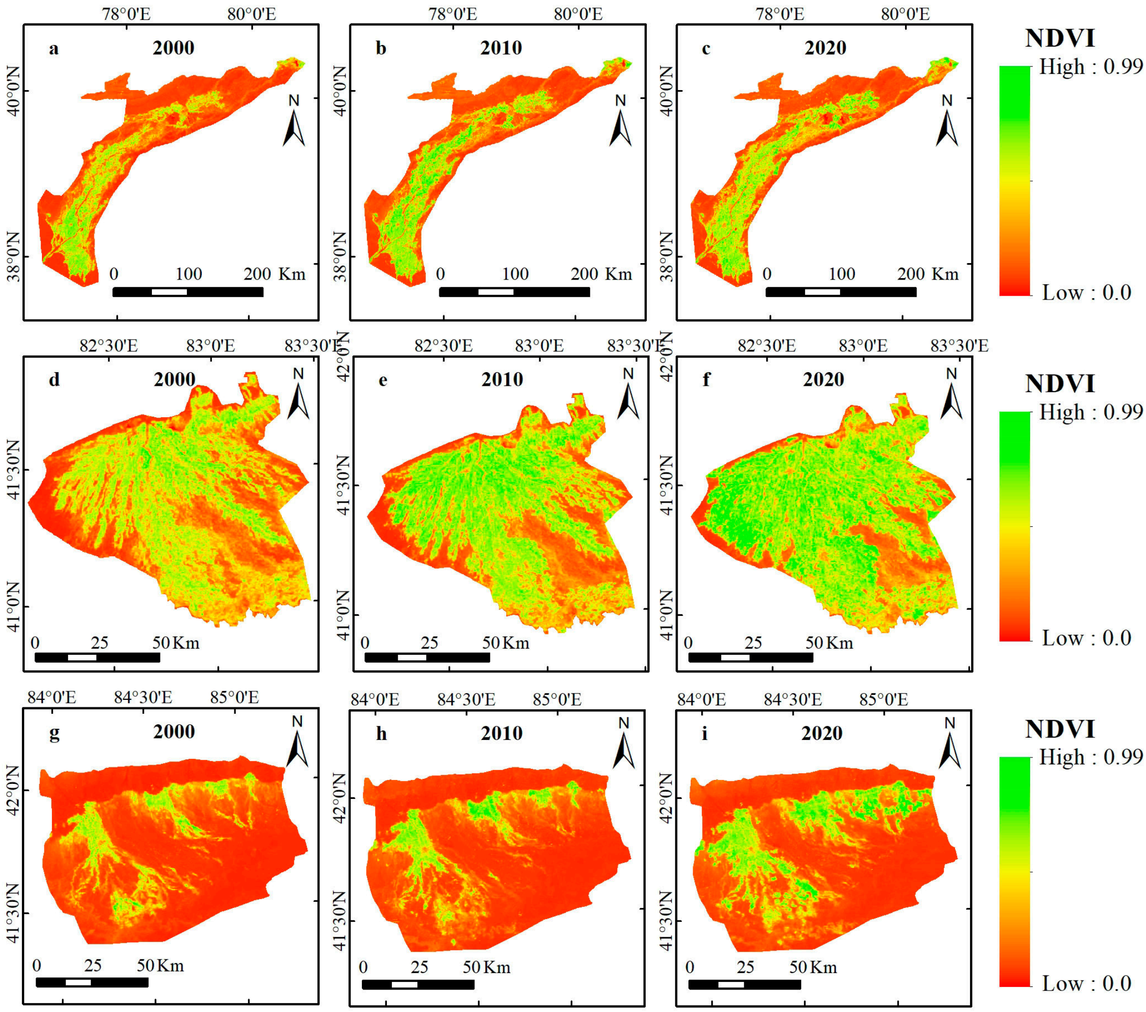

Figure 3. Distributions of annual average NDVI in the plains of Yarkand River (**a**–**c**), Weigan-Kuqa River (**d**–**f**), and Dina River (**g**–**i**) for 2000 (**a**,**d**,**g**), 2010 (**b**,**e**,**h**), and 2020 (**c**,**f**,**i**), respectively. NDVI: normalized difference vegetation index.

4.2. Spatiotemporal Variations of Groundwater Level

The average DGL (depth to groundwater level) of monitoring wells in the Yarkand, Weigan-Kuqa, and Dina Rivers from 2019 to 2021 are shown in Figure 5. DGL exhibited significant variability among the monitoring wells, and the spatial pattern of DGL varied among the three rivers. Overall, DGL in the Dina River was significantly shallower than that in the Yarkand River but deeper than that in the Weigan-Kuqa River (Figure 5). In general, DGL in the downstream of Yarkand, Weigan-Kuqa, and Dina Rivers from 2019 to 2021 showed a weakly increasing trend mainly due to human activities, with increasing rates of 0.025, 0.125, and 0.067 m/year, respectively. In the downstream of the Yarkand River, DGL ranged from 5.06 to 9.97 m with a mean value of 7.38 m. The variation amplitude of DGL was larger in K5 and K10 (1.22 m and 1.07 m), while it was smaller in K7 and K9 (0.20 m and 0.35 m). In the downstream of the Weigan-Kuqa River, DGL ranged from 1.16 to 10.48 m with a mean value of 5.47 m. The variation amplitude of DGL was larger in W1 and W4 (2.88 m and 3.22 m), while it was smaller in W9 (0.97 m). In the downstream of Dina River, DGL ranged from 4.32 to 12.68 m with a mean value of 6.87 m. The variation amplitude of DGL was larger in D1, D2, D6, and D10 (1.13, 0.96, 1.00, and 1.12 m), while it was smaller in D4 (0.80 m).

