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Spatio-Temporal Study on Irrigation Guarantee Capacity in the Northwest Arid Region of China

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Abstract: Irrigation guarantee capacity is the critical factor in evaluating the development level of irrigated agriculture and is also a future development trend. It is necessary to carry out scientific planning and reasonable allocation of irrigation water resources to ensure the sustainable development of irrigated agriculture and improve the efficiency and effectiveness of water resource utilization. This study is based on remote sensing meteorological data and the principles of the Miami model and water balance. We calculated the annual irrigation water requirement and effective irrigation water, and used the ratio between the effective irrigation water and irrigation water requirement as the basis for evaluating an irrigation guarantee capability index. By using irrigation guarantee capability evaluation indicators from multiple years, we evaluated and assessed the irrigation guarantee capability in the arid region of northwest China. In addition, we analyzed three indicators (i.e., irrigation water requirement *IWR*, effective irrigation water *EIW*, and irrigation guarantee capacity index *IGCI*) to explore the rational allocation of water resources in the northwest arid area. *IWR*, *EIW*, and *ICGI* in northwest China from 2001 to 2020 were analyzed, and the average values were 379.32 mm, 171.29 mm, and 0.50, respectively. Simultaneously, an analysis was conducted on the temporal and spatial distribution of *IWR*, *EIW*, and *IGCI* in the northwest region of China from 2001 to 2020. The results indicated that the rainfall in the southwestern edge of the Yellow River Basin and the eastern part of the Qaidam Basin could meet the irrigation water demand. The northwest edge of the Yellow River Basin, the central Hexi Inland River Basin, most of Northeast Xinjiang, central and southeastern Xinjiang, and other regions mainly rely on irrigation to meet agricultural water requirements. The rest of the region needs to rely on irrigation for supplementary irrigation to increase crop yield. All districts in the 'Three Water Lines' area of northwest China should vigorously develop sprinkler irrigation, micro-irrigation, pipe irrigation, and other irrigation water-saving technologies and support engineering construction. Under the premise of ensuring national food security, they should reduce the planting area of rice, corn, and orchards, and increase the planting area of economic crops such as beans and tubers in the 'Three Water Lines' area. That is conducive to further reducing the agricultural irrigation quota and improving the matching degree of irrigation water resources. It provides a scientific reference for optimizing water resource allocation and improving irrigation water-use efficiency in northwest arid areas.

Keywords: irrigation water requirement; effective irrigation water; irrigation guarantee capacity index; irrigated agriculture

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1. Introduction

The arid area of northwest China is a resource-water-scarce area with low precipitation and high evaporation, uneven spatial and temporal distribution, and a very fragile ecological environment. There is a need to continuously optimize irrigation techniques and planting structures and allocate water resources rationally to alleviate the problem of insufficient water resources for irrigated agriculture. Due to the uneven spatial and temporal distribution of rainfall, agriculture in the arid areas of northwest China is highly dependent on irrigation. China's agricultural water consumption accounts for about 60% of the country's total water consumption, and irrigation water consumption on farmland accounts for 90–95% of the total agricultural water consumption. The total amount of agricultural water in the arid area of northwest China accounts for about 85% of the total water consumption in northwest China [1,2]. Scientifically effective irrigation water is the basis for scientific planning, management, and deployment of water resources [3]. Unreasonable irrigation water requirements and water use can lead to the waste of water resources, the formation of waterlogging disasters, increased soil salinization and nutrient loss, lower irrigation water utilization, and reduced irrigated area [4,5]. The study found that the matching degree of agricultural water resources in the arid area of northwest China gradually decreased from the core area of climate to the southeast. The matching water resources degree in irrigated agriculture was higher than in rainfed agriculture [6]. Agricultural land development conditions are poor, and water resources match severe dislocation [7]. Therefore, it is necessary to assess the irrigation guarantee capacity index ratio in the arid area of northwest China and provide theoretical guidance for the rational allocation of water resources in northwest China.

The northwest arid region is characterized by natural ecological features of arid and semi-arid conditions, influenced by topography, climate, and other factors [8]. The region is mainly composed of cultivated land, grassland, and unused land. Cultivated land occupies a high proportion, has steep slopes, and has low water resource matching; it has unique geographical features and agricultural characteristics. Cultivated land is mainly distributed in river delta areas, river alluvial plains, and other areas that are easy to water. These areas have fertile soil and are suitable for planting various crops. In terms of crops, the main agricultural crops in the northwest arid region are maize and wheat, while the featured economic crops are cotton and potatoes, and the featured forest and fruit trees are apples and red dates. Drought-resistant varieties are mainly grown to enhance the adaptability of crops to water and soil resources. From the perspective of vegetation, most of the region is desert grassland, with few biological species, a fragile ecological system, and the land being highly susceptible to desertification. Vegetation coverage is low, mainly consisting of drought-tolerant and salt-tolerant plants, such as saltbush, sand sagebrush, reed, and Ephedra [9–13]. The development of irrigated agriculture has caused waste of water resources to some extent, and caused deterioration of the ecological environment. Irrigation practices have led to soil salinization and alkalinization due to unreasonable irrigation [8].

For arid and semi-arid areas, irrigation is necessary for crop growth, in addition to rainfall. Therefore, by utilizing the relationship between meteorological data and crop water requirements, the irrigation guarantee capacity in arid and semi-arid areas can be effectively improved [14]. With the update and iteration of computer technology and aerospace technology, modern geographic information technologies such as GIS and remote sensing have entered the agricultural field, effectively promoting large-scale regional irrigation agriculture [15]. The Google Earth Engine (GEE) platform could quickly access, extract, and calculate many open geographic information data resources, particularly suitable for large-scale and long-duration monitoring. It has excellent potential for application in drought, disasters, food security, climate monitoring, and ecological and environmental protection [16]. The GEE-based platform has been widely used for crop identification [17], surface water [18], forest change [19], vegetation cover change [20], and other areas. Utilizing remote sensing to estimate regional irrigation guarantee capacity compensates for the lack of meteorological station data and can obtain more accurate spatial and temporal distribution maps of regional irrigation water demand, effective water use, and irrigation guarantee capacity index results [14,21]. Liang [22,23] used geographic information systems and the Miami model to calculate the irrigation water demand for nine global regions and to provide feasibility analysis and evaluation for water transfer projects. Huang [14] used MODIS as the data basis and, based on the principle of water balance, calculated the irrigation water demand and effective irrigation water amount for the research area. The ratio between effective irrigation amount and irrigation water demand was used as the basis for evaluating irrigation guarantee capacity. Using multi-year irrigation guarantee capacity indicators, the irrigation guarantee capacity of cultivated land was detected and evaluated.

This study used the GEE platform to analyze the irrigation water requirement, effective irrigation water, and irrigation guarantee capacity index and their changes in time and space in the northwest arid region from 2001 to 2020. This could improve the utilization efficiency of irrigation water, and provide a scientific reference for managing agricultural irrigation water in the northwest arid area.

2. Materials and Methods

2.1. Study Area

Based on hydrometeorology, ecological landscape, and social economy in the northwest arid area, Deng Mingjiang [1] put forward the spatial pattern of northwest 'Three Water Lines' facing the optimal allocation of water resources and the coordinated development of ecology and economy. From east to west are the 'Hu Huanyong Line', 'Yangguan Line', and 'Qice Line' (Figure 1). Studies have shown that the 'Hu Huanyong Line' is a natural dividing line between China's socio-economic, ecological landscape, and meteorological precipitation. 'Yangguan Line' is a roughly parallel line from the 'Hu Huanyong Line' westward to Dunhuang City, which is the geographical boundary between China's extreme arid zone (average annual precipitation of less than 100 mm) and the arid zone. The 'Qice Line' divides Xinjiang into two parts of roughly equal size, with Qitai County in the north and Cele County in the south as the two points of the line. While taking into account the economic development and water resources allocation gap between the north and south of Xinjiang, the 'Qice Line' highlights the huge difference in the spatial distribution of water resources and the huge gap in economic and social development between the east and west of Xinjiang [1]. The region's area is 3.45×10^6 km^2, mainly in the mountainous and desert Gobi, with many plateaus and basins and few oases. The cultivated land area is 2.27×10^7 ha, and the area of irrigated agriculture is 1.13×10^7 ha, an essential base for food production in China [24]. The climate is dominated by a temperate continental climate, with scarce rainfall and a shortage of water resources. The average amount of water resources is 1.60×10^{11} m^3, accounting for less than 6% of the country's total water resources, making it a severe water shortage area [1]. Due to climatic and water resource constraints, the northwest arid area is mainly dominated by irrigated agriculture, oasis agriculture, and animal husbandry. According to the water-use structure data of the northwest arid area in China, agricultural water consumption is 7.71×10^{10} m^3, accounting for 83% of the total water. The shortage of and limited agricultural water distribution have become the main factors restricting agricultural development in northwest China [25].

