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The Distribution and Evolution of Groundwater Level Depths and Groundwater Sustainability in the Hexi Corridor over the Last Five Years

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Abstract: Groundwater overexploitation for agricultural irrigation is prone to lead to numerous ecological concerns. This study delved into the present distribution and recent trend of groundwater levels in the plain areas of the Hexi Corridor in Northwest China according to the groundwater level depth (GWD) data from 264 monitoring wells in the Shiyang River Basin (SYB) and 107 in the Shule River Basin (SLB), recorded annually in April from 2019 to 2023. The key findings include the following: (1) Over the five-year span, the SYB's GWD experienced change rates (CRs) ranging from −12.17 to 9.11 m/a (average: −0.13 m/a), with the number of monitoring wells showing increased and decreased GWDs accounting for 50% and 50%, respectively. By contrast, the SLB's GWD exhibited CRs ranging from −1.87 to 2.06 m/a (average: 0.01 m/a), with the number of monitoring wells showing increased and decreased GWDs accounting for 52% and 48%, respectively; (2) the Wuwei (CR = 0.09 m/a) and Changning (0.58 m/a) basins in the SYB and the Yumen (0.06 m/a), Guazhou (0.05 m/a), and Huahai (0.03 m/a) basins in the SLB, witnessed rising groundwater levels. In contrast, the Minqin Basin (0.09 m/a) in the SYB and the southern Dunhuang Basin (0.04 m/a) in the SLB witnessed declines in the groundwater levels; (3) The groundwater sustainability assessment showed that the groundwater is still extremely unsustainable. This study's insights are instrumental in targeted treatment, as well as the preparation and adjustment of sustainable groundwater protection strategies.

Keywords: groundwater level depth; change rate; cause analysis; arid region; Hexi Corridor

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1. Introduction

Groundwater is an essential resource for drinking, irrigation, industry, and ecological needs. Its overexploitation is a global issue, particularly in areas like America, India, China, and Africa [1–5]. In China, the North China Plain exemplifies areas of significant groundwater overexploitation, leading to eco-environmental consequences such as groundwater depletion cones, land subsidence, seawater intrusion, and wetland reduction [6–9]. Intense ecological issues due to groundwater overexploitation occur in China's inland arid regions, notably the Tarim River basin in Xinjiang [10,11], Qingtu Lake in the SYB [12–14], and Xihu Lake in the SLB [15,16], Gansu. Implementing corrective measures has yielded considerable progress in controlling this overexploitation. The annual decline of groundwater levels in the North China Plain since the 1970s has largely stabilized in the last five years, with roughly 90% of monitored regions achieving a balance between groundwater extraction and recharge. Continuous monitoring of groundwater levels remains a vital tool for directly and effectively determining groundwater exploitation statuses. Evaluating long-term groundwater level trends is foundational for understanding its historical evolution and forecasting future changes.

The plain oases of the Hexi Corridor are pivotal for grain and fruit production regions in Northwest China, and occupy 10% of the Hexi Corridor, support 85% of the region's population and contribute to more than 90% of the region's gross domestic product (GDP) [17,18]. Following over five decades of groundwater extraction, groundwater levels in the plain areas have sharply decreased, leading to eco-environmental challenges, such as groundwater depletion cones, wetland reduction, and the desiccation of rivers and springs [19,20]. In the corridor's eastern portion, the SYB exhibits phased groundwater level shifts, influenced by varying exploitation and management techniques. Specifically, the SYB's groundwater level saw a steady decline from 1970 to 1990, an accelerated drop between 1990 and 2010, and a decelerated decline with localized increases post-2010. Following China's stringent water resource management policies of 2012–2013 [21], targeted measures like sealing pumping wells, curtailing cultivated lands, promoting water-conserving agriculture, and facilitating inter-basin water transfers were implemented. As a result, groundwater level changes have shown spatial variations, indicating a new phase in groundwater fluctuations. However, the specifics regarding regional groundwater level increases and their rates remain undetermined. Understanding the current groundwater level trends is vital for optimizing groundwater resource management and enhancing the eco-environment. Existing research on groundwater dynamics generally lacks basin-wide analyses, focusing on sub-basin scales, such as the Minqin Basin within the SYB [22,23]. Some studies have examined groundwater reserve shifts using low-resolution GRACE satellite data [24,25], necessitating further validation, especially for irrigation-intensive plain areas. In contrast to the SYB, the SLB in the Hexi Corridor's western segment demonstrates a slightly declining groundwater level, maintaining a comparatively stable eco-environment. Few studies address its groundwater evolution. Yet, the decreasing groundwater level in the SLB threatens the terminal lakes and wetlands downstream. To forestall ecological degradation and encourage sustainable groundwater usage in the SLB, a comparative analysis of the evolutionary trajectories and origins of groundwater levels in both river basins is essential.

In order to develop sustainable water resource utilization and management policies, it is first necessary to identify the dynamic changes of groundwater levels in the new stage, especially the differences in different regions. Relying on groundwater monitoring data spanning 2019–2023 across the SYB and SLB plains, this study investigates the contemporary distributions and evolutionary trends of groundwater levels within these river basins. This research aims to elucidate the following: (1) the current GWD distributions in both the river basins; (2) the inter-annual changes and development trends of GWDs on a basin-wide scale over the past five years; and (3) the distribution differences and origins of GWDs across the two river basins.

2. Materials and Methods

2.1. Study Areas

The Hexi Corridor, located in the northwestern section of Gansu Province, China, encompasses three inland river basins: the Heihe River basin, the SLB, and the SYB [26,27]. The SYB, situated in the corridor's eastern section (Figure 1a), spans an area of roughly 41,600 km^2. It borders the Qilian Mountain to the south, the Tengger Desert to the east, and the Yabulai Mountain and Badain Jaran Desert to the north [17]. The SYB's topography rises in its southwestern part and descends in its northeastern section. The Wuwei and Minqin basins, delineated by the Hongya Mountains, occupy the southern and northern portions of the SYB (Figure 1b), respectively [28]. Additionally, the Changning Basin is located in the SYB's western section, housing Jinchang City. The SLB, positioned in the corridor's western segment (Figure 1a), extends over 101,884 km^2. It is bounded by the Qilian Mountain to the south and the Mazong Mountain to the north. The SLB's core is an east–west oriented plain. The Huahai, Yumen-Tashi, and Guazhou-Dunhuang basins spread across the eastern, central, and western zones of the SLB, respectively, with the latter two divided by the Shuangta Reservoir. The Hexi Corridor's climate is typified by arid inland conditions. The Qilian Mountain to the south experiences average annual temperatures ranging from −5 °C to 5 °C and receives yearly precipitation between 250 mm and 800 mm. Conversely, the central and lower plain areas record average annual temperatures of 6–8 °C and annual precipitation ranging from 50 to 200 mm, which diminishes with decreasing altitude [29]. The sub-basins in the middle plain, including the Wuwei Basin and Jinchang Basin in the SYB and the Yumen Basin and Huahai Basin in the SLB, are bounded by the Qilian Mountains in the south and reservoirs in the north. The lithology of the aquifers in these basins is mainly composed of gravel and coarse sand with a thickness of approximately 100–300 m (Figure 1b). The main sources of groundwater recharge are surface water infiltration, precipitation infiltration, and lateral runoff. The downstream sub-basins, including the Minqin Basin in the SYB and the Guazhou Basin and the Dunhuang Basin in the SLB, have finer aquifers with a thickness of 50–100 m, mainly composed of fine and medium sand. The main sources of groundwater recharge are lateral runoff and irrigation infiltration [28].

