
Dan Dai 1, Angelos Alamanos 2,*, Wenqian Cai 3,*, Qingqing Sun 4 and Liangsuo Ren 5

1 Soil, Water, and Ecosystem Sciences Department, University of Florida, Gainesville, FL 32611, USA; dandai@ufl.edu
2 Department of Civil Engineering, University of Thessaly, 38334 Volos, Greece
3 Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, China
4 Institute of Surface-Earth System Science, Tianjin University, Tianjin 300072, China; sunqingqing17@tju.edu.cn
5 School of Geographic Science and Planning, Nanning Normal University, Nanning 530100, China; renhslock@foxmail.com

* Correspondence: alamanos@civ.uth.gr (A.A.); caiwenqian@tcare-mee.cn (W.C.)

Abstract: Northwest China (NWC) is one of the driest areas of the world. Over the past decades, NWC has experienced rapid socio-economic development, further stressing its freshwater quantity and quality. However, there is little knowledge on the long-term status of NWC’s water resources and the anthropogenic impacts—positive (environmental policies) or negative (uncontrolled development). We present a holistic spatiotemporal assessment of NWC’s water quantity, water scarcity, and water quality based on water use intensity (WUI), water scarcity index (WSI), and statistical analyses and tests, combining multiple datasets spanning the past two decades. Moreover, we analyze the impacts of socio-economic development on water resources and mention the relevant governmental efforts and policies to preserve NWC’s water resources. NWC’s water use was found to be unsustainable, having significantly increased by 10% over the past two decades, but without being able to adequately cover the needs of most sectors. Our results also reveal water scarcity inequalities among NWC’s provinces; perennial water scarcity exists in Xinjiang and Ningxia Provinces, and there is no water stress in Qinghai. A remarkable wastewater treatment rate (from 27.3% in 2003 to 97.1% in 2020) and river water quality improvement have been achieved under continuous efforts, huge restoration and water pollution control investments. However, water shortages are a persistent issue. Balancing the water availability and demand will be crucial to achieve a truly sustainable development.

Keywords: water resources; water management; water scarcity; water quality; Northwest China; sustainability

1. Introduction

As one of the driest regions in the world, Northwest China (NWC) is located in the hinterland of the Eurasian continent, an extremely important part of the “Silk Road Economic Belt”. Over the past several decades, NWC’s socio-economic development has taken place at the expense of excessive water consumption, and most environmental damage is caused by water scarcity [1–3]. The general depletion of aquifers and river baseflows has become one of the most serious environmental threats to ecosystem services, food safety and a threat to sustainable water supply [4–7]. At the same time, scarce water resources and intensive water consumption make water pollution control and river water quality improvement very challenging [8,9].

Currently, the increased irrigation, energy production industry and domestic water demands nearly interrupted the natural inland river flow in NWC [10] because this arid
region is a net virtual water exporter [11], not to mention the degradation of susceptible water ecosystems caused by anthropogenic climate change [5,12,13]. The main water consumers in NWC are agriculture and industries (including energy production), being significant and increasing pressures on water safety and ecosystem health [12,14]. Moreover, water pollution issues induce, in turn, water scarcity phenomena. Riverine water quality has been a major issue in the region, for example in the Yellow River Basin, where poor water quality is the main cause hindering the potential to use water [15,16].

Many ecological conservation and restoration projects were initiated by the national and regional governments since 2000 to address water-related problems and to work towards sustainable development in NWC [10,13,17]. Such initiatives include the ecological water conveyance project, artificial forest planting, returning farmland into forest or grassland and the establishment of nature reserves, and other local water-saving and pollution-control measures.

Most papers up to date have focused on some positive impacts of these policies, but at different scales [18,19], while there are studies highlighting NWC’s continuous water shortages and poor water quality [9,11]. Currently, the main research focus has been on food safety, ecosystem restoration problems, challenges, and the associated climate change impacts [10,14,17]. With respect to water sustainability, the literature so far has concentrated on virtual water output, water transfers, and quantitative assessment of water resources [3,11,20]. Little work has been carried out to evaluate water sustainability in NWC from a more holistic perspective, considering both the water quantity and quality status of the region, along with the effects of the ongoing management efforts to water quantity and quality, compared to the development trends of the broader region.