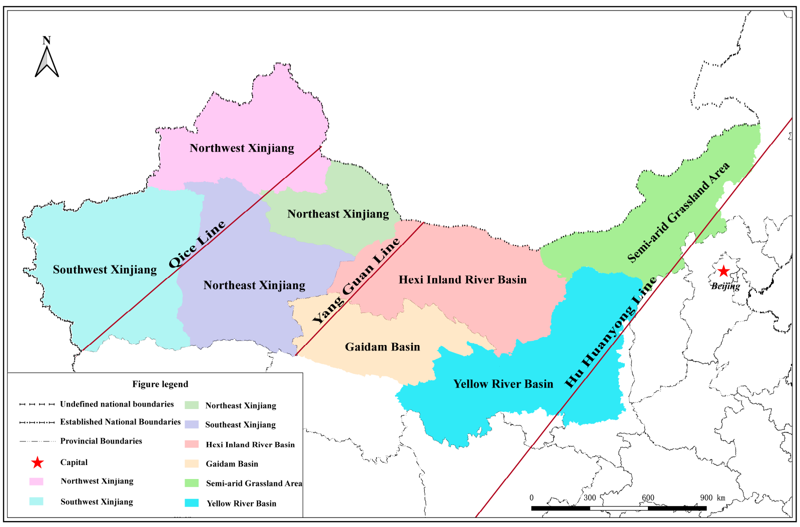

Figure 1. 'Three Water Lines' area of northwest China.

2.2. Research Method

2.2.1. Mathematical Model

The Miami model uses numerous global meteorological observations and measurements of plant productivity to regress an empirical formula for the relationship between plant productivity and multi-year average temperature and precipitation [22,23,26]. The model utilizes the empirical formula and Liebig's Law of the Minimum to calculate a climate productivity distribution map of Earth's land vegetation, which is often used for global net primary productivity assessments [27–29]. Numerous domestic scholars have found that the Miami model has been used to study the relationship between average multi-year rainfall, average multi-year temperature, and irrigation water requirement (*IWR*) and has been widely used in China [26]. Irrigation water demand refers to the amount of water that a crop needs to be replenished by irrigation during growth (the amount of water required to meet evapotranspiration, leakage losses, and other water requirements), which cannot be provided by soil water and rainfall entering the soil [30–32].

$$Y = \frac{3000}{1 + e^{1.315 - 0.119t}} \quad (1)$$

$$P_Y = 1506 \times \ln \frac{3000}{3000 - Y} \quad (2)$$

$$IWR = P_Y - P \quad (3)$$

where t is the mean annual temperature, °C; Y is the light-temperature potential productivity, g·m^{-2}; P_Y is the light-temperature potential water demand, mm; *IWR* is the irrigation water requirement, mm; and P is the mean annual rainfall, mm.

The amount of water used for irrigation is the amount of irrigation water that needs to be supplied to the crop from the water source through engineering measures out of the water demand of the various crops in the irrigation area. Effective irrigation water (*EIW*) calculation can be reduced to the difference between the amount of water transpired by plants and evaporated from the soil and adequate rainfall during the year [21].

$$EIW = T_p + E_s - P \quad (4)$$

where P is the average annual rainfall, mm; *EIW* is effective irrigation water, mm; T_p is plant transpiration, mm; and E_s is soil evaporation, mm.

Irrigation guarantee capacity index is the ratio of effective irrigation water to irrigation water demand, and it is a valuable way of evaluating the efficiency of effective irrigation water [14,21].

$$IGCI = \frac{EIW}{IWR} \quad (5)$$

where *IGCI* is the irrigation guarantee capacity index, which represents the irrigation guarantee capacity index degree.

2.2.2. Study Methods and Steps

By referring to the flow chart (Figure 2), we can intuitively and clearly understand how to calculate the irrigation guarantee capacity index degree using meteorological resource data. The specific steps for calculating the *IWR*, *EIW*, and *IGCI* indicators on the GEE platform are as follows.

Firstly, instructions are written in the Earth Engine Code Editor interface to extract annual average precipitation, annual average temperature, plant transpiration, and soil evaporation data for the study area. These data are then converted into raster data and raster layers with resolutions of 4638.3 m, 0.25°, 500 m, and 500 m, respectively. Secondly, using Equations (1)–(4), the light-temperature potential productivity, the light-temperature potential water demand, irrigation water demand, and effective irrigation water of each raster are calculated based on the raster data and raster layers of annual average precipitation, annual average temperature, plant transpiration, and soil evaporation. Finally, the raster data and raster layers of irrigation water demand and effective irrigation water are used to calculate the irrigation guarantee capacity index of each raster based on Equation (5).

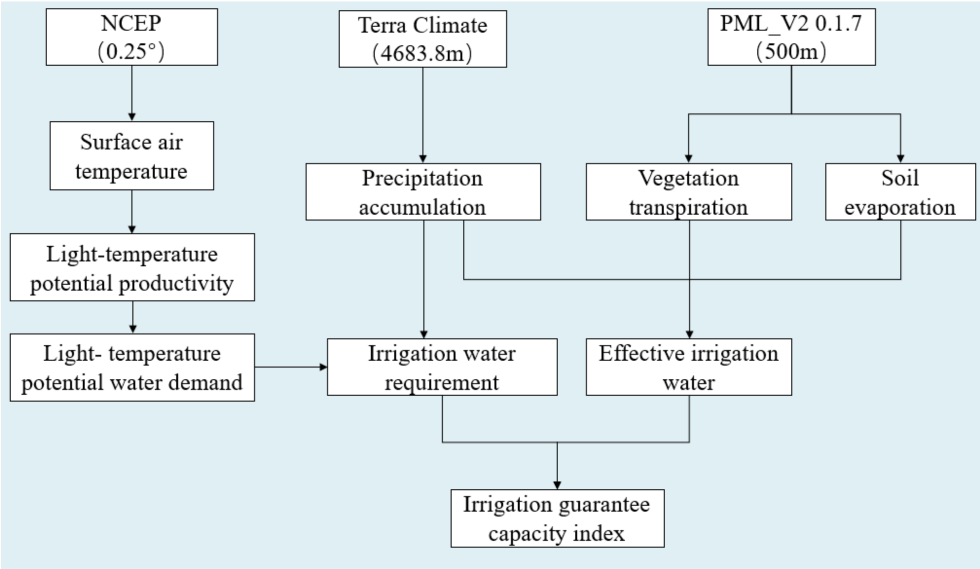

Figure 2. The framework for computing *IGCI* based on the GEE platform.

Spatial distribution TIFF layers for *IWR*, *EIW*, and *IGCI* for each year from 2001 to 2020 were calculated using the GEE platform for the study area. These TIFF layers were then imported into the QGIS software for color and layer adjustments, resulting in visual spatial distribution maps for each indicator.

In this study, the data sources of irrigation water demand and meteorological resources in water consumption are shown in Table 1.

Table 1. Sources of meteorological datasets.

Data Sets		Provider	Time	Resolution	Data Sources
Precipitation [33]	Terra Climate	University of California Merced	2001–2020	4638.3 m	https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE (accessed on 1 November 2022)
Temperature [34]	NCEP	Climate Data Store	2001–2020	0.25°	https://developers.google.com/earth-engine/datasets/catalog/NCEP_RE_surface_temp (accessed on 1 November 2022)
Plant transpiration water [35–37]	PML_V2 0.1.7	PML_V2	2001–2020	500 m	https://developers.google.com/earth-engine/datasets/catalog/CAS_IGSNRR_PML_V2_v017 (accessed on 1 November 2022)
Soil evaporation water [35–37]	PML_V2 0.1.7	PML_V2	2001–2020	500 m	https://developers.google.com/earth-engine/datasets/catalog/CAS_IGSNRR_PML_V2_v017 (accessed on 1 November 2022)

Note: 'PML_V2' refers to Penman–Monteith–Leuning Evapotranspiration, which was developed by Gan et al. [36] and Zhang et al. [35,37].

3. Results

3.1. Characteristics of Temporal Changes of IWI, EIW, and IGCI

The irrigation water requirement, effective irrigation water, and irrigation guarantee capacity index of the northwest arid area from 2001 to 2020 (data were missing in 2017) were calculated based on the GEE platform (Table 2). The region belongs to a water-abundant area when $IWR \leq 0$ or $IGCI < 0$. It represents the excess rainfall in the region, and the rainfall can meet the irrigation water requirement. The cultivated land in the water-abundant area is about 7.04×10^5 ha, accounting for 3.10% of the cultivated area in the arid area of northwest China. The region is a water shortage area when *IWR* > 0 or 0 < *IGCI* < 1; the irrigation water requirement is satisfied by irrigation and rainfall together. The cultivated land area in the water shortage area is about 2.75×10^6 ha, accounting for 12.10% of the cultivated area in the arid area of northwest China. The region is over-irrigated when the *IGCI* > 1, where irrigation water consumption exceeds the irrigation water requirement. The cultivated area in the over-irrigated area is about 1.92×10^7 ha, accounting for 84.80% of the cultivated area in the arid area of northwest China [26]. The northwest arid area should be adapted to local conditions and reasonably promote efficient water-saving irrigation technology to develop irrigated agriculture further.