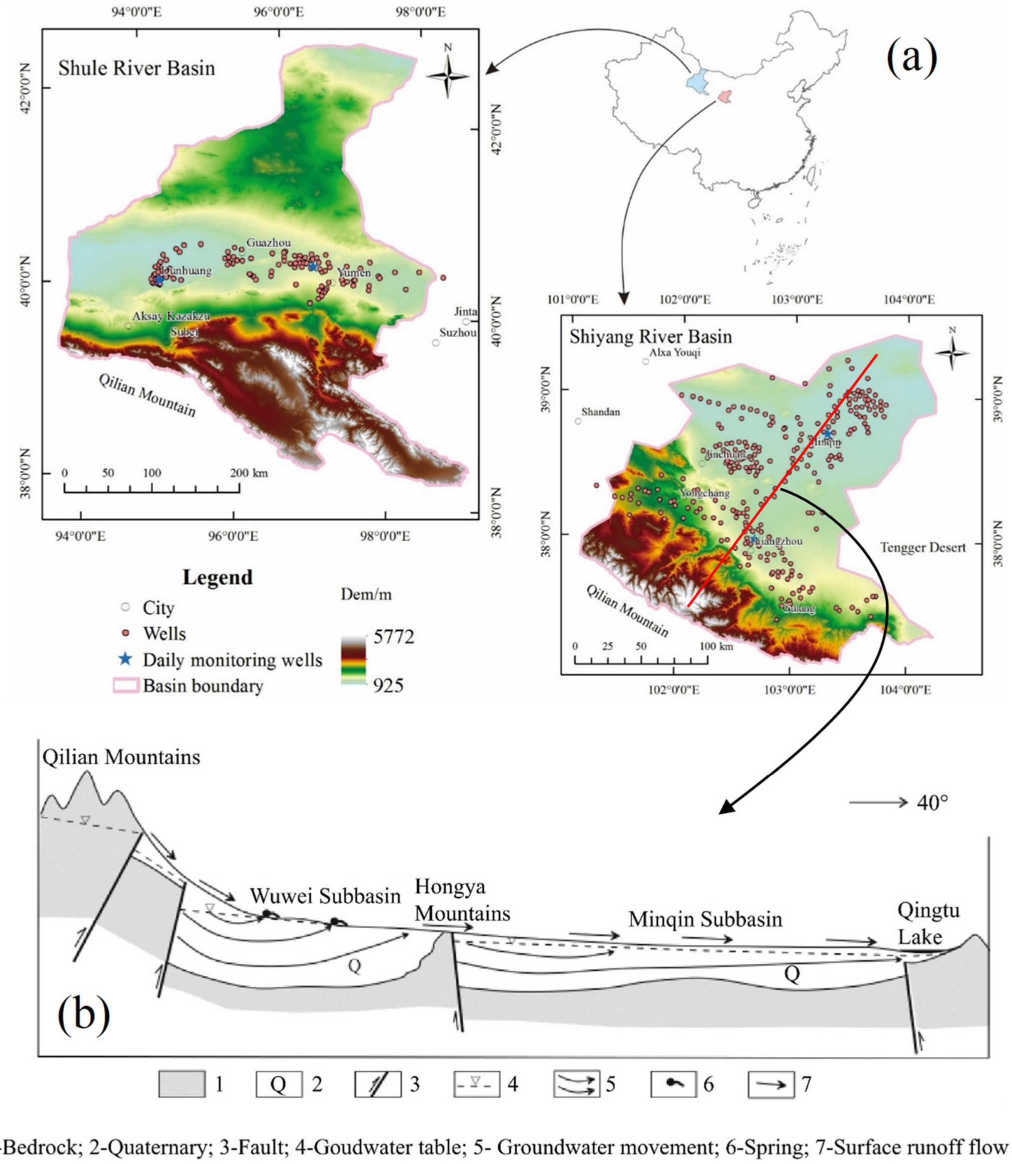


Figure 1. (**a**) Location of Hexi Corridor, and wells distribution of Shule River Basin (SLB) and Shiyang River Basin (SYB) and (**b**) hydrogeological section.

2.2. Data Source and Analytical Methods

The monitoring wells (comprising 264 wells in the SYB and 107 in the SLB) were assessed for GWDs every April from 2019 to 2023 (Figure 1a). All groundwater in these wells is phreatic. Using the GWD measurements from April 2023, this research illustrated the spatial distributions of GWDs across the plain areas of both river basins, employing the inverse distance weighting (IDW) method for spatial interpolation. Drawing from the five-year GWD data from all the monitoring wells, the CRs of the GWDs were determined via regression analysis, noting the coefficient of determination (R^2). Additionally, the monitoring wells positioned in representative areas of groundwater overexploitation within the river basins captured daily GWDs from 1 January 2019, to 31 December 2022. These daily data facilitated the examination of intra-annual groundwater level fluctuations. The data including precipitation, annual river runoff, water supply, irrigated area, and crop planting structure, were referenced from the Monthly Report on Groundwater Dynamics of the Ministry of Water Resources of China (http://www.mwr.gov.cn) accessed on 1 September 2023 and Statistical Yearbook of Gansu Provincial Bureau of Statistics (http://tjj.gansu.gov.cn/tjj/index.shtml) accessed on 1 September 2023.

3. Results and Discussions

3.1. Present Distribution of Groundwater Level and GWDs

3.1.1. The Shiyang River Basin (SYB)

In the SYB, the groundwater level elevation gradually decreased from southwest to northeast. The groundwater levels in the Wuwei, Minqin Basin and Jinchang sub-basins were concentrated at 1860–1400 m, 1400–1300 m, and 1420–1320 m, respectively (Figure 2), reflecting the overall runoff of groundwater in the basin from southwest to northeast. The GWDs ranged from 0.3 to 249.98 m (Figure 3). The maximum GWD was observed at the piedmont proluvial fan of the Qilian Mountain in the south (Figure 2), registering 248.98 m in Yongchang County (western Wuwei Basin) and 196.42 m in Gulang County (eastern basin). These areas, located near the piedmont proluvial fan, showcased significant groundwater depth. Moving northward, the GWD progressively decreased. Influenced by piedmont fault zones, there was a notable drop in the groundwater level transitioning from the mountain valley's alluvial–proluvial fan to the plains. Notably, the GWD shifted abruptly from >100 to <30 m, declining with diminishing altitude. The GWD values were <10 m south of the Hongyashan Reservoir (Figure 2), along the Shiyang River mainstream in the Wuwei Basin. In the downstream Minqin Basin, the GWDs typically remained <40 m, peaking between 30 and 40 m within the oasis irrigation zone, and tapering off to generally <10 m beyond this region. In the salt marsh areas near Qingtu Lake and Donghu Town, situated in the northern and eastern segments of the Minqin Basin respectively, the GWDs were <5 m. In the Changning Basin, to the basin's west, the GWDs showed a consistent decline, from 117.43 m (western side) and 65.47 m (southern) to 14.05 m in the northeastern plain irrigation zone.

Since the 1970s, the SYB's regional groundwater level has persistently declined due to prolonged groundwater overexploitation. A pronounced groundwater depletion cone, centered around Xiqu-Shoucheng-Donghu towns, emerged in the Minqin Basin (Figure 2b) and predominantly covered the irrigated area. Analyzing its development, it encompassed four sections: the sections established in 2001 in Minqin County and Xiqu-Donghu towns, the section from 2002 in Xiqu Town, and the 2004 section in Quanshan Town [22]. Based on the 2023 data, the Minqin Basin displayed a spatially varied groundwater depletion cone; its irregular shape attributed to the differential groundwater extraction across regions. Demarcated by the phreatic water contour of 1300 m, the cone covered about 422.7 km^2 in April 2023, with GWDs of 31.71 m centrally and 16.50 m at its periphery. While groundwater levels have seen modest increases post-2007 due to overexploitation mitigation, the depletion cone remains, indicating a marginal decline over the last four years. A similar depletion cone also manifested in the Changning Basin, west of the SYB (Figure 2). Using the 1320 m phreatic water contour for demarcation, this cone spanned roughly 88.50 km^2

in April 2023, with GWDs of 89.98 m at its core (Shuangwan Town; Figure 2) and around 60 m at its boundaries.