This is the contribution and novelty of the present paper: we explore the water resources sustainability of NWC focusing on its water use, availability, river water quality, and the spatiotemporal evolution of these factors over the past two decades, showing also the respective regional inequalities. This is achieved by the following: (1) investigating the water use trend and spatiotemporal patterns of water-use intensities and water scarcity, based on an 18-year (2003–2020) database of regional water resources, water use and river water quality, and municipal wastewater treatment capacity; and (2) analyzing the regional inequality of water scarcity and how the water management initiatives and restoration efforts introduced by the Chinese government have impacted the water sustainability of NWC. The significance of the results is two-fold: First, they provide a comprehensive data-driven overview of the situation of water challenges and management in NWC. Second, they provide a basis to further analyze the key factors affecting water sustainability and the support of similar studies assessing water sustainability more holistically.

The insights of this study can be useful in the future for exploring the efficiency of water management strategies for other arid and semi-arid areas facing similar problems, especially under the complex human–environmental challenges that we are increasingly facing [21,22]. The broader idea of this paper follows a holistic approach, considering water quantity (hydrologic), water quality, socio-economic, policy and decision-making parameters that can determine the way that water resources are managed [23,24]. This is in line with the concept of integrated water resources management (IWRM), as defined by the Global Water Partnership [25], emphasizing the integration of human–environmental systems to inform decision making in water management [26,27]. Such approaches have been increasingly used for complex water management problems [28–30], especially in arid and semi-arid areas [31], and are now a generally acceptable model of IWRM with strong interdisciplinary characteristics [32,33].

Below we provide a brief description of the study area, we present the necessary background information of the region. Next, we present the tools used in the analysis (data collected, water use intensity, water scarcity and trends estimations), followed by the respective findings in the results section. The results are discussed in the context of the agricultural and industrial water uses and environmental impacts, including scarcity and quality deterioration, as well as the impact of the different policies.
2. Study Area

NWC is located in the hinterland far away from the sea and occupies 31.7% of the national land area, including the provinces of Shaanxi, Gansu, Qinghai, the Ningxia Hui Autonomous Region, and the Xinjiang Uygur Autonomous Region (Figure 1). The region covers 32% of the country’s land area, while its water resources only account for 8% of the national total. Although the northwest is a vast region, its population and economy are 7.3% and 5.6% of the country’s total, respectively (Figure S1). The average annual precipitation is 247.8 mm and the evaporation is higher than 1000 mm, sometimes even reaching 2000 mm due to sustained high temperatures in summer [6,34]. The northwest region is rich in light and heat resources (it has the longest daylight time in China), so it is suitable for the development of agriculture. The diverse geographical and climatic conditions of the area create a highly unequal spatial distribution of water resources, as well as diverse social and economic development conditions.

Figure 1. Location of Northwest China (NWC) with the studied sub-regions.

3. Materials and Methods

3.1. Data Collection

We collected data from various sources to analyze and show the water status of the region and its socio-economic conditions and spatial distribution. Socio-economic data were collected from the National Bureau of Statistics of China [35] and the provincial yearbooks of the region [36]. The data on water use, supply and the description of water resources were obtained from the national [37] and provincial Water Resources Bulletins [38–42] from 2003 to 2020. Demographic (population), economic, and land use data were obtained by the Chinese Geographical Information Monitoring Cloud Platform, for the year 2015 [43].

3.2. Water Use Intensity

The water use intensity index was used for the agricultural and industrial sectors. Agricultural water use intensity (WUI) is defined as water use per unit of growth value added of the agricultural products. Industrial WUI is defined as water use per unit of gross value added (GVA) of industrial products [7]. WUIs were estimated for each region, according to Equations (1) and (2):

$$\text{Agricultural WUI}_{i,t} = \frac{\text{AWU}_{i,t}}{\text{AGVA}_{i,t}} \tag{1}$$
Industrial WUI,\textsubscript{t} = \frac{IWU,\textsubscript{t}}{IGVA,\textsubscript{t}} \quad (2)

where \( AWU,\textsubscript{t} \) and \( IWU,\textsubscript{t} \) are the agricultural and industrial water use of province \( i \) at time \( t \), respectively. \( AGVA,\textsubscript{t} \) and \( IGVA,\textsubscript{t} \) are the agricultural and industrial GVA of province \( i \) at time \( t \), respectively.