Table 2. *IWR*, *EIW*, and *IGCI* from 2001 to 2020.

Year	*IWR*/mm	*EIW*/mm	*IGCI*	Year	*IWR*/mm	*EIW*/mm	*IGCI*
2001	384.32	136.04	0.46	2011	338.28	189.46	−2.71
2002	394.30	159.35	0.48	2012	322.55	187.03	1.13
2003	347.62	139.22	0.50	2013	414.51	179.64	0.39
2004	384.11	148.52	0.68	2014	379.79	198.28	0.56
2005	365.06	175.36	0.47	2015	409.46	221.43	0.64
2006	410.80	165.62	0.48	2016	413.91	157.16	0.49
2007	404.55	170.40	0.29	2017	-	-	-
2008	370.94	167.61	0.48	2018	379.21	151.54	−0.55
2009	375.38	172.88	0.49	2019	408.13	180.97	0.45
2010	360.43	177.07	0.59	2020	343.70	176.83	1.91

Note: '-' refers to no data.

3.1.1. Analysis of Irrigation Water Requirement

The *IWR* in the arid area of northwest China from 2001 to 2020 was 323–415 mm, with an average value of 379.32 mm. Deng et al. [24] found that the water demand for the main crops and fruits in the arid areas of northwest China is between 300–900 mm, with an overall average of about 500 mm. Based on the Miami model, Liang et al. [26] calculated that China's irrigation water requirements range from 0 to 1290 mm, with the majority of regions falling between 280 and 460 mm. Therefore, the results of this study are generally consistent with Liang's findings. We found that Dominik et al. [38] used potential evapotranspiration to calculate the irrigation water demand in China, and the results ranged from 220 to 600 mm, with an average range of 350–420 mm, which is consistent with the results of this study. Based on the CFMC method, Jie et al. [39] calculated the irrigation water demand of the Jingdian irrigation area in northwest China from 2000 to 2020. The resultant value was between 231.9 and 721.9 mm, which is also consistent with the results of this study. Therefore, it further proved the rationality of the results of this article. The average annual rainfall and temperature are 280.65 mm and 5.52 °C, respectively (Figure 3). The maximum *IWR* (414.51 mm) appeared in 2013, which was an increase of 0.15–28.51% compared with other years. Moreover, the temperature (6.08 °C) increased by 0.56 °C compared with the annual average temperature. That indicated that the higher temperature in 2013 increased the amount of water evaporated from the crop and soil, increasing the *IWR*. The minimum *IWR* (322.55 mm) appeared in 2012, which was 4.65–22.19% lower than in other years. That year's temperature (4.60 °C) was 0.92 °C lower than the average annual temperature. That indicated that the temperature in 2012 was below the average and the amount of water evaporated from the crop and soil surface was 437.14 mm, resulting in a minimum *IWR*.

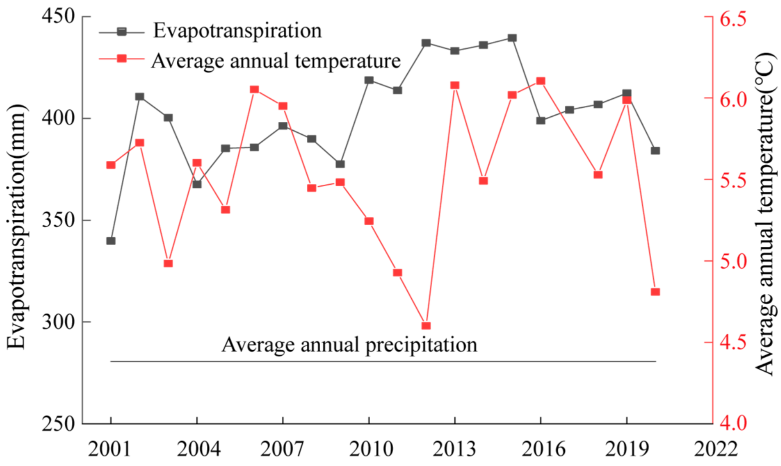

Figure 3. Meteorological data of northwest arid area from 2001 to 2020.

3.1.2. Analysis of Effective Irrigation Water

The *EIW* in the arid area of northwest China from 2001 to 2020 was 136–222 mm, with an average value of 171.29 mm. Several experts and scholars [40–43] have calculated the *EIW* in Shaanxi, Zhejiang, and the North China Plain using the water balance formula. The relative error between their results and the water resources bulletin is within 10%, and the effective irrigation water amount ranges from 176.6 to 338.7 mm. Therefore, the results of this study are consistent with theirs. Furthermore, the average multi-year plant transpiration and soil evaporation were 401.80 mm (Figure 3). The maximum *EIW* (221.43 mm) appeared in 2015, which was an increase of 11.67–62.77% compared with other years. The plant transpiration and soil evaporation amount (439.54 mm) increased by 9.39% compared with the multi-year average. That means crop growth consumes more water, resulting in maximum irrigation water. The minimum effective irrigation water (136.04 mm) appeared in 2001, which was a decrease of 2.28–38.56% compared with other years. The plant transpiration and soil evaporation (339.77 mm) decreased by 15.47% compared with the multi-year average. It showed that the water consumption of crop growth decreased the most and the *EIW* reached the minimum in 2001.

3.1.3. Analysis of Irrigation Guarantee Capacity Index

The northwest arid area was over-irrigated in 2012 and 2020 because the irrigation guarantee capacity index was more significant than 1 in both years. That indicated an increase in the area where effective irrigation water was greater than *IWR* in 2012 and 2020 compared to the rest of the years. The *IGCI* (−2.71) in 2011 and the *IGCI* (−0.55) in 2018 were less than 0, indicating that the area where rainfall can meet the *IWR* has increased in the arid area of northwest China in these two years compared to other years. The *IGCI* in the remaining years is in the range of 0.29–0.68 mm, with an average value of 0.50 mm. Huang et al. [14], Nan et al. [6], and Nan et al. [21] calculated the *IGCI* for Hengshui, the northwest arid area, and Hailun cities, respectively. The majority of the results for most areas were between 0.4 and 0.8, and in years with higher rainfall, some of the results were negative. Therefore, the results of this study are consistent with theirs. The maximum *IGCI* (0.68) appeared in 2004 and increased by 5.29–136.92% compared with other years. The minimum *IGCI* (0.29) appeared in 2007 and decreased by 27.49–57.79% compared with other years. It shows that the *IGCI* in the northwest arid area is 0–1 in most years, and the effective irrigation water cannot meet the irrigation water demand, so it is a water shortage area. The matching of irrigation water resources in the northwest arid area is unreasonable, and it is necessary to redistribute water resources.

3.2. Spatial-Temporal Analysis of the IWR in the 'Three Water Lines' Area

3.2.1. Spatial Distribution Characteristics of the *IWR* from 2001 to 2020

The spatial distribution of the *IWR* in the arid area of northwest China from 2001 to 2020 is similar, and the distribution law is apparent. The spatial distribution of the *IWR* in the northwest 'Three Water Lines' area from 2001 to 2020 is shown in Figure 4. The *IWR* of 3.09% of cultivated land is negative, indicating the excess rainfall in this area. This is mainly distributed in the southwest edge of the Yellow River Basin and the east of the Qaidam Basin. It shows that the rainfall in this region can meet the irrigation requirements, as the Yellow River passes through it and the rainfall is significant. The *IWR* of 10.59% of cultivated land is within the range of 0–200 mm and is distributed in the southwestern part of the Yellow River Basin, the southeastern part of the semi-arid grassland region, and the northwestern part of Xinjiang. The *IWR* for 40.60% of cultivated land is within the range of 200–400 mm, and it is mainly distributed in the central and northern part of the Yellow River Basin, the southern part of the semi-arid grassland region, the southeastern part of the Hexi Inland River Basin, and the northern part of southwestern Xinjiang. The *IWR* of 36.03% of cultivated land is within the range of 400–600 mm, which is mainly distributed in the southeastern margin of the Yellow River Basin, the western semi-arid grassland, the southwestern margin of the Hexi Inland River Basin, the northwestern part of southeastern Xinjiang, and the central part of southwestern Xinjiang. The *IWR* of 9.69% of cultivated land is more than 600 mm, which is mainly distributed in the northwest edge of the Yellow River Basin, the middle of Hexi Inland River Basin, most areas of Northeast Xinjiang, and the middle and southeast of southwest Xinjiang. Because the effective rainfall in this area is deficient and mainly relies on irrigation to meet the agricultural water demand, the *IWR* is great.