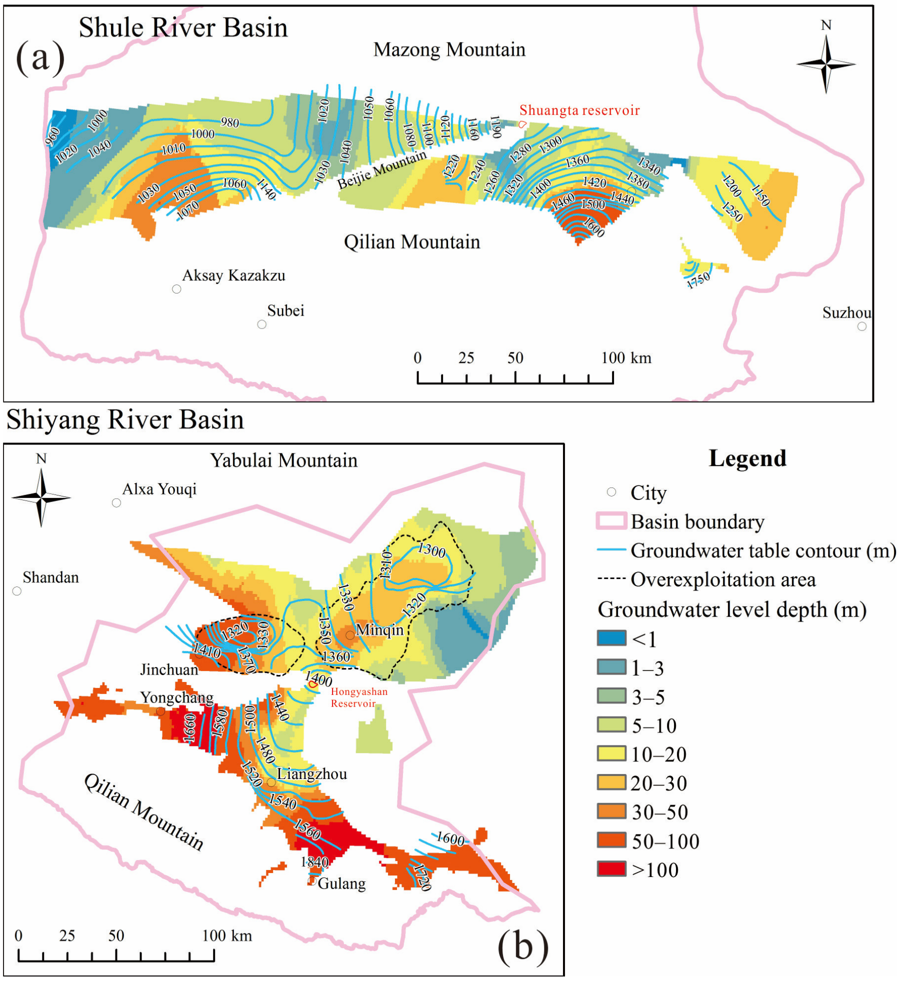


Figure 2. Spatial distribution of groundwater level depth (GWD) and contour in two major basins of the Hexi Corridor in March 2023. (**a**) The Shule River Basin (SLB), (**b**) the Shiyang River Basin (SYB).

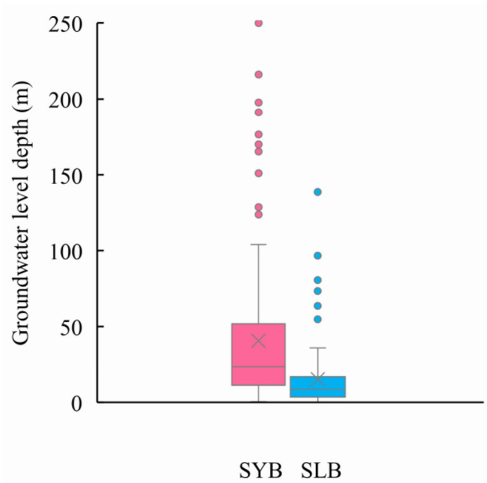


Figure 3. Box diagram of the groundwater level depth (GWD) in the Shiyang River Basin (SYB) and the Shule River Basin (SLB) of the Hexi Corridor. Boxes represent 25th, 50th, and 75th percentile values, and whiskers represent 10th and 90th percentile values. Scatter points represent extreme values.

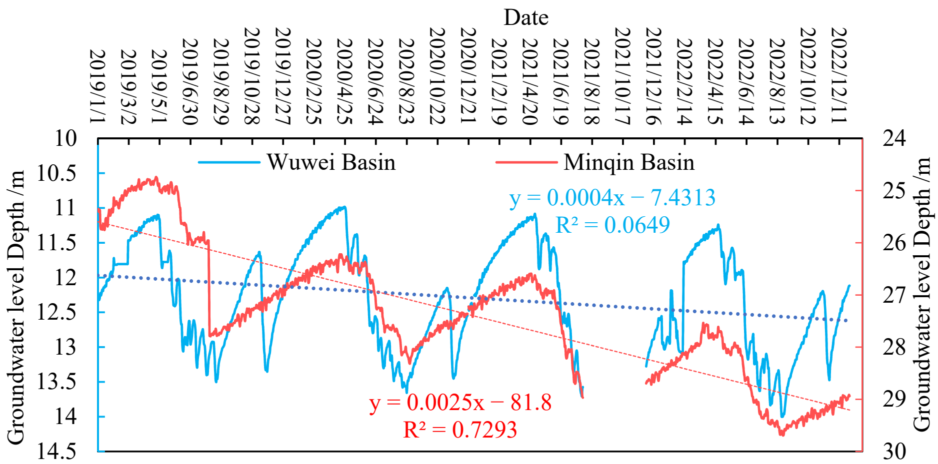
3.1.2. The Shule River Basin (SLB)

In the SLB, groundwater flowed from east to west and from south to north as a whole, and the elevation of the groundwater level gradually decreased with the direction of runoff. The groundwater level elevation in the Yumen sub-basin was concentrated at 1680–1200 m, and at 1200–960 m in the Guazhou and Dunhuang sub-basins (Figure 2). The GWDs ranged from 0.01 to 138.82 m (Figure 3). The maximum GWD, 88.11 m, was observed at the Changma proluvial fan situated in the southern region of Yumen City. From there, the GWD decreased to 32.65 m northwards, at the transition between the proluvial fan and the plain irrigation zone. Within the oasis-irrigated zones of the central and northern parts of Yumen City, the GWD stabilized between 5 and 10 m. Along the Shule River's banks and the upper sections of the Shuangta Reservoir (Figure 2a), at the irrigated zones' northern fringes, the GWDs were approximately 2 m, dipping to a minimum of 0.13 m. In Suoyangcheng Town's irrigation area, positioned in western Yumen City and southern Guazhou County, the GWDs fluctuated between 19.5 m and 24.23 m. In the natural vegetation area nestled amidst the oasis, the GWD varied from 1 to 5 m. Near the Guazhou urban sector's agricultural irrigation zone, the GWDs ranged between 10 and 20 m. They dropped to <5 m (with a minimum close to 1 m) on the irrigation zone's western outskirts, which is dominated by natural vegetation. Within the Dunhuang region, the southern segment exhibited more considerable GWDs, between 10 and 15 m, whereas the urban area peaked at 27.7 m, and the northern portion had lesser GWDs, from 4 to 10 m. In the SLB's western part, where the Dunhuang Xihu Nature Reserve (without irrigation pumping wells) is located, the GWDs spanned from 0.5 to 2.8 m, averaging 1.43 m. This reserve, housing the terminal lake of the Shule River, had the lowest GWD within the SLB.