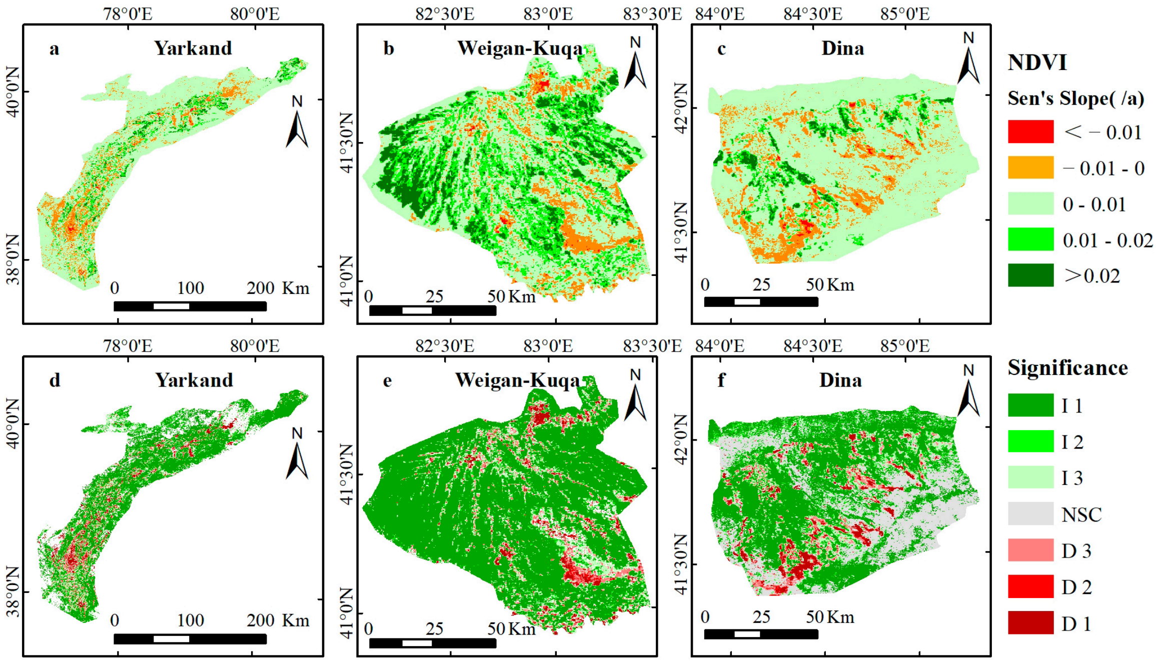

Figure 4. Sen's slope tested variation of NDVI (**a**–**c**) and its significance (**d**–**f**) in the plains of Yarkand River (**a**,**d**), Weigan-Kuqa River (**b**,**e**) and Dina River (**c**,**f**) from 2000 to 2020. NDVI: normalized difference vegetation index. I1: significant increase (a > 0, $p < 0.01$); I2: increase slightly significant (a > 0, $0.01 \leq p < 0.025$); I3: insignificant increase (a > 0, $0.025 \leq p < 0.05$); NSC: no significant change ($p > 0.05$); D3: decrease slightly significant (a < 0, $0.025 \leq p < 0.05$); D2: insignificant decrease (a < 0, $0.01 \leq p < 0.025$); D1: significant decrease (a < 0, $p < 0.01$).

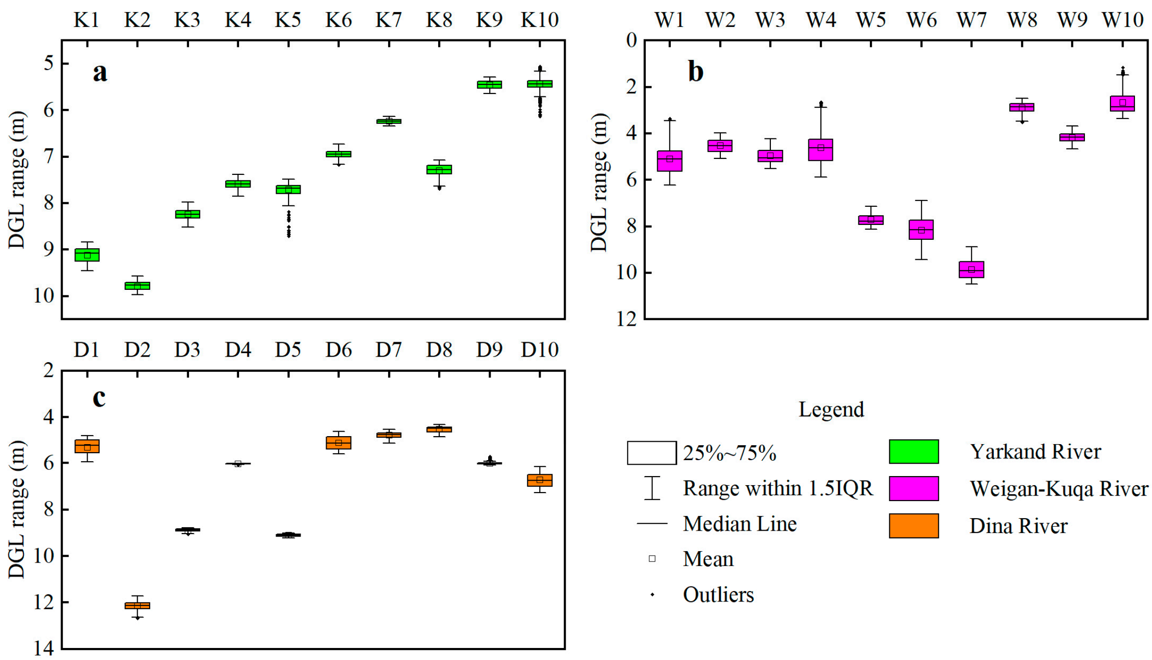

Figure 5. Box plots of the average DGL of monitoring wells in the Yarkand River (**a**), Weigan-Kuqa River (**b**), and Dina River (**c**) from 2019 to 2021. DGL: depth to groundwater level.