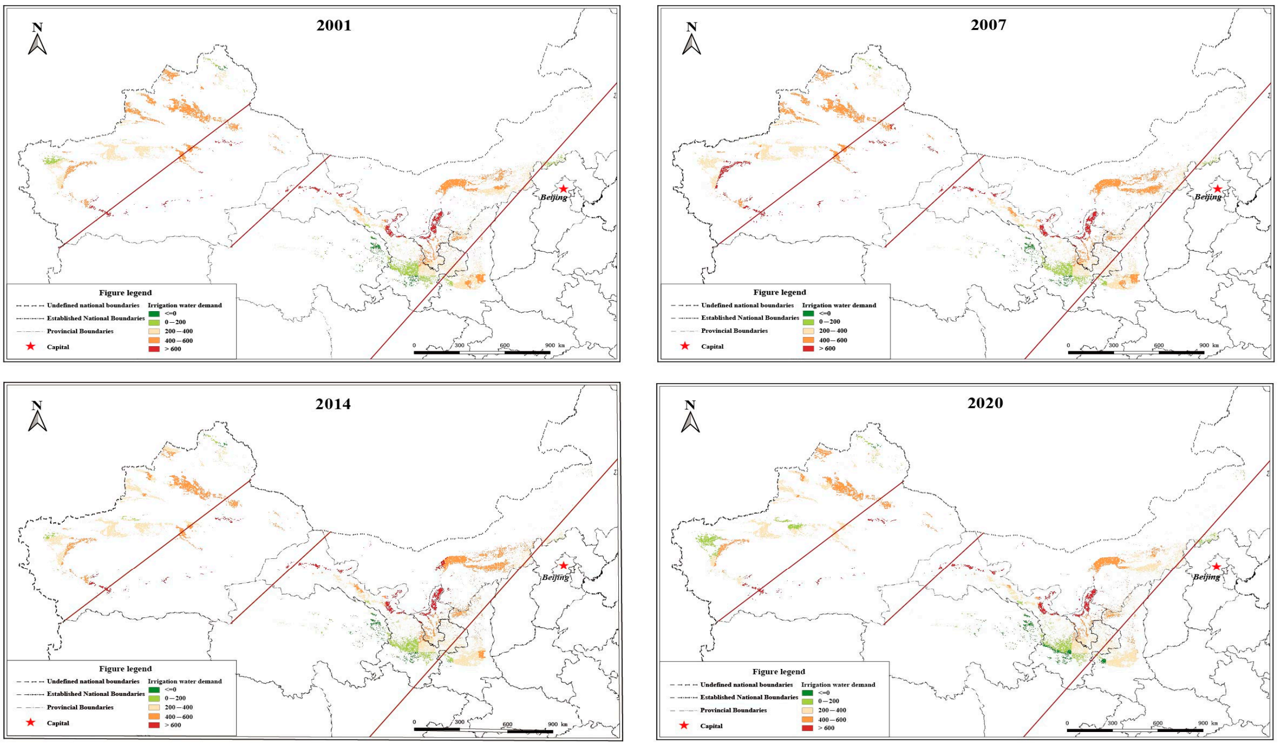

Figure 4. Spatial distribution of *IWR* in northwest 'Three Water Lines' area.

3.2.2. Characteristics of the *IWR* in Sub-Regions of the 'Three Water Lines' Area

Statistics on the *IWR* in the northwest 'Three Water Lines' region from 2001 to 2020 are shown in Table 3. Moreover, the trend of meteorological changes in the northwest 'Three

Water Lines' region from 2001 to 2020 is shown in Figure 5. The above data are used to analyze the various characteristics of the *IWR* in the northwest 'Three Water Lines' area.

Table 3. *IWR* in sub-regions of 'Three Water Lines' area from 2001 to 2020.

Year	Northwest Xinjiang	Southwest Xinjiang	Northeast Xinjiang	Southeast Xinjiang	Yellow River Basin	Qaidam Basin	Hexi Inland River Basin	Semi-Arid Grassland District
2001	444.20	354.48	605.96	542.82	309.49	523.34	59.32	408.42
2002	462.82	357.08	631.03	543.89	324.18	534.39	70.54	405.27
2003	387.12	319.85	543.14	481.15	286.97	491.30	68.02	367.11
2004	448.57	380.30	619.22	544.74	294.16	502.61	53.44	416.15
2005	435.89	363.94	582.68	549.10	283.76	493.41	70.84	355.32
2006	465.54	409.42	618.05	574.49	339.36	532.38	90.64	409.70
2007	469.19	400.34	632.72	559.04	315.21	524.94	72.94	436.59
2008	463.73	383.85	622.42	544.77	270.92	488.72	62.77	365.69
2009	419.79	369.66	579.20	522.17	308.87	520.00	78.79	374.07
2010	405.31	384.38	549.61	501.93	295.19	495.87	88.54	328.15
2011	397.51	371.56	546.24	481.69	248.98	471.75	71.51	330.90
2012	372.26	332.05	560.72	513.74	241.90	473.49	46.68	312.63
2013	460.34	391.90	615.05	583.23	352.06	565.86	89.61	413.84
2014	390.87	339.66	586.30	480.86	314.93	525.04	70.31	467.43
2015	473.43	387.69	664.69	563.86	335.30	553.73	87.37	414.07
2016	468.57	408.84	641.23	584.17	345.54	566.01	108.23	392.49
2017	-	-	-	-	-	-	-	-
2018	395.96	370.90	584.16	512.62	313.05	522.44	79.94	419.82
2019	468.33	383.38	657.65	563.64	329.12	555.35	65.40	431.71
2020	387.63	287.93	574.97	427.45	289.45	493.22	9.88	383.68

Note: '-' refers no data; the unit of all data in the table is mm.

(1) Northeast Xinjiang, Southeast Xinjiang, and the Qaidam Basin

The average annual *IWR* in Northeast Xinjiang (600.79 mm), Southeast Xinjiang (530.28 mm), and the Qaidam Basin (517.57 mm) increased by 221.47 mm, 150.96 mm, and 138.25 mm, respectively, compared with that in the northwest arid area, indicating that these three regions have a great demand for irrigation water resources. Data analysis shows that rainfall in the Northeast and Southeast of Xinjiang is much lower than in the northwest arid area. Compared with the average annual rainfall in the northwest arid area, it is reduced by 79.70% and 74.83%, respectively. It mainly depends on irrigation to meet crops' growth and development. The Qaidam Basin receives more rainfall than northeastern Xinjiang and southeastern Xinjiang, which is 31.21% lower than the northwest arid area. The average annual temperature in Northeast Xinjiang and the Qaidam Basin is higher than that in the northwest arid area, which increases by 0.38 °C and 1.01 °C, respectively. The water consumption of plant transpiration and field evaporation increased, further increasing the *IWR*. The average annual temperature in the Southeast of Xinjiang is 1.06 °C lower than that in the northwest arid area. Therefore, its transpiration water is lower than in Northeastern Xinjiang and the Qaidam Basin. However, its rainfall is far lower than that of the northwest arid area, resulting in a higher *IWR* than the multi-year average of the northwest arid area.

(2) Northwest Xinjiang and the Semi-Arid Grassland District

The average annual *IWR* in Northwest Xinjiang (432.48 mm) and the semi-arid grassland area (391.21 mm) increased by 53.16 mm and 11.89 mm, respectively, compared with that in the northwest arid area, which was close to the average annual *IWR*. That is mainly since the average multi-year rainfall in Northwest Xinjiang is 29.62% lower, and the temperature is 0.21 °C lower, than that in the northwest arid area. The rainfall in this area decreased significantly, but the decrease in temperature led to a decrease in water consumption, such as by plant transpiration, which led to the requirement of the *IWR* being the same as that of the northwest arid area. The difference between the average annual rainfall and temperature of the semi-arid grassland and northwest arid areas is 6.20% and 3.87%, respectively, which is relatively small. Therefore, the *IWR* is the same as that of the northwest arid area.