3.2. Changes and Evolutionary Trends of the Groundwater Level in the Past Five Years

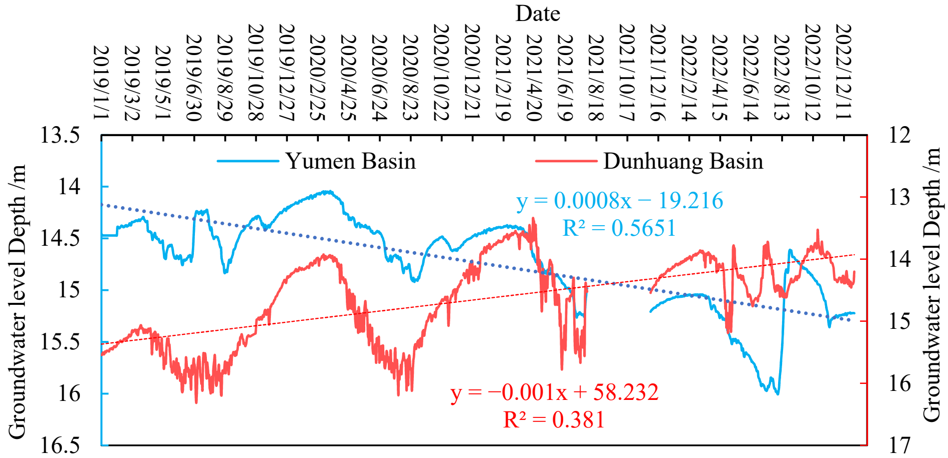
3.2.1. Intra-Annual Changes in the Groundwater Level

As depicted in Figure 4, the groundwater level in the Hexi Corridor's plain areas exhibited a single-peak and single-valley fluctuation annually due to groundwater extraction for agricultural irrigation. This pattern has been consistent since the 1970s [30]. Intra-annual groundwater fluctuations differed within the river basins. For instance, the Wuwei Basin in the SYB's southern region had fluctuations ranging from 2.40 to 2.88 m, whereas the Minqin Basin in the north varied between 2.10 and 3.05 m (Figure 4a). For comparison, these figures were 1.16–1.41 m in 1980 and 1.68–2.01 m in 1999 [30,31]. On the other hand, the Yumen Basin in the SLB's eastern section fluctuated between 0.64 and 1.40 m, while the Dunhuang Basin in the west ranged from 1.65 to 2.44 m (Figure 4b). The narrower fluctuation amplitude in the SLB suggests a lesser groundwater extraction intensity than in the SYB during the irrigation phase.



(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. Daily variation of groundwater level depth in typical monitoring wells in the Hexi Corridor. (**a**) The Shiyang River Basin (SYB) and (**b**) the Shule River Basin (SLB).

3.2.2. Inter-Annual Changes in the Groundwater Level

Over the previous five years, the GWDs in the SYB have had CRs ranging from −12.17 to 9.11 m/a (Table 1). The monitoring wells with increasing GWDs (CR > 0 m/a) represented 50%, while those with decreasing GWDs (CR < 0 m/a) constituted 50% (Figures 5 and 6). Moreover, the wells with stable, declining, and rising groundwater levels accounted for 62% (−0.5 m/a < CR < 0.5 m/a), 21% (CR > 0.5 m/a), and 17% (CR < −0.5 m/a), respectively (Figure 6). The spatial distribution (Figure 5a) showed that the wells with declining levels were mainly concentrated in the Minqin Basin and proximate to Minqin County, representing a gradual groundwater decrease in these locales, corroborated by daily monitoring (Figure 4a). Contrastingly, the Wuwei Basin's daily monitoring (Figure 4a) did not identify a notable declining trend, especially around the Liangzhou District. The wells showing decline were primarily in the Wuwei Basin's eastern (Gulang County) and western (Yongchang County) sectors (Figure 5a).

Over the last five years, the GWDs in the SLB registered CRs ranging from −1.87 to 2.06 m/a (Table 1). The monitoring wells showing increased GWDs (CR > 0 m/a) comprised 52%, whereas those displaying decreased GWDs (CR < 0 m/a) made up 48% (Figures 6 and 7). Additionally, the monitoring wells with stable, declining, and rising groundwater levels represented 83% (−0.5 m/a < CR < 0.5 m/a), 6% (CR > 0.5 m/a), and 11% (CR < −0.5 m/a), respectively (Figure 6). The spatial distribution (Figure 7a) indicated the wells with declining groundwater were predominantly in the Changma proluvial fan in southern Yumen City and the agricultural irrigation zone in northern Dunhuang City. The wells with increasing groundwater levels were chiefly found in the irrigated regions in western Yumen City and southeastern Dunhuang City. Daily monitoring verified a steady increase in groundwater in southern Dunhuang City (Figure 4b).

Table 1. Statistical results of change rate of groundwater level depth (GWD) in two major basins of the Hexi Corridor.

	Shiyang River Basin		Shule River Basin	
	Change Rate (m/a)	**R^2**	**Change Rate (m/a)**	**R^2**
min	−12.17	0.00	−1.87	0.00
max	9.11	1.00	2.06	1.00
average	−0.13	0.47	0.01	0.49
median	0.00	0.48	−0.01	0.54
SD *	1.90	0.32	0.44	0.30
CV *	−14.15	0.69	33.63	0.62

* SD is the standard deviation, and CV is the coefficient of variation.

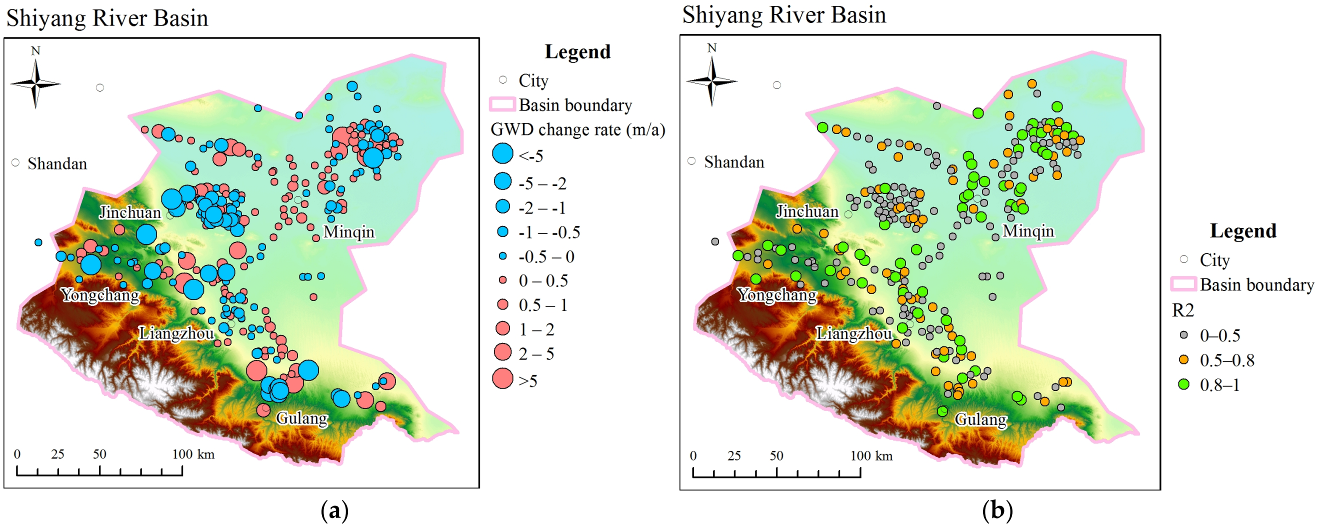


Figure 5. Distribution diagram of (**a**) groundwater level depth (GWD) change rate and (**b**) coefficient of determination (R^2) in the Shiyang River Basin (SYB) from 2019 to 2023.