Figure 6 exhibited the temporal variation of daily DGL for monitoring wells downstream of the Yarkand, Weigan-Kuqa, and Dina Rivers. Obviously, the value of DGL in the study area varied in time and space. DGL fluctuated obviously through the period from 2019 to 2021, and the fluctuation amplitude of DGL differed significantly among the monitoring wells (Figure 6). In the downstream of the Yarkand River, DGL was relatively smaller in K7, K9, and K10 (less than 6.5 m) and was relatively larger in other wells (from 7 to 10 m). DGL in K1, K2, and K7 varied gently; the maximum value occurred in mid-April and was smaller in winter and spring than in summer and autumn, mainly due to phreatic water evaporation (Figure 6a). The fluctuation of DGL in K3, K4, K5, K6, and K8 was synchronous, indicating a good hydraulic connection and the same recharge and discharge conditions [15]. Groundwater levels of K10 showed an increasing trend, which was attributed to the irrigation of cotton fields nearby. In the downstream of Weigan-Kuqa River, DGL was relatively smaller in W1, W2, W3, W4, W8, W9, and W10 (generally less than 6 m) and was relatively larger in other wells (generally more than 7 m), which was mainly attributed to land-cover change and agricultural activities [15]. DGL in W1, W4, and W10 increased from early March to late April, then decreased from late April to early September, and stabilized starting in mid-September (Figure 6b), which was attributed to the cultivated land nearby and irrigation water infiltration. In comparison, the intra-annual distribution of DGL in W6 was more complicated, maybe due to the coupling effects of irrigation and groundwater pumping. In the downstream of Dina River, the inter-annual and intra-annual variations of DGL in D3, D4, and D5 were not significant. DGL showed an increasing trend in D6 while exhibiting a slightly decreasing trend in D7, D8, D9, and D10 (Figure 6c).

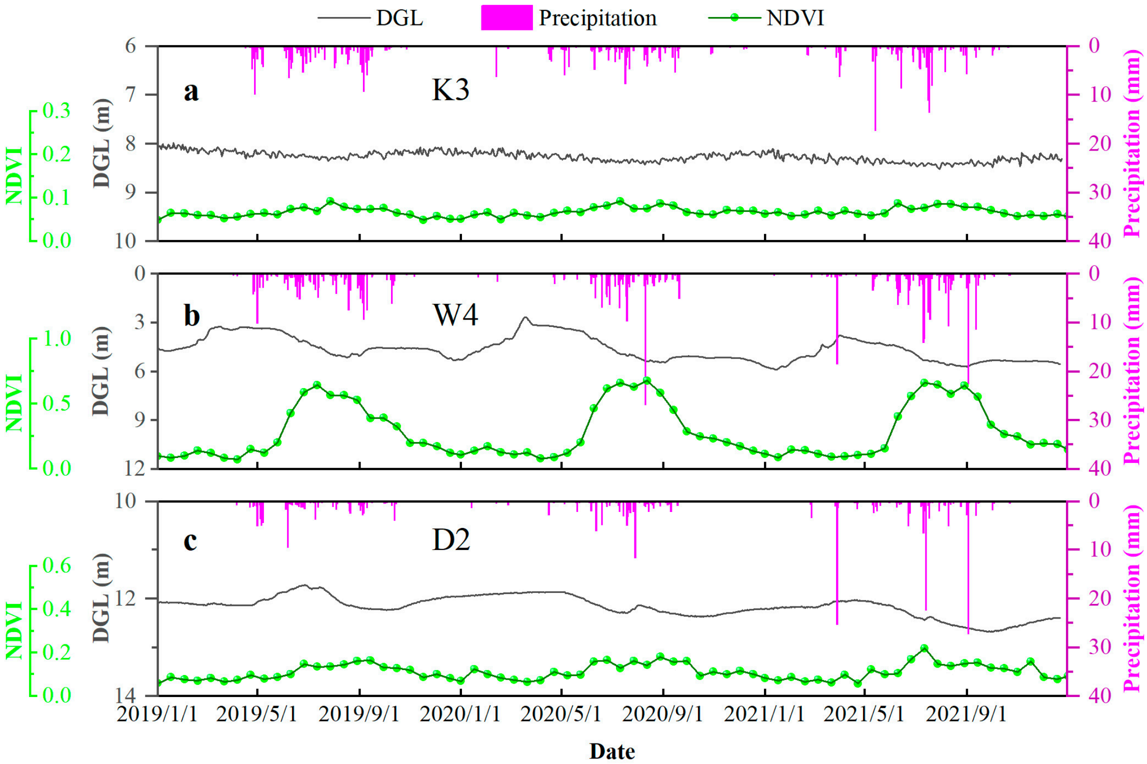

Figure 6. Temporal variations of precipitation, NDVI, and groundwater level depth (DGL) of typical monitoring well in the Yarkand River (K3 well; (**a**)), Weigan-Kuqa River (W4 well; (**b**)), and Dina River (D2 well; (**c**)) from 2019 to 2021. NDVI: normalized difference vegetation index.

The monthly change ranges of DGL for the 30 monitoring wells in our study area from 2019 to 2021 are shown in Figures 7–9. In the downstream of the Yarkand River, the intra-annual distribution of monthly change ranges of DGL was not significant (Figure 7).