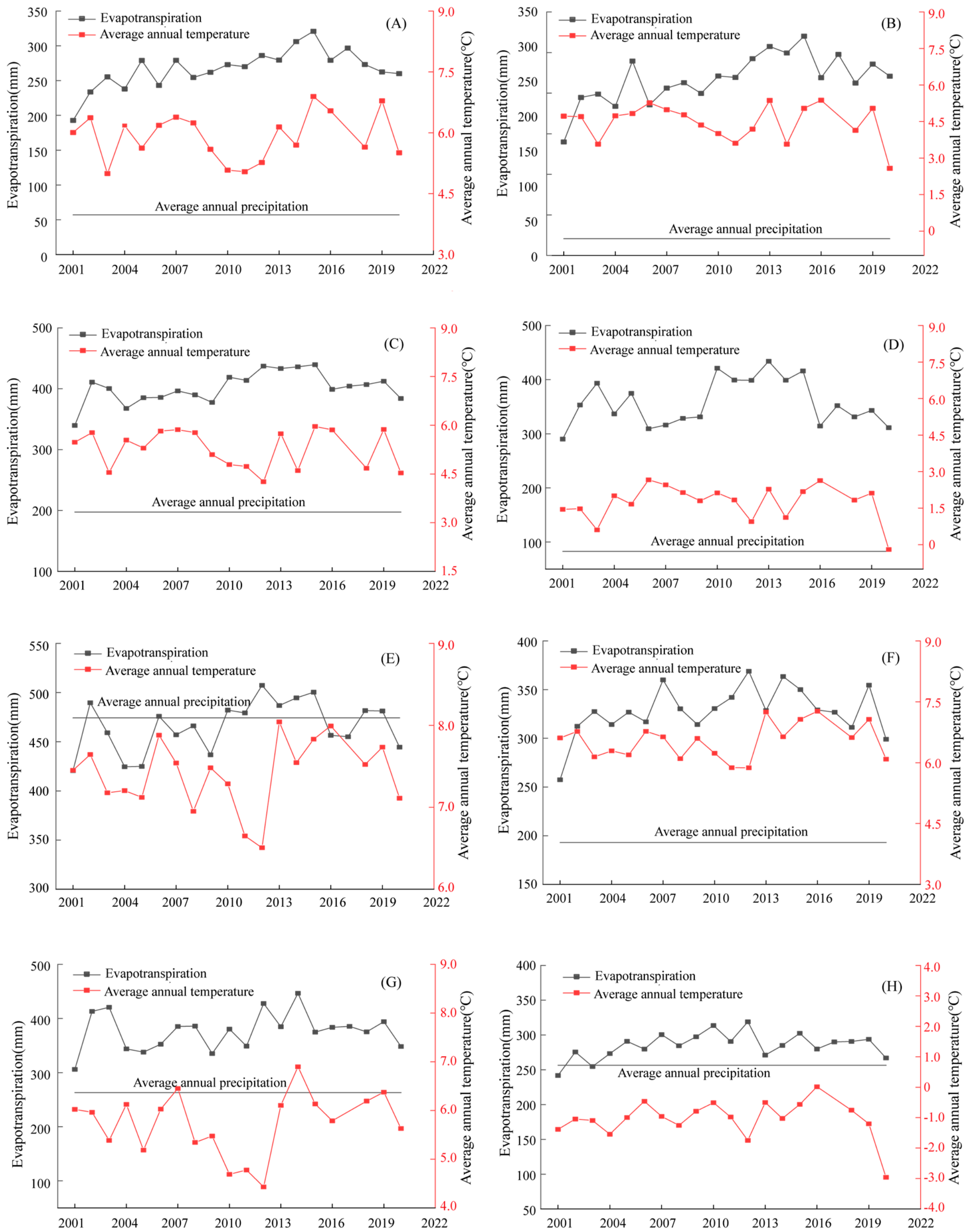

Figure 5. Meteorological variation trend of northwest 'Water Three Lines' area from 2001 to 2020. Among them, (**A**–**H**) represent Northwest Xinjiang, Southwest Xinjiang, Northeast Xinjiang, Southeast Xinjiang, Yellow River Basin, Qaidam Basin, Hexi Inland River Basin, and Semi-arid grassland district area respectively.

(3) Southwest Xinjiang and the Yellow River Basin

The average annual *IWR* in the southwest of Xinjiang (368.27 mm) and the Yellow River Basin (305.18 mm) is reduced by 11.04 mm and 74.14 mm, respectively, compared with that in the northwest arid area. This region is a relatively small area of *IWR*. That is mainly due to the increase of 193.64 mm in the average multi-year rainfall and increase of 1.88 °C in the temperature in the Yellow River Basin compared to the northwest arid area. Although water consumption, such as by plant transpiration and soil evaporation, in the Yellow River Basin is relatively high, rainfall can supplement the water required for crop growth, resulting in a lower *IWR* than the multi-year average in the northwest arid area. The average rainfall in Southwest Xinjiang is 198.12 mm lower, and the temperature is 3.78 °C lower, than that in the northwest arid area. The more significant decrease in temperature indicates that the *IWR* is more sensitive to temperature. Southwest Xinjiang receives less rainfall, but the multi-year temperature in Southwest Xinjiang is lower, so water consumption, such as by field transpiration, is also lower. This results in its *IWR* being slightly lower than the multi-year average for the northwest arid area but higher than that of the Yellow River Basin.

(4) Hexi Inland River Basin

The multi-year average *IWR* of the Hexi Inland River Basin (70.78 mm) is much lower than the multi-year average of the northwest arid area, which is 308.54 mm lower than that of the northwest arid area. This area has a minor *IWR* in the northwest 'Three Water Lines' area. Because of the small area of cultivated land and heavy rainfall (256.43 mm) in the Hexi Inland River Basin, the rainfall in most areas can meet the irrigation requirement. The average multi-year temperature in the Hexi Inland River Basin is −1.04 °C. The temperature is low, and the water consumption, such as by field transpiration, is low, resulting in its *IWR* being much lower than the multi-year average value in the northwest arid area.

3.3. Spatial-Temporal Analysis of the EIW in the 'Three Water Lines' Area

3.3.1. Spatial Distribution Characteristics of the EIW from 2001 to 2020

The spatial distribution of effective irrigation water in the arid area of northwest China from 2001 to 2020 is similar, and the distribution pattern is relatively apparent. The spatial distribution of effective irrigation water in the northwest 'Three Water Lines' area from 2001 to 2020 is shown in Figure 6. The effective irrigation water for 10.71% of cultivated land ranges from 0 to 50 mm, and it is distributed in the middle part of the Yellow River Basin. The effective irrigation water for 24.74% of cultivated land ranges from 50 to 100 mm, and it is primarily distributed in the central part of the Yellow River Basin, the southwest part of the semi-arid grassland district, the south part of the Hexi Inland River Basin, and the north part of the Northwest of Xinjiang. For 19.87% of cultivated land, the effective irrigation water ranges from 100 to 150 mm. The region is mainly distributed southeast of the Yellow River Basin and the eastern semi-arid grassland district. The effective irrigation water for 11.99% of cultivated land ranges from 150 to 200 mm, and it is mainly distributed in the southeast part of the Yellow River Basin. For 32.70% of cultivated land, the effective irrigation water is greater than 200 mm. The region is mainly distributed in the northwest edge of the Yellow River Basin, the southern edge of the semi-arid grassland district, most of the southern Hexi Inland River Basin, and most of Xinjiang. As adequate rainfall in the region is deficient, it mainly relies on irrigation to meet the water requirements of agriculture, and thus, irrigation water consumption is significant.

3.3.2. Characteristics of the EWI in Sub-Regions of the 'Three Water Lines' Area

Statistics on the *EWI* in the northwest 'Three Water Lines' region from 2001 to 2020 are shown in Table 4. The above data and Figure 5 are used to analyze the variation characteristics of the *EWI* in the northwest 'Three Water Lines' area.

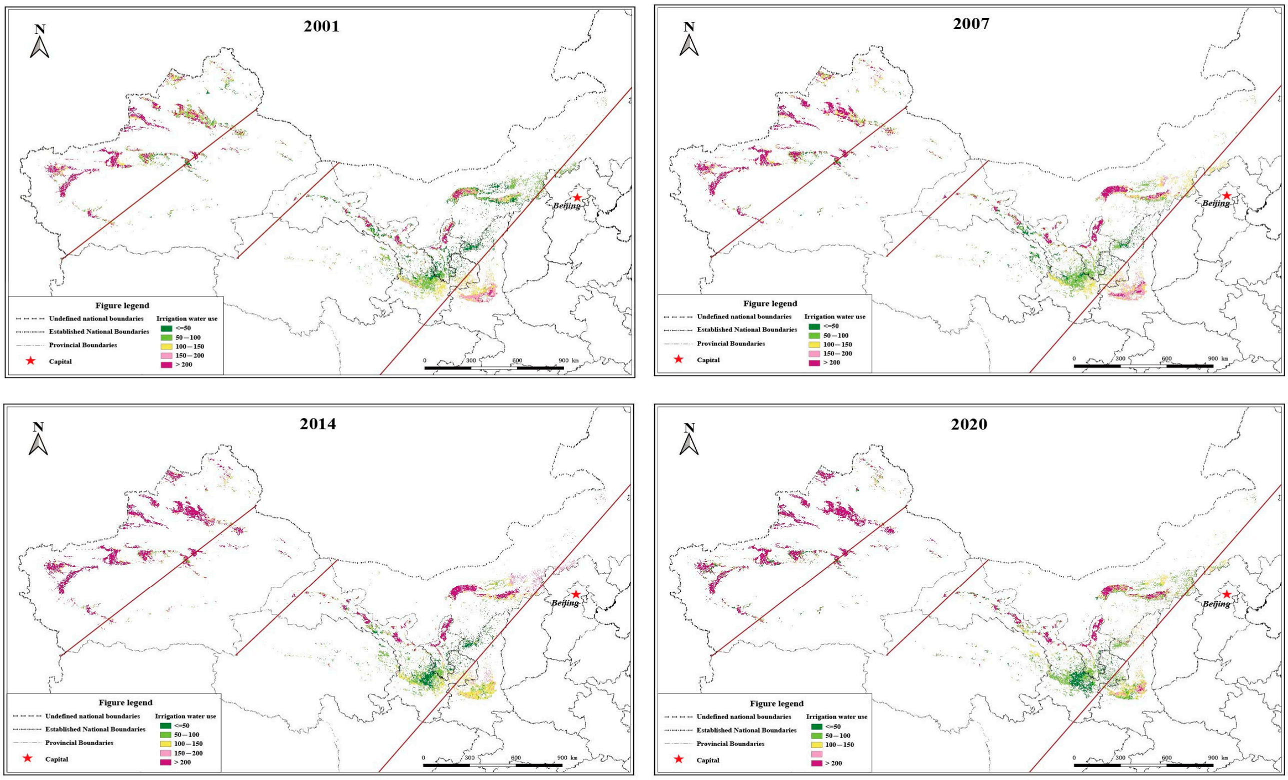

Figure 6. Spatial distribution of *EIW* in 'Three Water Lines' area of northwest China.