3.3. Water Scarcity Estimation

The water scarcity conditions were assessed using the water scarcity index (WSI). The WSI is the ratio of water withdrawals to water availability for humans [44], and it has been widely used in water scarcity assessments [5,45]. The WSI is estimated by Equation (3):

\[ WSI,\textsubscript{t} = \frac{TWW,\textsubscript{t}}{AWR,\textsubscript{t}} \quad (3) \]

where \( TWW,\textsubscript{t} \) is the total water withdrawals of province \( i \) at time \( t \), and it is the sum of water withdrawals (\( WW,\textsubscript{t,n,i} \)) for each sector \( n \) (agriculture, industry, domestic and eco-environmental flows), as expressed in Equation (4) below. The \( AWR,\textsubscript{t} \) is the available water resources of province \( i \) at time \( t \), according to Equation (5):

\[ TWW,\textsubscript{t} = \sum_n WW,\textsubscript{t,n,i} \quad (4) \]

\[ AWR,\textsubscript{t} = \gamma \times WR + OW \quad (5) \]

In Equation (3), OW stands for ‘other water’, including reclaimed water and any transboundary water transfers. The factor \( \gamma \) is the withdrawal ratio of the local water resources (WR). When the withdrawal ratio is greater than 40%, severe water stress and eco-environmental degradation would occur [46,47]. Considering the fragile ecological conditions and scarce precipitation of the region, the critical value of \( \gamma = 40\% \) was selected as the water withdrawal ratio to meet the demand of eco-environment water and the health of the water ecosystem health in NWC. Based on the results of Mekonnen and Hoekstra [4], Veldkamp et al. [44], and He et al. [45], we use \( WSI = 1.0 \) as a threshold value representing extreme water stress to identify the water scarcity areas. The provinces with annual \( WSI > 1.0 \) were identified as ‘perennial water-scarce’ sites; the provinces with annual \( 0.4 \leq WSI \leq 1 \) were considered as ‘moderate water-scarce’ sites with medium water stress conditions; and the provinces with annual \( WSI \leq 0.4 \) were identified as ‘no water stress’ sites.

3.4. Trend Analysis of the Water Use and Its Intensity Conditions

In order to detect and further study the trends and the change points of water use and its intensity in NWC during these 18 years, we applied two commonly used statistical tests [48]: The Mann–Kendall method was applied for trend analysis [49–51], while Pettitt tests were used for the identification of change points of the studied parameters [52,53]. These tests were particularly useful, because the detection of change points and trends can indicate the effect of the policies and measures, considering when they were put in place. All analyses were performed in Matlab R2018b [54].

4. Results and Discussion

4.1. Water Use Trends under Rapid Socio-Economic Growth

Following the national water consumption trends, NWC’s water use increased dramatically between 2003 and 2018 on a regional level (Table S1). However, the water use varied significantly between provinces in NWC. It is encouraging that a decreasing tendency of water use was found in Ningxia (\( p = 0.015 \)), Gansu, and Qinghai (\( p < 0.001 \)), with 2013 and 2011 serving as the abrupt transition (change) points for Gansu and Qinghai, respectively.
Shaanxi’s and Xinjiang’s water use dramatically rose \((p < 0.001)\) during this time period and sudden changes were observed in 2011 \((p = 0.003)\), lagging somewhat behind the nation’s water use during this time period (Figure 2a).

Based on our results, it is clear that from 2003 to 2020, NWC’s average agricultural water use ratio \((86.5\%)\) was significantly higher than the national average and other water uses (agricultural: \(62.7\%\), industrial: \(22.2\%\), and domestic: \(12.8\%\)); while the industrial and domestic water use ratios \((5.3\% \text{ and } 5.6\%, \text{ respectively})\) were lower (Figure 2a). These results are in line with similar research on China’s water uses \([55,56]\). It appears that irrigation is the major consumer in the region, and the results quantified the share of irrigation water use compared to the other sectors/users. The high irrigation water use, combined with the low precipitation (dryland irrigation), creates increased soil salinity conditions that reduce crop production \([57]\). This phenomenon has been observed in the Yellow River Basin in China \([15]\). Although there was no discernible trend for water usage in agriculture, industry, or the environment, a rising trend was observed for domestic water consumption (Table S2), indicating that significant efforts must be put into water conservation to sustain water resources. Additionally, surface water extraction provides the majority of NWC’s water supply (Figure 2b), such as the Yellow River water in Ningxia and the glacial melt water runoff in Xinjiang. Overexploitation of this runoff in Xinjiang may lead to a decrease in river ecological flow and oasis degradation, thus creating conflicts among competing water users \([58]\). In order to satisfy the goals for protecting the sensitive ecological environment and achieve water savings to support a sustainable development, broader water management among all sectors in NWC must be upgraded and reformatted.
4.2. Spatiotemporal Characteristics of Water Use Intensity

4.2.1. Agricultural Water Use Intensity

Considering that the amount of agricultural and industrial water use did not have significant trends (Table S2), we quantified the water use intensity (WUI) to qualify the agricultural and industrial water use, which partly offset the growth due to socio-economic development, i.e., population and economic growth [7].