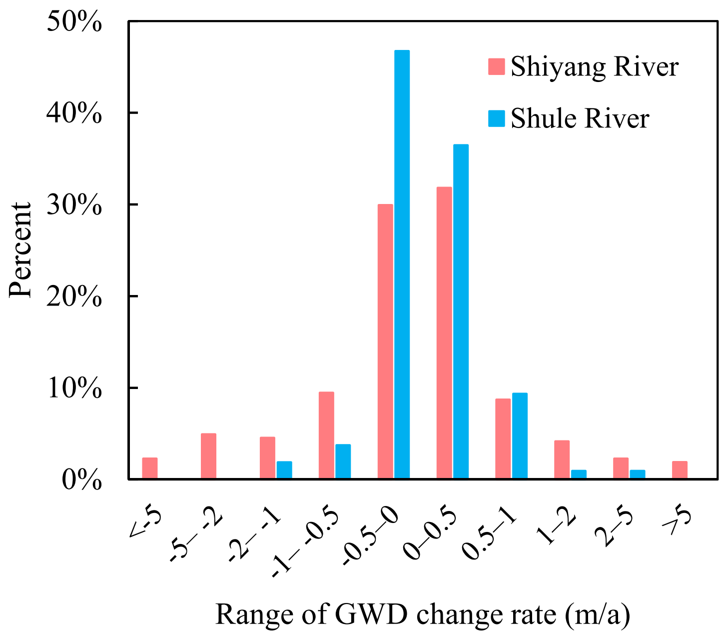


Figure 6. Statistical histogram of the change rate of groundwater level depth (GWD) in the Shiyang River Basin (SYB) and the Shule River Basin (SLB) of the Hexi Corridor.

In both the SYB and SLB, the wells with increasing and decreasing GWDs were nearly evenly split, representing close to 50% each (Figure 6). This pattern signifies a significant mitigation in groundwater level decline across both river basins (Table 2), with some areas showing groundwater level increases. Based on the five-year groundwater level trends, the SLB had a larger portion (94%) of stable and rising groundwater regions compared to the SYB (79%) (Figure 6). This suggests the SLB has a more favorable trend in groundwater elevation than the SYB. As a result, future groundwater monitoring and management should consider the nuanced changes within the river basins, implementing specific strategies and policies in areas where groundwater levels persistently decrease.

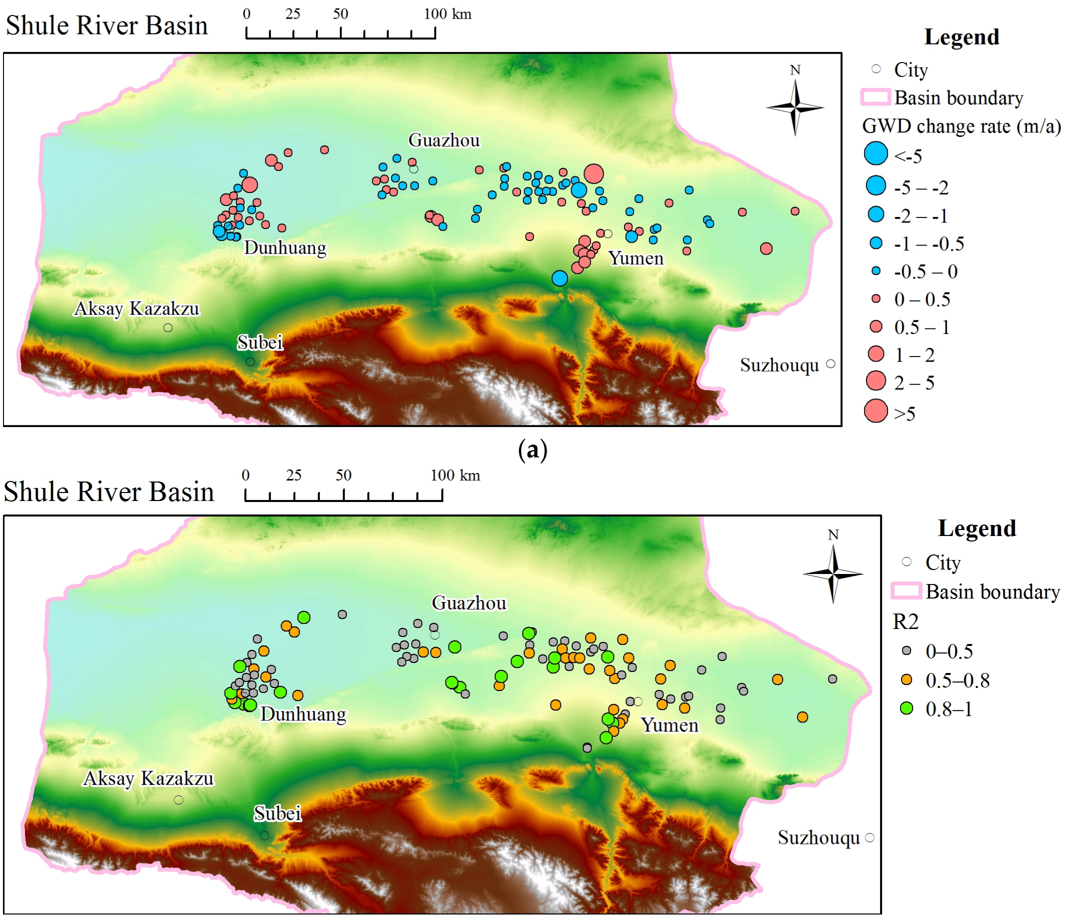


Figure 7. Distribution diagram of (**a**) groundwater level depth (GWD) change rate and (**b**) coefficient of determination (R^2) in the Shule River Basin (SLB) from 2019 to 2023.

Table 2. The change rate of groundwater level in two major basins of the Hexi Corridor.

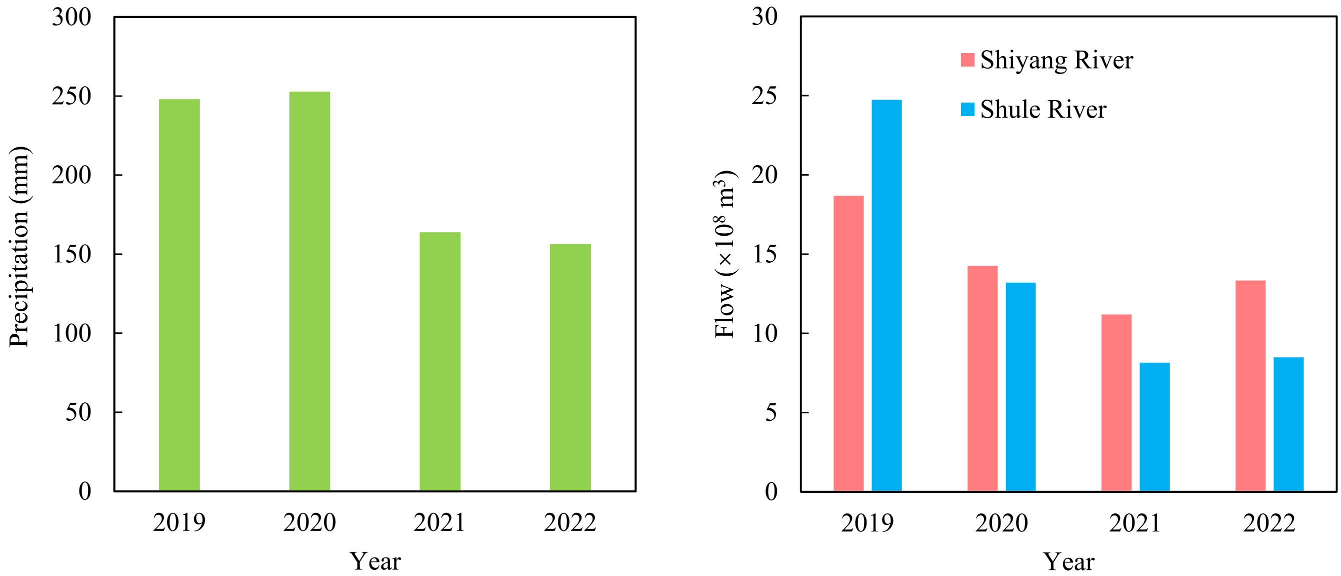
Basin	Sub-Basin	Period	Groundwater Level Decline Rate (m/a)	References
Shiyang River Basin	Minqin Basin	1984–2001	0.57	[32]
		1999–2013	0.33	[33]
		2010–2017	0.21	[23]
		2019–2023	0.09	This study
	Wuwei Basin	1984–2001	0.31	[32]
		2019–2023	−0.09 *	This study
	Changning Basin	2019–2023	−0.58 *	This study
Shule River Basin	Yumen Basin	1987–2000	0.07–0.21	[34]
		2003–2010	0.08	[35]
		2019–2023	0.06	This study
	Guazhou-Dunhuang	2003–2010	0.05	[35]
	Guazhou Basin	2019–2023	0.05	This study
	Huahai Basin	2003–2010	0.26	This study
		2019–2023	0.03	This study