Table 4. *EWI* of the northwest 'Three Water Lines' area.

Year	Northwest Xinjiang	Southwest Xinjiang	Northeast Xinjiang	Southeast Xinjiang	Yellow River Basin	Qaidam Basin	Hexi Inland River Basin	Semi-Arid Grassland District
2001	170.62	221.26	140.98	131.73	100.18	116.81	78.44	91.23
2002	193.89	257.93	169.10	156.10	104.16	123.03	57.10	153.20
2003	159.19	279.53	174.29	161.36	74.40	133.71	58.05	104.79
2004	207.96	245.00	182.93	166.73	92.56	162.42	64.28	83.56
2005	240.55	263.89	215.54	201.82	109.47	152.42	75.84	149.43
2006	237.32	245.82	194.98	157.46	110.62	145.35	80.62	123.04
2007	221.94	260.38	196.69	175.12	111.16	130.22	69.41	159.64
2008	234.82	258.55	188.05	175.97	120.93	154.64	73.84	93.66
2009	236.13	273.09	207.84	188.93	101.13	155.37	69.75	150.63
2010	248.79	309.41	200.18	200.94	94.21	156.57	91.12	132.97
2011	245.32	307.71	212.96	207.41	115.50	169.44	83.58	163.42
2012	260.88	319.28	208.35	224.73	111.82	172.43	67.97	118.37
2013	252.68	329.78	219.85	222.07	93.22	159.69	78.86	116.99
2014	272.43	324.47	237.79	233.07	100.12	171.87	67.60	193.81
2015	287.59	331.74	228.83	225.72	174.01	183.09	96.50	144.08
2016	263.76	200.30	199.47	169.87	104.20	108.97	36.65	114.05
2017	253.85	251.54	218.16	210.48	105.50	116.08	36.17	156.41
2018	277.48	225.99	179.08	170.64	74.79	102.36	54.92	101.74
2019	263.21	238.86	188.29	189.23	111.59	176.13	81.48	173.25
2020	300.65	243.85	195.97	204.16	94.03	158.04	70.90	136.94

Note: The unit of all data in the table is mm.

(1) Southwest Xinjiang and Northwest Xinjiang

The average annual *EWI* in the Southwest of Xinjiang (270.36 mm) and the Northwest of Xinjiang (240.80 mm) increased by 99.07 mm and 69.51 mm, respectively, compared with the average annual *EWI* in the northwest arid area. This area is the largest area of *EWI* in the northwest 'Three Water Lines' area. The main reason is that the amount of plant transpiration and soil evaporation in Southwest Xinjiang is 1.31% higher than that in the northwest arid area, but the rainfall is much lower than that in the northwest arid area. It mainly relies on irrigation to supplement the water required for plant transpiration and soil evaporation, and its *EWI* reaches the maximum. The water amount of plant transpiration and soil surface evaporation in Northwest Xinjiang is 11.02% lower than that in the northwest arid area. The rainfall is lower than the average value of the northwest arid area, and the decrease is less than the water amount of plant transpiration and soil surface evaporation, resulting in a higher *EWI* than that in the northwest arid area.

(2) Southeast Xinjiang and Northeast Xinjiang

The average annual *EWI* in southeastern Xinjiang (187.53 mm) and northeastern Xinjiang (196.90 mm) increased by 25.61 cm and 16.24 mm, respectively, compared with the average annual *EWI* in the northwest arid area. The *EWI* in this area is close to the average annual *EWI* in the northwest arid area. The main reason is that the average annual plant transpiration and soil evaporation in Northeast Xinjiang and Southeast Xinjiang increased by 33.36% and 33.51%, respectively, compared with the average annual average in the northwest arid area. At the same time, the rainfall decreased by 223.67 mm and 210.02 mm, respectively, resulting in basically the same *EWI* in this area. The difference between plant transpiration and soil evaporation and effective rainfall is close to that in the northwest arid area; the requirement of *EWI* is basically consistent with that in the northwest arid area.

(3) The Qaidam Basin and the Semi-Arid Grassland District

The multi-year average *EWI* in the Qaidam Basin (149.08 mm) and the semi-arid grassland district (131.83 mm) was 22.21 mm and 39.46 mm lower than that in the northwest arid area, respectively, which is a relatively low *EWI* region in the northwest 'Three Water Lines' area. This is mainly because plant transpiration and soil evaporation decreased by 18.34% and 6.33%, respectively, in the Qaidam Basin and the semi-arid grassland. At the same time, the average annual rainfall decreased by 87.59 mm and 17.40 mm, respectively, compared with the arid area of northwest China, so the *EWI* in this area was basically the same. The difference between plant transpiration and soil evaporation and effective rainfall is smaller than that in the northwest arid area, which leads to effective irrigation water in the Qaidam Basin and semi-arid grassland area being lower than the multi-year average in the northwest arid area.

(4) Yellow River Basin and the Hexi Inland River Basin

The average annual *EWI* of the Yellow River Basin (105.16 mm) and the Hexi Inland River Basin (71.42 mm) decreased by 66.13 mm and 99.87 mm, respectively, compared with the average annual irrigation water consumption in the northwest arid area. The *EWI* in this area is the least in the northwest 'Three Water Lines' area. Compared with the northwest arid area, the plant transpiration and soil evaporation in the Yellow River Basin increased by 16.01%, and the rainfall increased by 193.64 mm. The rainfall in some areas can meet the partial requirements of *EWI*, so the *EWI* is far lower than the multi-year average in the northwest arid area. At the same time, the plant transpiration and soil evaporation in the Hexi Inland River Basin were 29.06% lower than those in the northwest arid area, and the rainfall was 24.22 mm lower than that in the northwest arid area. Because the difference between plant transpiration and soil evaporation and effective rainfall is much smaller than that in the northwest arid area, the *EWI* in the Hexi Inland River Basin reaches the minimum.

3.4. Spatial-Temporal Analysis of the IGCI in the 'Three Water Lines' Area

3.4.1. Spatial Distribution Characteristics of the *IGCI* from 2001 to 2020

The spatial distribution of the *IGCI* in the arid area of northwest China from 2001 to 2020 is basically similar, and the distribution pattern is more obvious. The spatial distribution of the *IGCI* in the northwest 'Three Water Lines' area from 2001 to 2020 is shown in Figure 7. Some 3.26% of cultivated land had an *IGCI* of less than 0, indicating that effective rainfall can meet the irrigation water requirement. The region is mainly distributed in the western part of the Yellow River Basin and the eastern edge of the Qaidam Basin.

Some 35.52% of the cultivated land had an *IGCI* in the range of 0–0.3. The region is mainly distributed in the central part of the Yellow River Basin, the southern part of the semi-arid grassland area, the southern part of the Hexi Inland River, the central region of southeastern Xinjiang, and the southeastern region of southwestern Xinjiang. Some 32.22% of the cultivated land had an *IGCI* in the range of 0.3–0.6. The region is mainly distributed in the southeastern part of the Yellow River Basin and the southeastern part of the semi-arid grassland. Some 16.99% of cultivated land had an *IGCI* in the range of 0.6–1. The region is mainly distributed in the southeastern part of the semi-arid grassland region, most of the northwestern part of Xinjiang, and the northwestern part of the southeastern part of Xinjiang. Some 12.02% of the cultivated land had an *IGCI* of greater than 1, indicating that the *EWI* is greater than the *IWR*, and is over-irrigated. The region is mainly distributed in the southern edge of the Yellow River Basin, the southeastern part of the Qaidam Basin, most of the southwestern part of Xinjiang, and the southwestern part of northwestern Xinjiang.