Our results indicated that agricultural WUI decelerated 4.65-fold over the period 2003 to 2020 in NWC (Figure S2a). The expansion of advanced irrigation technologies was the main driver of the widespread decrease in agricultural WUI [7,59] (which was found significantly negative within the water-saving irrigated area (Figure S2b)). The stable (not increased) agricultural water use (Table S2) also indicates that the relevant measures such as the improvement in irrigation efficiency have contributed to agricultural water-saving. It is worth noting that during 2003–2011 (period P1), the primary industrial gross value added (GVA) was positively correlated with agricultural water use while during 2012–2020 (period P2), the primary industrial GVA was negatively correlated with agricultural water use (Figure S2c). This indicates that, at first, agriculture was developing at the expense of the environment (in terms of water overconsumption), and, gradually, after a series of water-saving measures, the agricultural sector became more water-use efficient.

Spatially (Figure 3), the agricultural WUI in P1 and P2 was extremely high for Xinjiang (P1: 8099.56 m³ per 10⁴ Yuan GVA year⁻¹, P2: 3541.52 m³ per 10⁴ Yuan GVA year⁻¹) and Ningxia (P1: 7242.61 m³ per 10⁴ Yuan GVA year⁻¹, P2: 2824.87 m³ per 10⁴ Yuan GVA year⁻¹), and the lowest in Shaanxi (P1: 1016.61 m³ per 10⁴ Yuan GVA year⁻¹, P2: 342.14 m³ per 10⁴ Yuan GVA year⁻¹). This is mainly due to extreme drought conditions in Xinjiang and Ningxia, while Shaanxi has the highest precipitation among the five provinces, so agriculture is less dependent on irrigation (Figure S3).

![Figure 3](image-url)

Figure 3. (a) Temporal and (b,c) Spatial pattern of the annual average agricultural WUI in the periods 2003–2011 (P1) (b), and 2012–2020 (P2) (c). The units of agricultural WUI are m³ per 10⁴ Yuan gross value added (GVA). The units of agricultural WUI are m³ per 10⁴ Yuan GVA. The year marked in the figure and the solid dots are the abrupt change point calculated by the Pettitt test, and the p values are the results of the Mann–Kendall test.
4.2.2. Industrial Water Use Intensity

Industrial WUI mainly depends on the industrial structure and cleaner production technologies. The results indicated that the industrial WUI decelerated 8.24-fold over the period 2003 to 2020 in NWC (Figure S4a). This is largely due to the expansion of more advanced water reuse technologies [7,11], as the industrial WUI had a significantly negative relation with the recycled industrial water use (Figure S4b). However, during 2003–2012 (period P1) and 2013–2020 (period P2), the industrial GVA has no significant correlation with industrial water use (Figure S4c). This means that the high water-consumption industries did not bring a particularly high industrial GVA in NWC. Thus, the region should focus on developing low- or non-water-consumption enterprises and industrial practices, according to its regional water resources capacity.

The industrial WUI in P1 and P2 was extremely high for Qinghai (P1: 293.50 m³ per 10⁴ Yuan GVA year⁻¹, P2: 165.88 m³ per 10⁴ Yuan GVA year⁻¹) and Gansu (P1: 166.50 m³ per 10⁴ Yuan GVA year⁻¹, P2: 47.69 m³ per 10⁴ Yuan GVA year⁻¹) and lowest in Shaanxi (P1: 57.46 m³ per 10⁴ Yuan GVA year⁻¹, P2: 17.22 m³ per 10⁴ Yuan GVA year⁻¹) (Figure 4). This is mainly attributed to Qinghai’s rich water resources, while Gansu, Ningxia and Xinjiang are energy production hotspots. Energy production requires considerable amounts of water for the operation of the facilities’ cooling. The arid north and northwest parts consumed more water for energy production than the south part of the region, and this contributed to their severe water scarcity, inducing multiple environmental damages [1,60]. In order to avoid regional water shortages, it is critical to monitor industrial water use, especially for the highly water-intense industries (such as energy production), always considering the local water availability and the associated environmental impacts.

![Industrial WUI trends](image)

Figure 4. (a) Temporal and (b,c) Spatial pattern of industrial water use trends in the periods 2003–2012 (P1) (b), and 2013–2020 (P2) (c). The units are the same as in Figure 3.

4.3. Regional Water Scarcity

In contrast with the water use trend, the WSI varied considerably by province (Figure 5). Severe water scarcity was observed over the studied period. The highest WSI above 1.0 was found in Xinjiang, Ningxia, and Gansu, indicating the water crises and eco-environment degradation of those provinces. Shaanxi was an exception, with moderate water stress found, as well as Qinghai with almost non-existent water scarcity (of a significant decreasing WSI (p = 0.003)). It is worth noting that although NWC has 8.4% of China’s water resources...
(annual average), its annual average water use ratio is up to 14.4% of the country’s total (Figures 5 and 6).