* Negative values represent the rate of groundwater level rise.

3.3. Factors Influencing the Dynamic Changes in the Groundwater Level

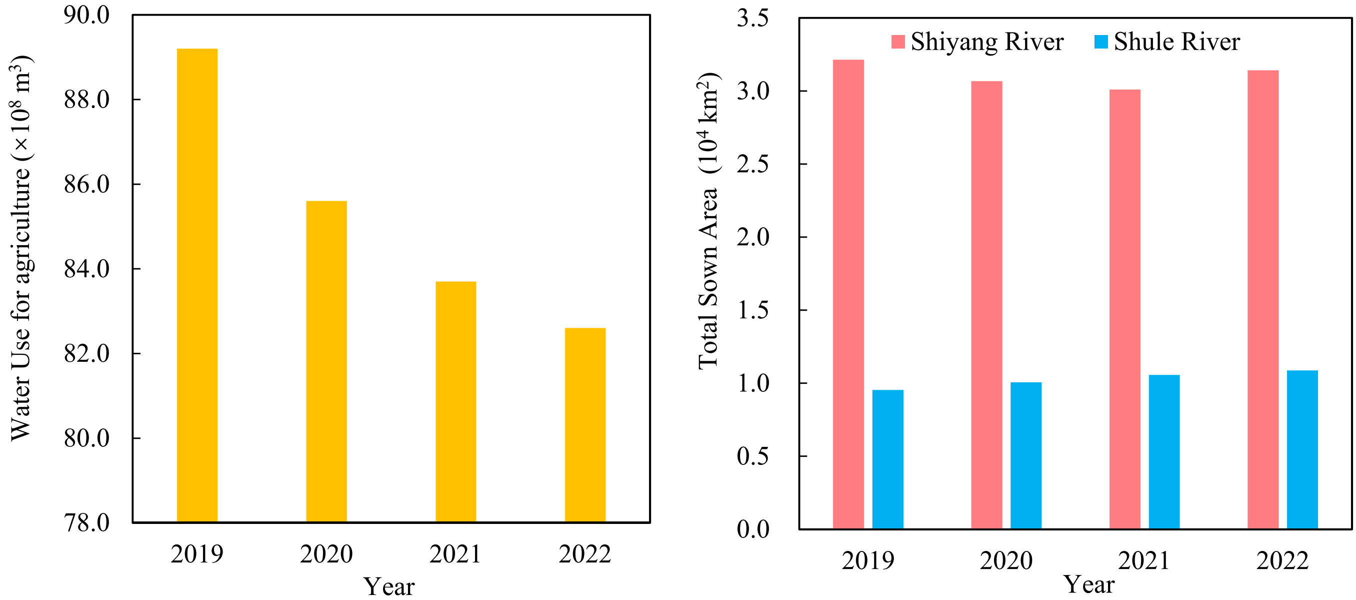
The sustained decline in groundwater levels in the Hexi Corridor's plain areas over previous decades largely stems from groundwater overexploitation for agricultural irrigation [22,36,37], with agricultural usage surpassing 85% of the total groundwater draw [38]. Studies indicate that in the Wuwei Basin, located in the SYB's middle reaches, human activities such as groundwater extraction influenced groundwater levels by 63%, whereas climate factors contributed 37%. In the Minqin Basin at the lower reaches, the contributions from human activities and climate factors were 79% and 21%, respectively [32]. The main dynamics influencing groundwater level variations in the Minqin Basin encompass inflow from the Hongyashan Reservoir and groundwater extraction. Over the last five years, the implementation of groundwater overexploitation control policies has tempered the declining trend in groundwater levels and decreased their inter-annual variability. Consequently, groundwater level shifts may be modulated by elements like arable land extent, water consumption, and the structure of the sown area, followed by climatic variables such as precipitation [9,39].

Figure 8a reveals a gradual decline in the Hexi Corridor plains' average annual precipitation from 250 mm/a to 160 mm/a between 2019 and 2022, indicating reduced precipitation-based recharge in the river basins. Additionally, the annual runoff within these river basins consistently diminished (Figure 8b), illustrating dwindling water resources in the middle and lower reaches. Furthermore, the runoff saw a sharper decline by 2/3 in the SLB. Figure 9a portrays a consistent decrease in agricultural water use in Gansu Province, where the Hexi Corridor is situated, indicating a reduced strain of agricultural practices on groundwater overexploitation. Concerning the total sown area (Figure 9b), both river basins exhibited marginal fluctuations. The SYB's sown area was 3.2135×10^4 km^2 in 2019, slightly decreasing to 3.1415×10^4 km^2 in 2022. In contrast, the SLB's sown area was 0.9536×10^4 km^2 in 2019, rising to 1.0873×10^4 km^2 in 2022. Owing to enhancements in irrigation infrastructure, such as transitioning from earthen to concrete-lined canals and the proliferation of water-conserving agricultural zones, the effectively irrigated area consistently expanded. Notably, in the SYB (Figure 10a), this area grew by 1146 km^2 annually. The SLB's effective irrigated area increased at an annual rate of 315 km^2. At the sub-basin level (Figure 10b), the SYB's effective irrigated areas in the Minqin, Wuwei, and Changning basins expanded by 82 km^2, 696 km^2, and 115 km^2 yearly, respectively. In the SLB, the growth rates were 51 km^2, 43 km^2, and 221 km^2 in the Dunhuang, Guazhou, and Yumen basins, respectively. Upgrades in irrigation practices and the endorsement of water-conserving agriculture have optimized water resource utilization, curtailed wastage, mitigated groundwater over-extraction, and locally reversed the groundwater decline. Concerning the sown area structure, minimal variations were observed in both the river basins' plains (Figure 11). Wheat and corn, as primary water-intensive crops, constituted about 53–55% of the total sown area [40,41]. Their shifts in sown area proportions were under 2%, suggesting the sown area structure marginally influenced the groundwater level ascents. Summarily, over the last five years, the primary drivers for groundwater level elevation in the Hexi Corridor's two river basin plains encompassed reduced agricultural water use, expanded effective irrigated area, and the advancement of water-conserving agriculture.



(**a**) (**b**)

Figure 8. (**a**) Annual precipitation and (**b**) annual flow of rivers of the Hexi Corridor from 2019 to 2022.