The monthly change ranges of DGL in K1–K9 and D1–D9 were not more than 0.3 m under natural conditions. The variation of DGL in K5 fluctuated significantly from April 2019 to July 2019, mainly due to human activities (groundwater extraction for building highways). The maximum monthly variation of DGL in K10 occurred in August, which may be caused by the sharply increased DGL resulting from groundwater pumping for irrigation. As shown in Figure 8, downstream of the Weigan-Kuqa River, the monthly change ranges of DGL in W1, W4, W6, and W10 were large and showed an obvious intra-annual distribution, which was close to the oasis. The maximum monthly variation of DGL occurred in March, which was the spring irrigation period for winter wheat in the oasis (groundwater pumping for irrigation). While the monthly variation of DGL was relatively small in September, at this moment, the agriculture irrigation activities were basically ending [15]. In the downstream of Dina River, the monthly variation of DGL in D1 and D2 exhibited a decreasing trend before April, then gradually increased and reached the maximum value in June (Figure 9). The monthly variation of DGL in D10 corresponded well with the oasis irrigation activities and the streamflow of the Tarim River Mainstream because D10 was close to the Tarim River Mainstream and was affected by the irrigation return water and stream water. Furthermore, in the desert area of Weigan-Kuqa and Dina Rivers, the monthly variation of DGL increased initially and decreased afterward during the year and was greater during the growing season than in the non-growing season. This indicates that desert vegetation is dependent on groundwater [3].

Figure 7. Monthly variation amplitude of groundwater level depth (DGL) for the 10 monitoring wells in the Yarkand River from 2019 to 2021.

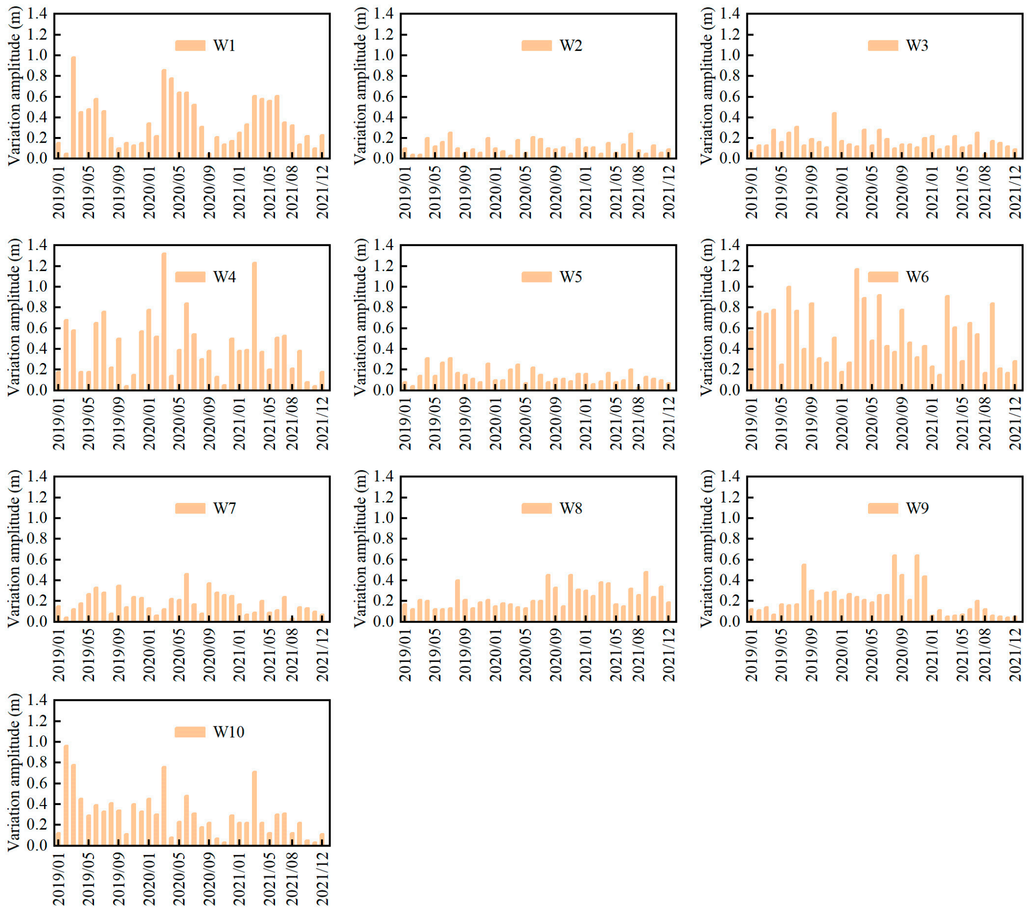

Figure 8. Monthly variation amplitude of groundwater level depth (DGL) for the 10 monitoring wells in the Weigan-Kuqa River from 2019 to 2021.

Figure 10 shows the groundwater level difference for 30 monitoring wells in the study area from 2019 to 2021. Groundwater level differences in K1–K4 were negative, indicating that the discharge of the groundwater system was greater than the recharge (Figure 10a). Groundwater level difference in K5–K10 was positive or negative during our study period, suggesting that groundwater was in dynamic equilibrium. Overall, downstream of Yarkand River, the groundwater system was in negative equilibrium in 2021 (groundwater resources decreasing), and the groundwater level difference from K1 to K10 increased initially and decreased afterward. That is, the closer to the oasis, the greater the groundwater level difference was. In the downstream of the Weigan-Kuqa River, the groundwater level difference was negative from 2019 to 2021 (Figure 10b), which indicated that the groundwater system in the whole region was in negative equilibrium and groundwater level exhibited a decreasing trend. The groundwater system was in positive equilibrium for W1, W6, and W9 in 2019 and for W4, W7, and W10 in 2021. Groundwater level difference was negative for W2 and W8 in 2019, 2020, and 2021, indicating the occurrence of groundwater decline funnel near the two Wells or the decreasing of lateral groundwater recharge [15]. Groundwater level difference was negative for W1, W6, and W9 from 2020 to 2021 and needs to be monitored in the future. In the downstream of Dina River, groundwater level difference was negative for D1, D3, D4, and D6 in 2019, 2020, and 2021 (less than −0.1 m for D1 and D6), suggesting that the discharge of groundwater was always greater than the recharge (Figure 10c). Groundwater level difference was positive for D7, D8, and D9 and was negative for D1 and D2. Generally, the groundwater system was in negative equilibrium near the oasis, influenced by agricultural irrigation activities, was basically in dynamic equilibrium in the desert region, and was in positive equilibrium near the Tarim River Mainstream, influenced by the irrigation return water and streamflow.