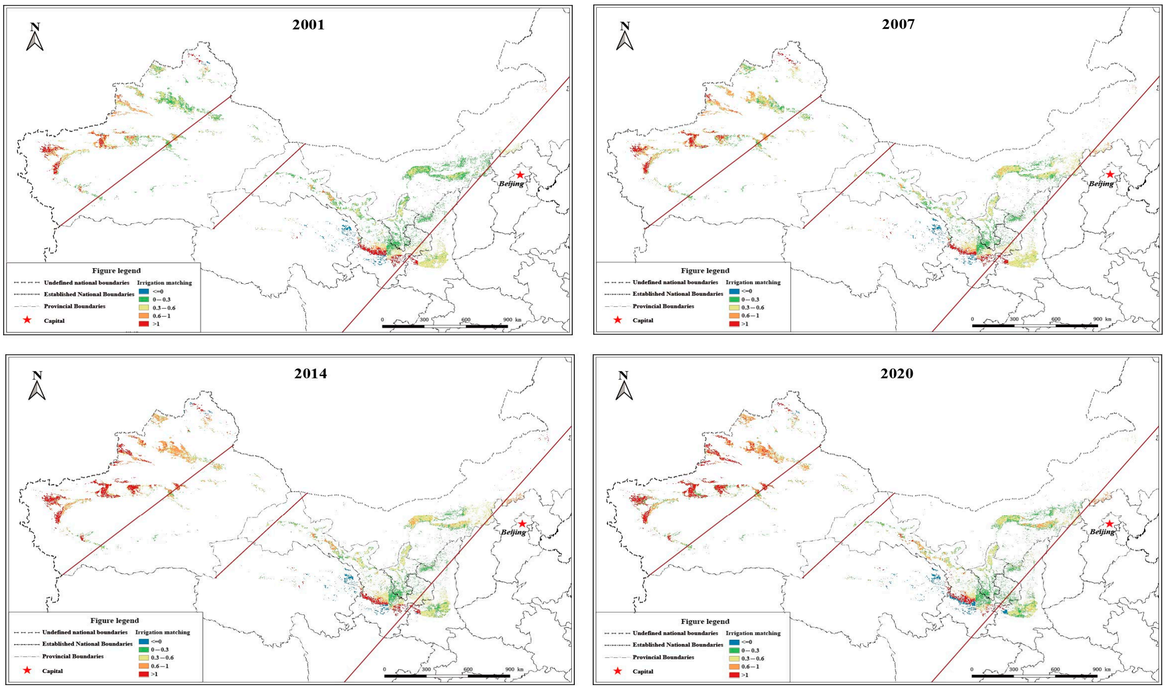

Figure 7. Spatial distribution of *IGCI* in northwest 'Three Water Lines' area.

3.4.2. Characteristics of the *IGCI* in Sub-Regions of the 'Three Water Lines' Area

The data of northwest 'Three Water Lines' irrigation guarantee capacity index from 2001 to 2020 are shown in Table 5. According to data analysis, the multi-year average *IGCI* of the Northwest of Xinjiang (0.55), the Southeast of Xinjiang (0.42), and the Yellow River Basin (0.42) were close to that of the northwest arid area (0.50). This shows that the rationality of the allocation of irrigation water resources in these three regions is consistent with that in the northwest arid region. The multi-year average *IGCI* in Southwest Xinjiang (0.88) was higher than that in the northwest arid area, increasing by 0.38. This indicates that the *EWI* in the basin matches the *IWR*. The allocation and utilization of irrigation water resources are reasonable, and the utilization rate is high. The *IGCI* in Northeast Xinjiang (0.32), the semi-arid grassland area (0.36), and the Qaidam Basin (0.32) was lower than the multi-year average of the northwest arid area, which decreased by 0.18, 0.14, and 0.18, respectively. This indicates that the irrigation water consumption in the basin is low, matched with the *IWR*. The allocation and utilization of irrigation water resources are unreasonable, and the utilization rate of irrigation water resources is low. There is less cultivated land and uneven spatial distribution of rainfall in the Hexi Inland River Basin. An *IGCI* in the range of 0–1 is low. However, the *IGCI* of most areas is in the range of less than 0 and greater than 1. This shows that the rational allocation of water resources should be based on the actual irrigation situation in various regions.

Table 5. *IGCI* in sub-regions of 'Three Water Lines' area.

Year	Northwest Xinjiang	Southwest Xinjiang	Northeast Xinjiang	Southeast Xinjiang	Yellow River Basin	Qaidam Basin	Hexi Inland River Basin	Semi-Arid Grassland District
2001	0.27	0.76	0.23	0.29	0.59	0.25	0.83	0.24
2002	0.22	0.88	0.26	0.34	0.58	0.25	−0.54	0.38
2003	0.47	1.07	0.31	0.40	0.43	0.29	−0.46	0.27
2004	0.48	0.77	0.29	0.36	0.31	0.36	3.24	0.19
2005	0.53	0.86	0.36	0.43	0.31	0.33	−0.14	0.44
2006	0.67	0.70	0.31	0.32	0.40	0.29	0.76	0.32
2007	0.35	0.76	0.30	0.36	0.50	0.25	0.66	0.37
2008	0.71	0.78	0.29	0.37	0.44	0.35	−4.76	0.27
2009	0.31	0.88	0.35	0.42	0.47	0.32	0.28	0.44
2010	0.75	0.93	0.35	0.47	0.40	0.35	2.49	0.50
2011	0.62	0.96	0.38	0.52	0.46	0.40	−0.66	0.53
2012	0.69	1.16	0.36	0.52	0.46	0.39	−0.42	0.42
2013	0.34	0.98	0.35	0.44	0.24	0.29	−1.29	0.28
2014	0.29	1.14	0.40	0.58	0.53	0.35	0.96	0.44
2015	0.88	1.01	0.34	0.47	0.54	0.37	0.76	0.35
2016	1.03	0.58	0.32	0.34	0.31	0.22	0.17	0.31
2017	-	-	-	-	-	-	-	-
2018	0.70	0.72	0.32	0.40	0.32	0.22	1.73	0.25
2019	0.41	0.74	0.29	0.40	0.41	0.38	−1.04	0.42
2020	0.80	1.08	0.35	0.59	0.32	0.40	−1.25	0.38

Note: '-' refers no data; the unit of all data in the table is mm.

4. Discussion

The available potential of cultivated land resources in the northwest arid region is considerable. Improving the allocation of irrigation water resources in the northwest arid region can effectively improve the matching degree of irrigation area and water resources, ensure food security, and promote increased agricultural and animal husbandry production [44]. The local agricultural irrigation quota standards in Xinjiang Uygur Autonomous Region, Qinghai Province, Ningxia Hui Autonomous Region, Inner Mongolia Autonomous Region, Gansu Province, and Shaanxi Province, and the northwest arid area main crop irrigation quota were investigated (Table S1). We should follow the laws of nature, adjust the planting structure based on local conditions, choose appropriate irrigation methods, increase investment in construction projects, develop supporting facilities and carry out technical transformations in irrigation areas, promote agricultural technology, strengthen innovative breeding, and scientifically manage and allocate irrigation water resources [8].

4.1. Southwest Xinjiang and Northwest Xinjiang

The multi-year average *IGCI* of Southwest Xinjiang (0.88) and Northwest Xinjiang (0.55) is the largest of two places in the northwest 'Three Water Lines' area, indicating that the irrigation water distribution in these two regions is relatively reasonable. The *IGCI* in Southwest Xinjiang in 2003, 2012, 2014, 2015, and 2020 is greater than 1, indicating that the region was over-irrigated in these years. However, the difference between effective irrigation water and water requirement is relatively small. The reason is that the Southwest of Xinjiang belongs to the development area of irrigated agriculture, in which agricultural water accounts for 92.80% of the total water consumption. The main irrigated food crops are wheat and corn, and the economic crops are cotton, grape, and jujube [45]. However, due to the uneven spatial and temporal distribution of water resources and the low quality of cultivated land, the utilization rate of irrigation water is low. Therefore, water conservancy projects and field engineering measures should be built in Southwest Xinjiang [8]. Wheat, corn, and cotton are mostly irrigated by micro-irrigation. Southwest Xinjiang should reduce the planting area of forest and fruits, increase the planting area of beans and potatoes, or adopt the planting mode of interplanting forest and fruits with crops to optimize the planting structure further and reduce the crop irrigation quota [46]. At the same time, chemical, physical, and biological measures are needed to improve cultivated land quality and further increase production and income while protecting the ecological environment.

The *IGCI* in Northwest Xinjiang was less than 1 (the *IGCI* in 2016 was 1.03). That indicated that the distribution of irrigation agricultural water use in Northwest Xinjiang is not reasonable compared with Southwest Xinjiang. The main reason is the arid oasis of the Ili Valley, which is located in Northwest Xinjiang. The climate is mild and humid, and agriculture and animal husbandry are relatively developed. Water resources are the main factors in maintaining ecological stability [47]. At the same time, the main irrigated crops in Northwest Xinjiang are wheat and corn, and the economic crops are cotton, soybean, and fruit trees [45]. Therefore, the Northwest of Xinjiang should change its original agricultural cultivation structure by reducing the area of cotton and fruit trees and increasing the area of wheat, corn, and soybeans. While reducing the agricultural irrigation quota, the conventional irrigation methods were changed to film irrigation, sprinkler irrigation, and micro-irrigation [8,38]. Especially in the Ili Valley, while strengthening the ecological protection of farmland, some excellent varieties are selected according to local climatic conditions, and efficient supporting cultivation techniques are integrated to improve grain's total production capacity [48].