(**a**) (**b**)

Figure 9. (**a**) Water use for agriculture and (**b**) total sown area in plain area of the Hexi Corridor from 2019 to 2022.

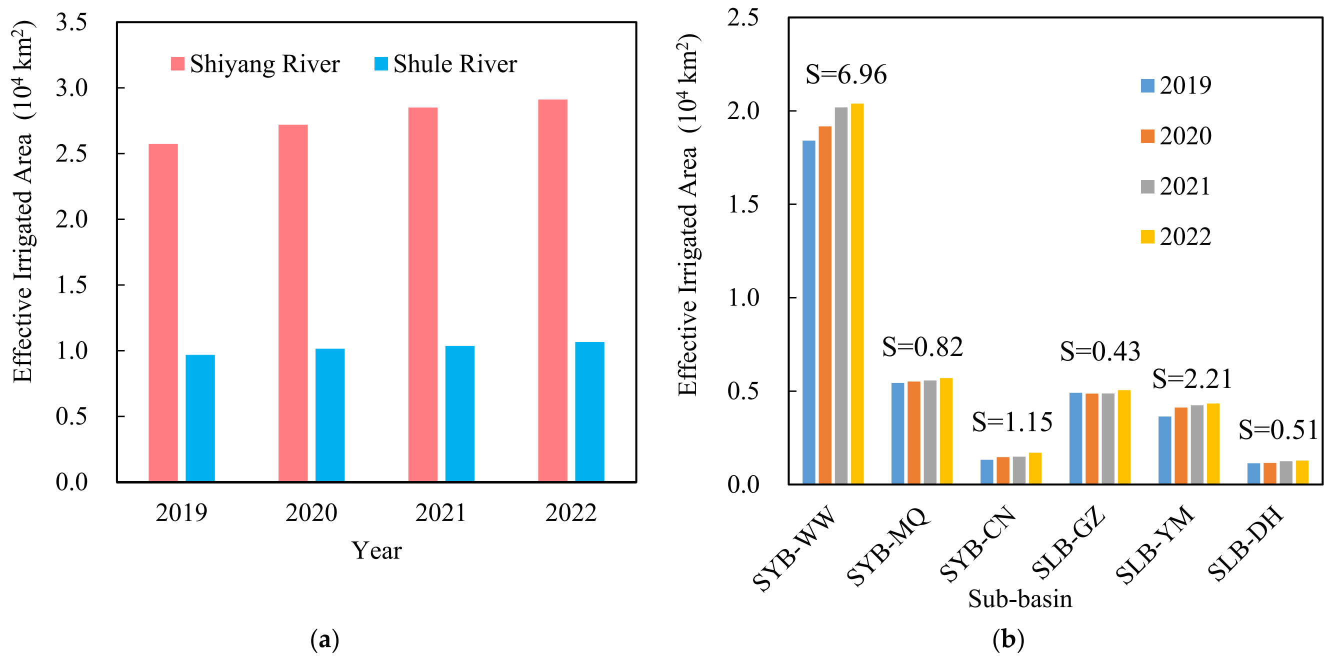


Figure 10. Effective irrigated area in plain area of (**a**) the Hexi Corridor and (**b**) sub-basins from 2019 to 2022. S represents the growth rate of effective irrigation area (10^4 km^2/a). Sub-basins include the Wuwei Basin (SYB-WW), the Minqin Basin (SYB-MQ), and the Changning Basin (SYB-CN) in the Shiyang River Basin (SYB), and the Guazhou Basin (SLB-GZ), the Yumen Basin (SLB-YM,) and the Dunhuang Basin (SLB-DH) in the Shule River Basin (SLB).

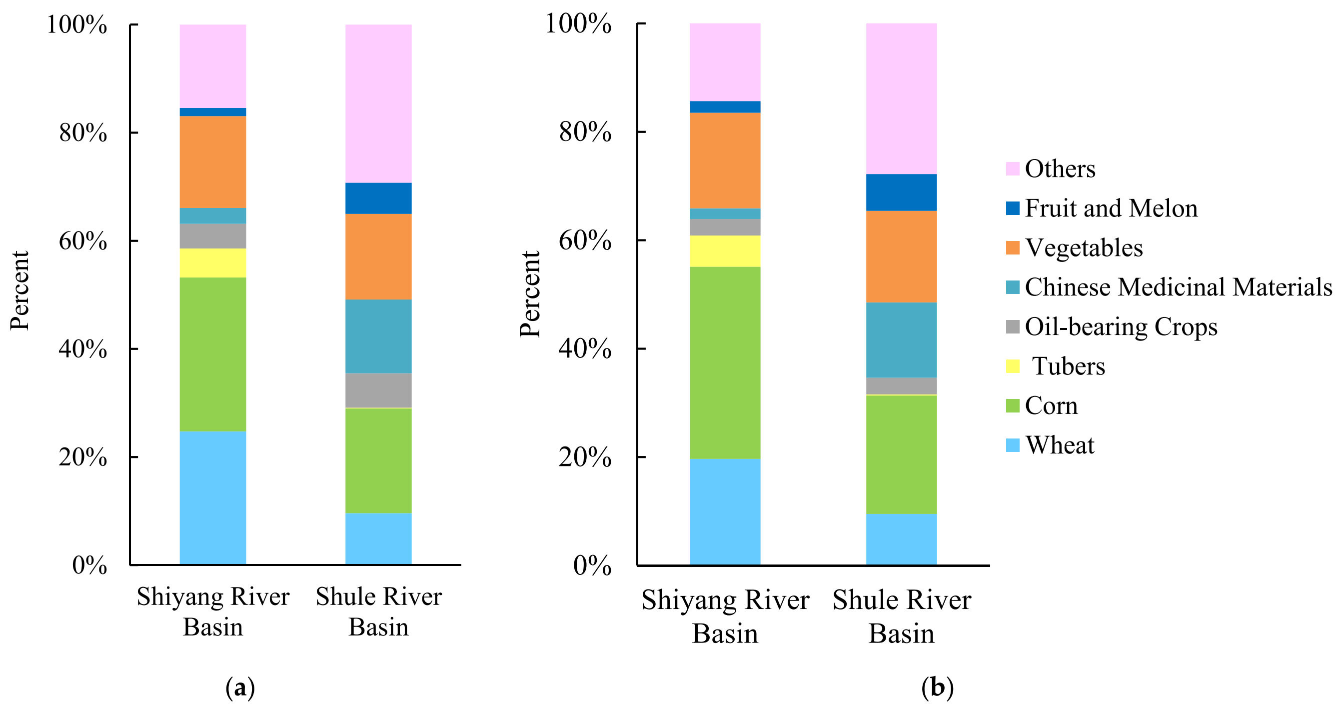


Figure 11. Sown area structure of major farm crops of the Hexi Corridor in (**a**) 2019, and (**b**) in 2021.