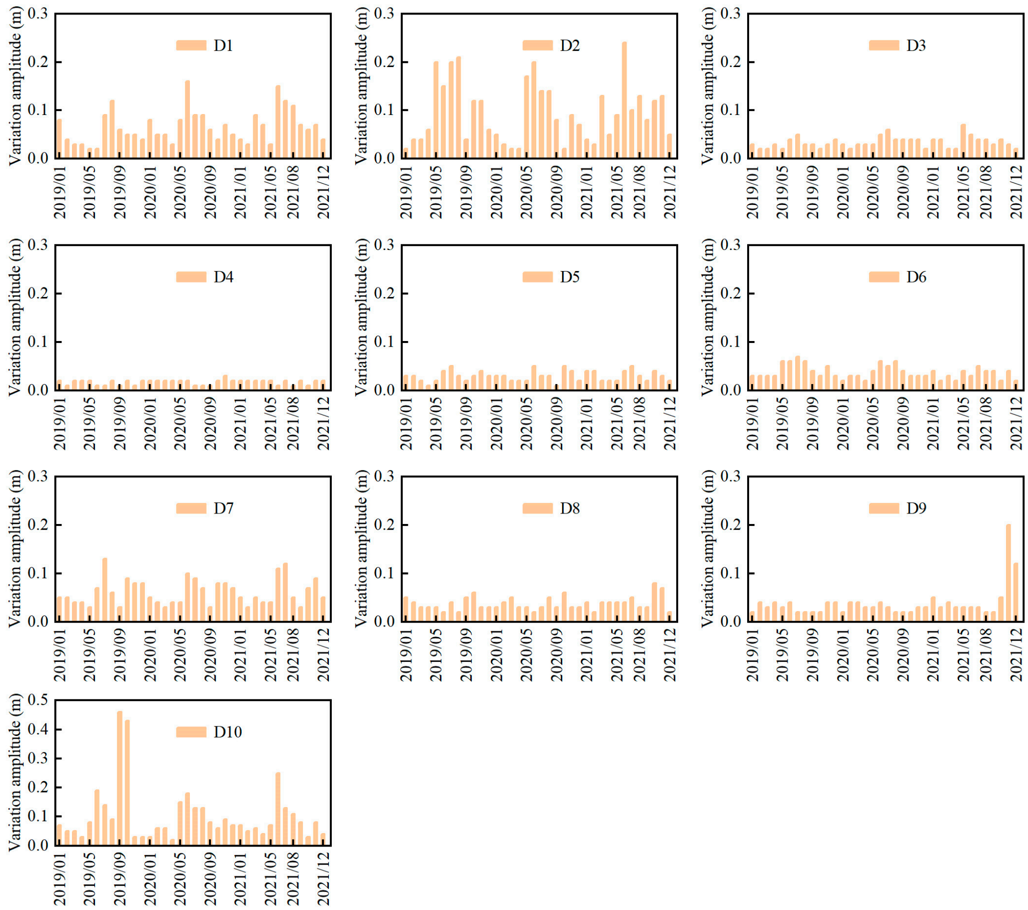

Figure 9. Monthly variation amplitude of groundwater level depth (DGL) for the 10 monitoring wells in the Dina River from 2019 to 2021.

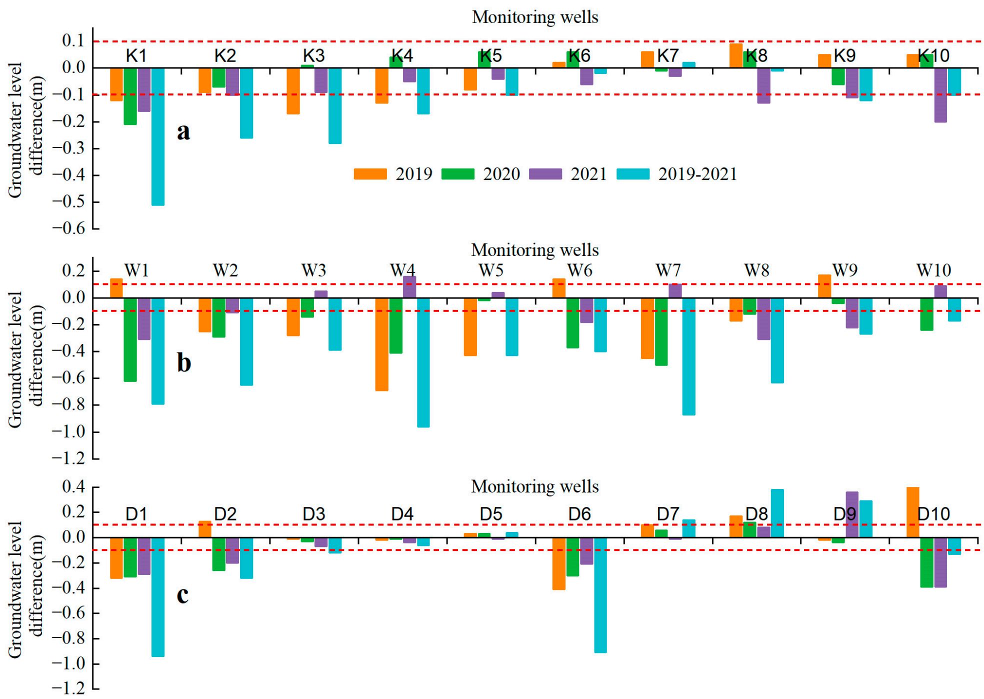

Figure 10. Groundwater level difference for monitoring wells in the Yarkand River (**a**), Weigan-Kuqa River (**b**), and Dina River (**c**) from 2019 to 2021.