4.2. Southeast Xinjiang and the Yellow River Basin

The multi-year average *IGCI* of southeastern Xinjiang (0.42) is consistent with that of the Yellow River Basin (0.42). Among them, 14 years of irrigation guarantee capacity index in Southeast Xinjiang from 2001 to 2020 were between 0.3 and 0.5, indicating that the irrigation water allocation in the region was less reasonable. The Bosten Lake Basin is located in the Southeast of Xinjiang, a region with a typical continental climate and rapid development of irrigated agriculture [49]. Its main irrigated food crops are wheat and maize, and its cash crops are cotton, grapes, and balsam pears [45]. Therefore, the Southeast of Xinjiang should reduce the planting area of wheat, maize, and cotton, increase the planting area of beans and tuber crops, and adopt water-saving irrigation methods such as micro-irrigation [46]. In developing unique forestry and fruit industries simultaneously, forestry and fruit and inter-crop planting patterns should be considered to optimize the crop planting structure further and improve the matching of agricultural irrigation [49].

The *IGCI* of 13 years in the Yellow River Basin is between 0.4–0.6, which indicates that the irrigation water allocation in this region is more reasonable than that in the Southeast of Xinjiang. Irrigation agriculture is the basis and critical factor of agricultural development in the Yellow River Basin [50]. Low effective irrigation water is the biggest challenge restricting the development of irrigation agriculture in the Yellow River Basin. The main food crops in the Yellow River Basin are rice, maize, and wheat, while the cash crops are beans, potatoes, and fruit trees. In order to reduce the irrigation quota of agricultural irrigation water, the Yellow River Basin should reduce the planting area of rice [46]. At the same time, the original irrigation method should be changed [8]. The Yellow River Basin should vigorously develop sprinkler irrigation and micro-irrigation irrigation technology. About half of the water used in agriculture is lost during the water transfer process, while the construction of reservoirs further increases the loss of evaporated river water [51,52]. Therefore, the Yellow River Basin should change the way of water delivery in the field, further promote the development of water-saving agriculture, and scientifically manage the allocation of irrigation water resources to improve its irrigation guarantee capacity index.

4.3. Northeast Xinjiang, the Qaidam Basin, and the Semi-Arid Grassland District

The multi-year average *IGCI*s of Northeast Xinjiang (0.32), the Qaidam Basin (0.32), and the semi-arid grassland (0.36) are the smallest in the northwest 'Three Water Lines' area, indicating that the irrigation water allocation in these three areas is unreasonable. The *IGCI* in Northeast Xinjiang is between 0.2 and 0.4. The reason for the unreasonable irrigation amount is that there is a traditional agricultural irrigation area. The main irrigated food crops are wheat and maize, and the economic crops are cotton and red dates [45]. However, long-term winter and spring irrigation and an unstable change in agricultural planting structure lead to the loss of agricultural water and secondary soil salinization, which restricts the development of agriculture in local irrigation areas. Therefore, the northeastern region of Xinjiang should change its original irrigation methods, planning and construction of water-saving irrigation facilities, and renovation projects [8]. Secondly, it should adjust and optimize its agricultural planting structure, increase water-saving crops such as beans and potatoes, and reduce water-consuming crops such as fruit trees [46]. It should improve irrigation water allocation reasonably to ensure irrigation agriculture's sustainable development.

The reason for the unreasonable amount of irrigation water in the Qaidam Basin is that its typical alpine, arid, and continental desert climate restricts the development of local irrigation agriculture [53,54]. The distribution of water resources is highly unreasonable. Some areas are seriously short of water, and the amount of irrigation water cannot meet the normal growth needs of crops. The other part of the water resources is rich, the waste of water resources is serious, and the contradiction between the supply and demand of water resources is very prominent. The main crops grown in the Qaidam Basin are wheat, beans, and potatoes. Therefore, the Qaidam Basin should be managed according to the actual local conditions and adapted to the local conditions. The construction and transformation of water-saving irrigation technology supporting facilities such as sprinkler irrigation and micro-irrigation should be carried out in the irrigation area to improve the standardization of field engineering [8]. According to the requirements of crop water demand, a scientific water-saving irrigation system should be formulated to promote water-saving agriculture development actively. This is in order to improve the water-use efficiency of irrigation and achieve the purpose of high-quality development of irrigation agriculture.

The environment seriously deteriorates, the contradiction between the supply and demand of water resources is intensified, and the development of irrigation agriculture is greatly affected [55]. At the same time, the main irrigated food crops in the semi-arid grassland area are rice, wheat, and maize, while the cash crops are soybeans, potatoes, and fruit trees. Therefore, the semi-arid grassland area should adjust the crop planting structure according to the actual water resources situation, reduce the planting area of rice and fruit trees, and increase the planting area of potato crops [46]. While reducing the agricultural irrigation quota, we should implement scientific water resource allocation policies and vigorously promote the development of water-saving irrigation agriculture, such as pipe irrigation and sprinkler irrigation, to improve water resource utilization efficiency [8]. At the same time, ecological restoration projects are being carried out to prevent soil desertification and soil erosion and to return farmland to forests and grasses to improve the primary productivity of the soil and restore the natural ecological environment.

4.4. Hexi Inland River Basin

The multi-year average *IGCI* (0.07) is smallest in the Hexi Inland River Basin, and the irrigation water distribution is unreasonable. Among them, the *IGCI* in 2002, 2003, 2005, 2008, 2011, 2012, 2013, 2019, and 2020 is less than 0. At the same time, the *IGCI* in 2004, 2010, and 2018 is greater than 1, indicating that the irrigation water in this area was relatively abundant in these years and was in a state of excessive irrigation. Due to the small cultivated land area in the Hexi Inland River Basin, the irrigated food crops are mainly spring maize and spring wheat, and the cash crops are sunflower, oilseed rape, and other oilseed crops [56]. A relatively perfect water-saving agricultural system has been established in the Hexi Inland River Basin. According to statistics, the irrigation area of water-saving agriculture accounts for 31% of the actual irrigation area [57,58]. At the same time, soil erosion and nutrient loss in the Hexi Inland River Basin have increased, leading to decreased crop yield and affecting the agricultural economy [56,59]. Therefore, the inland river area on the west of the river should focus on the planning and design of an agricultural irrigation pipeline system, planting vegetation and protective forest in the wasteland and bare land with certain primary productivity. In order to meet the water demand of crops, more water will be used to irrigate protective forests and vegetation through the irrigation network [8]. That will further improve the area's ecological environment and increase the available arable land, thus promoting the development of agriculture.

5. Conclusions

In this study, scientific planning and rational allocation of irrigation water resources were re-conducted according to the research status of agricultural water resources matching in the northwest arid region. By analyzing *IWR*, *EIW*, and *IGCI*, the rational allocation of water resources in the northwest arid region was explored to improve the utilization efficiency of irrigation water resources. *IWR*, *EIW*, and *IGCI* in northwest China from 2001 to 2020 were analyzed and calculated based on the GEE platform, which provided a scientific reference for the optimal allocation of water resources and the improvement of effective irrigation water efficiency in the arid region of northwest China. The main conclusions are as follows.

(1) The southwestern edge of the Yellow River Basin and the eastern part of the Qaidam Basin have sufficient rainfall to meet irrigation requirements. In the northwestern edge of the Yellow River Basin, the central part of the Hexi Inland River Basin, most of the northeastern part of Xinjiang, and the central and southeastern parts of southwestern Xinjiang, irrigation is mainly relied upon to meet agricultural water requirements. The rest of the region relies on a combination of irrigation and rainfall to meet irrigation requirements.
(2) From 2001 to 2020, the average *IWR* and effective irrigation water in the northwest arid area were 379.32 mm and 171.29 mm, respectively. The average annual rainfall and temperature were 280.65 mm and 5.52 °C, respectively. Temperature is more sensitive to *IWR* and water use than rainfall. When temperature increases, plant transpiration and soil evaporation increase, increasing *IWR* and use.
(3) Northwest 'Three Water Lines' areas should be adapted to local conditions, using more sprinkler irrigation, micro-irrigation, tube irrigation, and other water-saving irrigation technology while planning and constructing water-saving irrigation facilities and transformation projects to promote the development of water-saving agriculture further. It is suggested to optimize the agricultural irrigation quota in each district, reduce the planting area of crops with large water consumption, such as rice and fruit trees, and further increase the planting area of crops, such as beans and potatoes. At the same time, considering the characteristic fruit and crop intercropping mode, the rationality of irrigation water distribution should be improved to ensure the sustainable development of irrigation agriculture. Moreover, ecological restoration projects should be carried out to improve soil primary productivity and restore the natural ecological environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15071396/s1, Figure S1: Spatial distribution of *IWR* from 2001 to 2020 in Northwest 'Three Water Lines' area; Figure S2: Spatial distribution of EIW from 2001 to 2020 in Northwest 'Three Water Lines' area; Figure S3: Spatial distribution of *IGCI* from 2001 to 2020 in Northwest 'Three Water Lines' area; Table S1: Irrigation Quota of Main Crops in Northwest Arid Area.

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