3.4. Groundwater Sustainability

The evaluation of groundwater sustainability in this study used the method of combining ΔGWD and the sustainability index. ΔGWD is the difference between the groundwater level depth in the next year and that in the previous year, and

$$\text{REL} = \frac{\text{No.of times } \Delta\text{GWD} < 0}{\text{n}} \quad (1)$$

where REL is the quotient of the number of times (ΔGWD < 0) and the total number of ΔGWD data points.

$$\text{RES} = \frac{\text{No.of times } \Delta\text{GWD} > 0 \text{ followed by } \Delta\text{GWD} > 0}{\text{No.of times } \Delta\text{GWD} > 0} \quad (2)$$

where RES is the quotient of the number of times (ΔGWD < 0) followed by ΔGWD > 0, and the number of times when ΔGWD > 0; if the number of times (ΔGWD > 0) is 0, the value of RES is specified as 1.

$$\text{VUL} = \frac{\text{No.of times } \Delta\text{GWD} > 0}{\text{n}} \quad (3)$$

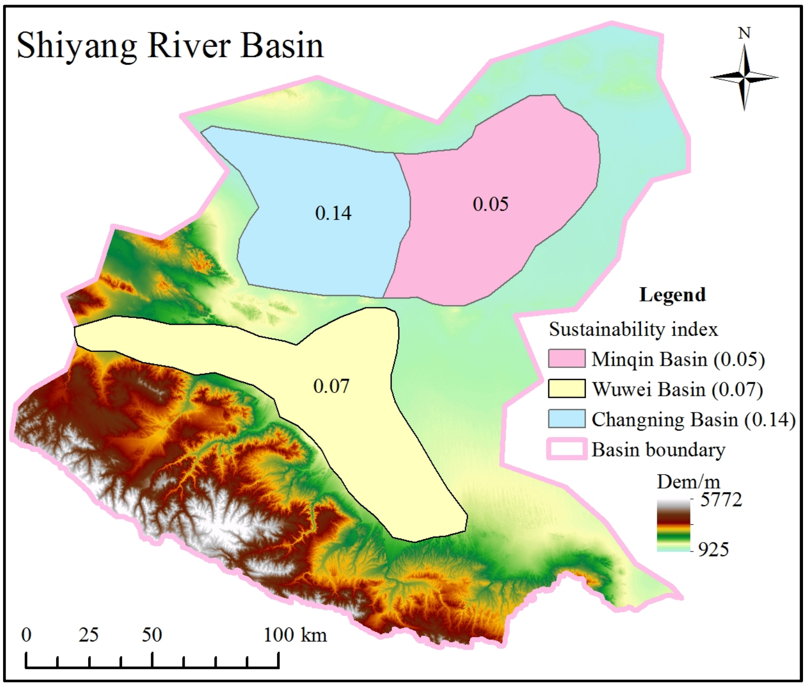
where VUL is the quotient of the number of times (ΔGWD > 0) and the total number of ΔGWD data points.

Lastly, the groundwater sustainability index (SI) is expressed as follows [42,43], and REL, RES and VUL represent the reliability, resilience and vulnerability of groundwater storage, respectively [44].

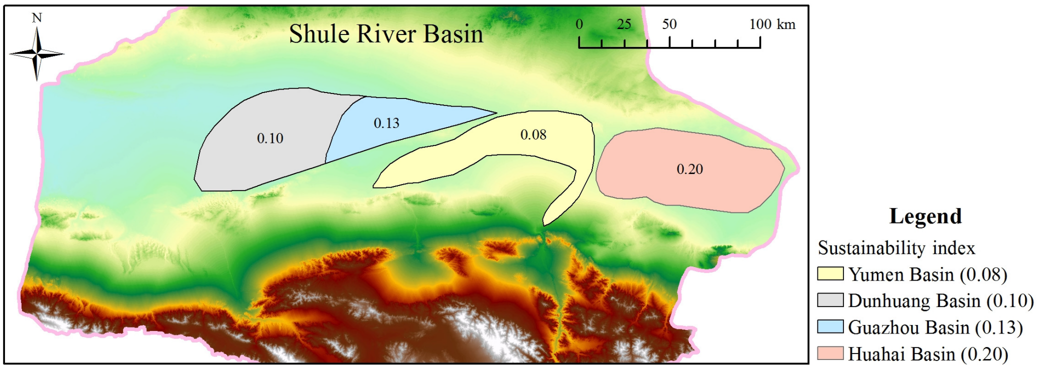
$$\text{SI} = \text{REL} \times \text{RES} \times (1 - \text{VUL}) \quad (4)$$

where REL, RES, VUL, and SI are all non-dimensional values between 0 and 1. The five ranges of SI from 0 to 0.2, 0.2 to 0.3, 0.3 to 0.5, 0.5 to 0.75, and 0.75 to 1 represent extremely unsustainable, severely unsustainable, slightly unsustainable, moderately sustainable, and highly sustainable [25].

We used the SI to evaluate the groundwater sustainability of 2019–2023; the results showed that the groundwater was still extremely unsustainable with a SI < 0.2 in the SYB and the SLB (Figure 12). According to all the wells data from the different watersheds, the groundwater sustainability in the SYB (SI = 0.08) was worse than that in the SLB (SI = 0.11). Although the SI indicated that the groundwater was extremely unsustainable, the SI values in the past 5 years were significantly higher than the values of the SI = 0.002–0.008 from 2007 to 2016 [25]. However, there was still a significant gap compared to the value of the SI = 0.46 from 1985 to 1990, so the promotion of water-saving irrigation technology and the limitation of groundwater extraction is still needed to maintain the current situation. We also analyzed the groundwater sustainability in the secondary basins within the watershed, and found slight differences between them. For instance, the SI values of the Changning Basin, Wuwei Basin, and Minqin Basin in the SYB were 0.14, 0.07, and 0.05, respectively (Figure 12a). And the SI values of the Huahai Basin, Guazhou Basin, Dunhuang Basin, and Yumen Basin in the SLB were 0.20, 0.13, 0.10, and 0.08, respectively (Figure 12b). This reflects that the Minqin is still a key area in the Hexi Corridor for sustainable groundwater management.



(**a**)



(**b**)

Figure 12. Groundwater sustainability index of (**a**) the Shiyang River Basin (SYB) and (**b**) the Shule River Basin (SLB).

4. Conclusions

This study aimed to analyze the current groundwater level status in the plain areas of the two major river basins in the Hexi Corridor of Northwest China in the new stage. The research results are conducive to targeted treatment of areas where the groundwater level is still declining, as well as the adjustment and formulation of groundwater protection policies.

The results showed the following: (1) In the past 5 years, the GWD change rate in the Shiyang River Basin has ranged from −12.17 to 9.11 m/a, with an average of −0.13 m/a. The number of monitoring wells increased by GWD accounted for 50%, while the number of monitoring wells decreased by GWD accounted for 50%. The GWD change rate in the Shule River Basin ranged from −1.87 to 2.06m/a, with an average of 0.01 m/a; the number of monitoring wells increased by GWD accounted for 52%, while the number of monitoring wells decreased by GWD accounted for 48%. (2) The areas with rising groundwater levels in the Shiyang River Basin are distributed in the Wuwei Basin (0.09 m/a) and the Changning Basin (0.58 m/a), while the groundwater level in the Minqin Basin still showed a slow decline (0.09 m/a), but the decline rate has significantly decreased. The areas with rising groundwater levels in the Shule River Basin are distributed in the Yumen Basin (0.06 m/a), the Guazhou Basin (0.05 m/a), and the Huahai Basin (0.03 m/a), while the groundwater level in the southern part of the Dunhuang Basin still showed a slow decline (0.04 m/a). (3) In the new stage, the main reasons for the rise of groundwater level in the plain areas of the two major basins are the decline in the extraction of agricultural water, followed by the increase in effective irrigation area, and the promotion of water-saving agriculture. The impact of meteorological factors such as precipitation was not significant. (4) The groundwater sustainability index of the Hexi Corridor was less than 0.2, reflecting that the groundwater is still extremely unsustainable.

Overall, the downward trend of groundwater levels in the two major watersheds has been fundamentally reversed year by year, and groundwater levels in most regions have shown a rising trend. In order to maintain the current good trend, groundwater exploitation should continue to be restricted, and some water-saving measures should be adopted, for example, building intensive farmland to promote drip irrigation, using computer technologies such as big data to optimize water resource management, and mixing saltwater and freshwater to improve the efficiency of water resource utilization. Meanwhile, the study of groundwater level changes based on water cycle processes such as infiltration, recharge, and runoff is an important aspect of our future work.

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