4.3. Relationship between Groundwater Level and Vegetation

Figure 11 illustrates the correlation between groundwater level and natural vegetation in the desert regions of the entire study area. Overall, the NDVI values of natural desert vegetation increased as the groundwater level increased. In general, the NDVI spatial profile was significantly negatively correlated with the groundwater level depth (DGL) in the desert regions of Yarkand, Weigan-Kuqa, and Dina Rivers during the study period (R^2 = 0.78, $p < 0.05$). Larger groundwater level depth was accompanied by lower NDVI value, which was consistent with the existing research results identified in the Tarim Basin [39]. Moreover, when the DGL was greater than 6 m in the desert regions, the NDVI of natural vegetation was less than 0.15, and the rate of NDVI decreasing was not significant with the DGL increasing (Figure 11). In contrast, when the DGL was less than 6 m, the NDVI of natural vegetation increased significantly with the DGL decreasing. That is, there is a threshold of ecological groundwater level in arid regions [39].

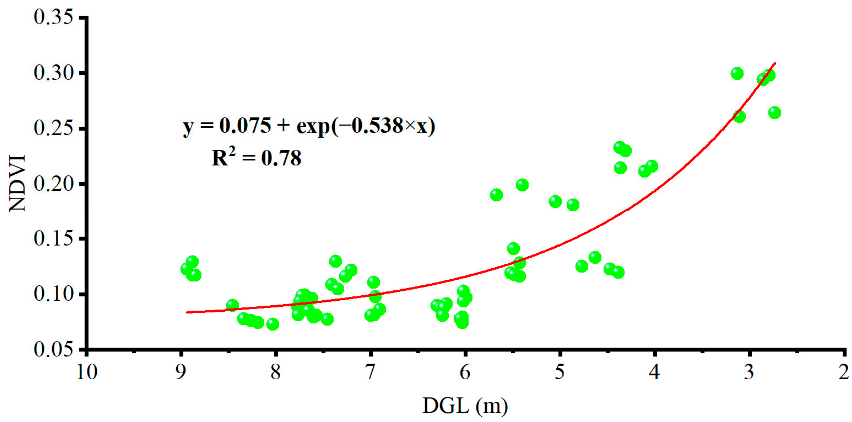

Figure 11. Relationships of groundwater level depth (DGL) and NDVI in the desert regions of Yarkand, Weigan-Kuqa, and Dina Rivers. NDVI: normalized difference vegetation index.

As shown in Figure 6, in the desert region of the Yarkand River, the NDVI of natural vegetation fluctuated little in the seasons, with low vegetation coverage, and the annual fluctuation of DGL was small, indicating the weak effect of groundwater on natural vegetation. In the desert region of the Dina River, as the DGL decreased from early April to September, the NDVI of desert vegetation increased obviously from late May to October (Figure 6c). In the desert region of the Weigan-Kuqa River, the intra-annual variations of DGL and NDVI exhibited obvious seasonal cycles (Figure 6b). As the DGL decreased from March to August, impacted by oasis agricultural irrigation, the NDVI values of natural vegetation increased significantly from May to October (growing season), indicating that phreatic water was the dominant source of desert vegetation during the growing season [40]. This again proved that the relationship between natural vegetation and groundwater level depth was significant in the desert region of the Weigan-Kuqa River with smaller DGL, while it was weak in the desert regions of Yarkand and Dina Rivers with larger DGL. The growing season of *Populus euphratica* is from March to October [23].

5. Discussion

5.1. Influence of Land-Cover Change on Groundwater Level

Land-cover change significantly affected groundwater level. Our results showed that groundwater level dynamics were noticeably related to land-cover types (Figures 2 and 5). Groundwater in arid areas depends on rainfall, surface water infiltration (stream water and agricultural irrigation water), and lateral groundwater flow [3,31]. The recharge of phreatic water from precipitation is limited in arid regions owing to high evaporation rate, scarce rainfall, and high groundwater depth (Figure 6) [21,22,41]. More precipitation during the growing season could stimulate vegetation growth by increasing soil water content and thus result in lower groundwater levels due to greater water absorption by deep-rooted vegetation [5,12]. Precipitation in the study area mainly occurred from May to mid-September, and the maximum daily precipitation did not exceed 27 mm from 2019 to 2021 (Figure 6). The groundwater level did not exhibit a rising trend after rainfall, indicating the weak effect of precipitation on groundwater in the plains [15].

Land-cover change could control the water balance and redistribute groundwater resources by altering groundwater recharge and discharge processes, thus influencing groundwater level dynamics [42,43]. Generally, the groundwater system was in negative equilibrium near the oasis influenced by agricultural irrigation activities, was basically in dynamic equilibrium in the desert region, and was in positive equilibrium near the Tarim River Mainstream influenced by the irrigation return water and streamflow (Figure 10). Increased cultivated land area in the oases could decrease groundwater level due to greater groundwater pumping for agricultural irrigation, but could also enhance soil water content by increasing irrigation water infiltration and thus result in higher phreatic water level [5,22]. However, irrigation return water infiltration could not completely offset the negative effect of groundwater exploitation within the groundwater system because the promotion of water-saving irrigation has significantly reduced the amount of agricultural irrigation water infiltration [11,29]. Porhemmat et al. [29] found that the maximum vertical infiltration depth of irrigation water was less than 50 cm under drip irrigation conditions. Oasis agriculture is completely dependent on irrigation in arid regions [10]. In 2016, the total amount of groundwater exploitation in the Tarim Basin was 48.33 $\times$ 10^8 m^3, of which 43.07 $\times$ 10^8 m^3 was used for agricultural irrigation, accounting for 89.1% (Figure 12). This indicates that groundwater was mainly used for irrigation agriculture in oases, with low economic benefits [31]. As shown in Figure 6b, DGL in the Weigan-Kuqa oasis was the shallowest in April (annual average value of 3.57 m) due to the spring flood irrigation and was the largest in October, reflecting the cumulative effect of groundwater exploitation in the irrigation period, but became smaller in November due to winter irrigation [15]. In contrast, the seasonal variation of DGL was not obvious in the grassland and bare land, with a relatively small fluctuation range (Figure 6c). Nevertheless, groundwater level variation may respond slowly to anthropogenic forcing, and a lag between irrigation activities and groundwater level fluctuation was observed over the plains [5,33,44].

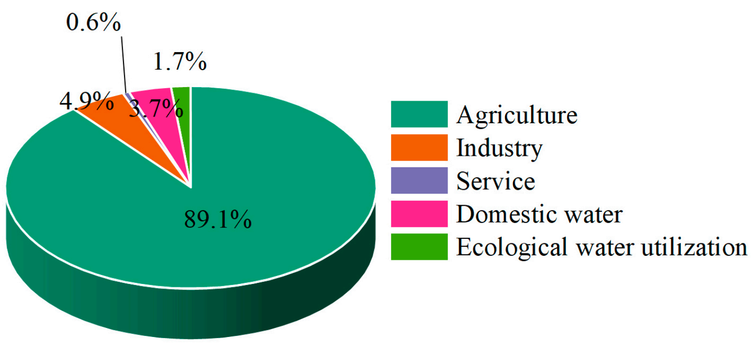

Figure 12. Proportion of groundwater utilization amount by different sectors in the Tarim Basin (data from the Water Resources Bulletin of Xinjiang Uygur Autonomous Region, China).

Furthermore, the different oasis expansion extent could exert a different influence on regional groundwater level dynamics in the three plains. In our study area, cultivated land was generally transferred from grassland and bare land over the recent 20 years (Figure 2). Cultivated land area was significantly negatively correlated with groundwater level [15]. Compared to the Yarkand and Dina Rivers, the increase of cultivated land area in the Weigan-Kuqa plain was larger, with larger interannual variation and seasonal fluctuation of groundwater level (Figures 2, 5 and 6). The continuous increase of cultivated land area could need greater groundwater extraction to meet agricultural irrigation water demands owing to the limited surface water resources in arid regions, leading to the continuous decline of groundwater level [6,45]. Wang et al. [15] reported that the cultivated land area increased by 472.7 km^2 (11.9%) across the Weigan-Kuqa plain from 2000 to 2018, while the groundwater level decreased by about 4.1 m on average. In the Weigan-Kuqa River basin, the groundwater level declined rapidly from 2004 to 2015 (groundwater overexploitation period), but the amount of groundwater exploitation was limited after 2015 due to the implementation of the strictest water resources management system [15]. The amount of groundwater exploitation in the Tarim Basin increased from 16.0×10^8 m^3 in 2006 to 57.0×10^8 m^3 in 2014 (the average increase rate of 4.3×10^8 m^3/year), and the proportion of groundwater exploitation in groundwater resources increased from 5.2% to 22.7%, but has gradually decreased and stabilized since 2015 due to policy regulation (data from the Water Resources Bulletin of Xinjiang Uygur Autonomous Region, China). Moreover, for the downstream of the Dina River, the absorption of groundwater by vegetation was little due to the sporadic distribution of herbs and *Populus euphratica* in the desert area, thus leading to the unobvious intra-annual variation of groundwater level [3]. In addition, groundwater exploitation in the Yarkand River plain increased sharply from 2005 to 2013 due to large-scale land reclamation, while the intensity of groundwater exploitation has remained relatively large since 2014, resulting in a large DGL in desert areas [10,18].

5.2. Correlation between Groundwater and Vegetation

Groundwater levels may exert a strong impact on natural vegetation in arid regions. Our results showed that the NDVI values of natural desert vegetation were noticeably positively related to groundwater level (Figures 6 and 11). Groundwater level dynamics control the absorption of groundwater by desert vegetation roots, thus affecting vegetation growth and coverage [18]. This is because the natural vegetation in arid areas is heavily dependent on groundwater due to scarce rainfall and river water [15,31]. In general, extreme climate and extensive human groundwater exploitation could trigger the depletion of groundwater in arid areas, which in turn results in lower groundwater levels, leading to lower vegetation coverage in the desert regions [9,10,39]. Fan et al. [39] reported that the most suitable value of groundwater level depth for the *Populus euphratica* growth was 2~4 m in the lower reaches of the Tarim River. When groundwater level decline exceeds the depth of water absorption for desert vegetation roots, desert vegetation degrades, and the relationship between groundwater level and NDVI is very weak in the desert regions (Figure 11) [23]. However, the threshold of ecological groundwater level differs among different desert vegetation [5,39]. Further study is needed to quantitatively examine the groundwater level threshold for the various desert vegetation growth, especially in the desert regions of dried-up river basins.

Furthermore, the relationship between groundwater level depth and NDVI was not obvious near the oasis, owing to the influence of irrigation activities on soil water content and phreatic water (Figure 6) [10,15]. Groundwater level decreased by 4.1 m in the Weigan-Kuqa Oasis from 2000 to 2018, but the mean NDVI value increased by 0.19 over the same period, which was mainly attributed to the effects of agricultural irrigation on artificial vegetation (cropland and artificial economic forest) in the growing season [15]. Moreover, there was a lag in the influence of groundwater level dynamics on natural vegetation coverage, especially for the deep-rooted arbors (e.g., *Populus euphratica*) (Figure 6) [10,46]. Chen et al. [10] reported that the dry reaches in Tarim Basin caused by the oasis expansion have led to the sharp decline of groundwater level near the river channel, thus, in turn, resulting in the desert riparian forest degradation gradually. In addition, decreased groundwater levels due to groundwater overexploitation in the arid oases could lead to lower groundwater levels in the desert region due to the decreasing supply from lateral groundwater flow, which in turn results in the degradation of natural desert vegetation [3,11,15]. Based on stable isotopic indicators and end-member mixing analysis method [31], lateral groundwater flow from the oasis was the dominant source of shallow groundwater in the desert region of the Yarkand River, accounting for 75%.

5.3. Recommendations for Groundwater Resource Management

Obviously, the gradual depletion of local groundwater resources (quantity) was the result of groundwater overexploitation and large-scale land reclamation associated with the water-saving irrigation agriculture development in the plain regions of the Tarim Basin [3,11]. This has caused some socioeconomic and environmental consequences and threatens the security of local water, economy, and ecological systems, such as the decrease of local groundwater level and death of desert riparian forests [10]. Specifically, the principal issues of groundwater in arid oasis-desert regions were as follows: (i) There was a lack of reasonable planning for groundwater wells in some irrigation regions (e.g., the location, density, water pumping layer, and water withdrawal of groundwater wells), resulting in a serious decline of groundwater level and the drying of aquifers in some regions. This would threaten the sustainable utilization of groundwater resources. (ii) The utilization of surface water and groundwater lacked unified planning. The allocation of agricultural, industrial, and domestic water usage was unreasonable. More than 90% of water resources were used for agricultural irrigation in the Tarim Basin, which was much higher than the national average (65%) and the world average (70%) [10]; (iii) The monitoring Wells in Xinjiang Uygur Autonomous Region primarily monitor the phreatic water level, but groundwater extraction usually occurs in multiple aquifers (both phreatic and confined aquifers). The depletion of deep groundwater would threaten local water resources and ecological security [15]. (iv) The promotion of water-saving irrigation in arid areas could reduce the recharge of groundwater systems from irrigation return water infiltration, affecting the balance of the groundwater system [29].

In order to manage the depleted groundwater resource and avoid further depletion, the following recommendations for groundwater resource management in arid oasis-desert regions were proposed: (i) The scientific and reasonable plan for groundwater exploitation should be determined based on the hydrogeology, groundwater resources, and technical conditions. Groundwater extraction intensity in the oases of Tarim Basin has sharply increased in the recent 30 years due to policy guidance, resulting in the continuous decline of groundwater level [10]. (ii) It is necessary to strengthen the groundwater dynamic monitoring in the plain area and popularize the monitoring technology of multiple aquifers to monitor the water level of different aquifers so as to provide a scientific basis for the accurate evaluation, rational utilization, and effective protection of groundwater resources. That then could explore the hydraulic connection between phreatic water and confined water, the overexploitation status, and the recovery ability of deep groundwater. (iii) It is urgent to strengthen the research on the relationship between groundwater and ecological environment, land-cover change, and water-salt balance in the Tarim Basin, which would be helpful for the sustainable development of the regional economy and society [19]. (iv) Efficient water-saving technology should be further promoted to improve the utilization efficiency of groundwater resources. The optimum proportion of agricultural, industrial, and domestic water should be explored and implemented to promote the transformation of the regional economic structure, such as reducing the proportion of agricultural water in the Tarim Basin [47]. (v) Ecological water delivery should be implemented to protect the seriously degraded desert riparian forests, especially in the lower reaches of the Yarkand River. Desert riparian forest ecosystem is extremely important for maintaining the ecological environment in arid areas. The irrigation return flow under the water-saving irrigation could primarily increase the water storage of the vadose zone rather than phreatic water recharge due to the thick vadose zone, preventing any meaningful recovery of groundwater level and natural vegetation in the desert regions [3].

6. Conclusions

In this study, spatiotemporal characteristics of groundwater level and its response to land-cover change were examined using 3-years in-situ groundwater monitoring data of 30 wells in the desert regions of northern Tarim Basin. The results showed that groundwater level exhibited obvious spatial and seasonal variations, and the fluctuation of DGL differed significantly among the wells. The cultivated land area increased by 1174.6, 638.0, and 732.2 km^2 from 2000 to 2020 in the plains of Yarkand, Weigan-Kuqa, and Dina Rivers, respectively, which were mainly transferred from bare land and grassland. Annual average NDVI values increased with time during the period (0.003/year, 0.004/year, and 0.009/year for the Dina, Yarkand, and Weigan-Kuqa Rivers, respectively). In general, DGL was characterized by a weakly increasing trend from 2019 to 2021, mainly due to human activities (e.g., land-cover change, agriculture irrigation, groundwater pumping). DGL in the Dina River (6.87 m) was significantly smaller than that in the Yarkand River (7.38 m) but larger than that in the Weigan-Kuqa River (5.47 m). Land-cover change significantly affected the dynamic variation of groundwater level. Generally, the groundwater system was in negative equilibrium near the oasis influenced by agricultural irrigation activities, was basically in dynamic equilibrium in the desert region, and was in positive equilibrium near the Tarim River Mainstream influenced by the irrigation return water and streamflow. Moreover, NDVI values of natural desert vegetation were significantly negatively correlated with the DGL in the desert regions ($R^2 = 0.78$, $p < 0.05$). Groundwater levels may exert a strong impact on natural vegetation in arid regions. Obviously, large-scale land reclamation and groundwater overexploitation associated with water-saving irrigation agriculture development have caused groundwater level declines in arid oasis desert regions. Hence, controlling groundwater extraction intensity, strengthening groundwater monitoring, promoting efficient water-saving technology, and implementing ecological water delivery would be viable methods to sustainably manage groundwater resources and maintain the ecological environment in arid areas.

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