![Figure 5](image1.png)

**Figure 5.** Water scarcity index (WSI) for NWC’s provinces and Mann-Kendall test results for the past 18 years. The dashed gray line is the threshold of WSI = 0.4, and the solid gray line is the threshold of WSI = 1.0.

![Figure 6](image2.png)

**Figure 6.** Local water resources availability and use for NWC’s provinces. The dashed gray line is the absolute water scarcity threshold of the per capita local water resources of 500 m$^3$ and the solid gray line is the per capita local water resources of 1700 m$^3$ per year.
According to Fan et al. [16], there is no vulnerability in water scarcity if the local water resources reach above 1700 m$^3$ per capita, and absolute water scarcity occurs if the threshold of local water resources is below 500 m$^3$ per capita. So, Ningxia is under absolute water scarcity, followed by Gansu and Shaanxi. Qinghai was found to have no water crisis, according to the WSI results. Although Xinjiang’s per capita local water resources availability is above 1700 m$^3$, it still faces a water crisis due to the overuse of water for agriculture (Figure 2a).

4.4. Efforts towards Water Conservation

As one of the world’s most “thirsty” areas, NWC has been facing situations where scarce water resources are inadequate to meet the basic needs of most sectors, struggling with food safety, causing insufficient ecological baseflow of rivers and hindering the efforts for better living standards [60–65]. To address the water crisis and support a hydro-ecological restoration, the Chinese State Council, the National Development and Reform Commission, and the Chinese Ministry of Water Resources have issued about 40 major laws, plans, and guidelines targeting water saving and conservation, since 2002 (Table S3). These policies are mainly concentrated on water use quantity, water use efficiency and water resources allocation for all provinces in NWC (e.g., determined water-use quotas for different industries in each province, regional water resources allocation quotas, water rights trading and irrigation water-saving subsidies). Under these measures, the total water use (Table S1), and the agricultural, and industrial WUI in NWC have shown a significant decrease (Figures 3 and 4). However, WSI remains high, especially for the Xinjiang and Ningxia provinces, mainly because of the irrigated agriculture (Figure 2a). Furthermore, it seems that the increased household water use following the economic development (Figure S2), causes water shortages in NWC. This is arguably the main challenge for regional water management and water sustainability.

4.5. Efforts towards Water Quality Improvement

4.5.1. Controlling Main Pollutants and Increasing Wastewater Treatment Capacity

In addition to efforts to deal with water shortages, there have also been many measures in place to improve water pollution in NWC. The Chinese national government has invested almost 27.49 billion CNY and 20.23 billion CNY in controls of domestic and industrial wastewater discharges from 2003 to 2017 (Figure S4). These efforts are reflected in the rapid increase in wastewater treatment (WWT) capacity (Figure 7a) and treatment rate in urban regions (Figure 7b) [66]. Before 2011, the annual WWT capacity in urban regions could not meet the demand for wastewater discharge with an annual average treatment rate of 44.7%. Since 2018, the municipal WWT expansion rate in NWC has exceeded the national average (Figure 7b). In 2020, the annual WWT capacity in NWC’s urban regions reached up to 3.90 billion m$^3$, with a treatment rate of 97.1% (Figure 7b). The WWT capacity is still greater than the wastewater discharge input it can receive.

To further demonstrate the significant results of the investment in WWT in NWC, we analyzed the discharge of the two main pollution indicators for river waters in China [67,68]: the chemical oxygen demand (COD) and the ammonia nitrogen (NH$_4$), from 2003 to 2020. Although these two measurements alone do not serve as a comprehensive evaluation of the efficiency of policies established for water quality improvement, they can provide the broader picture of the evolution of water quality status since they have been traditionally the major threats for river waters [67,68]. Figure 8 shows that the major pollution discharge from wastewater in NWC presents a trend similar to an Environmental Kuznets Curve [69]. That is, the pollutants first increased and then significantly declined.
Figure 7. The wastewater treatment (WWT) capacity: (a) its treatment rate; (b) the volume of wastewater during the period 2003–2020.

Figure 8. The COD (a) and NH₄ loadings (b) (in 10³ tons) from wastewater discharge in NWC during the period 2003–2020.

Before 2011, the pollutant discharge increased, and after 2015, it decreased significantly. COD and NH₄ loadings from wastewater declined during the period from 2003 to 2020, especially after 2015. Similar trends have also been observed at the national level, supporting our findings [70,71]. This is mainly attributed as a positive outcome of the implementation of the Chinese Action Plan for Water Pollution Control that was put in place in 2015 [72] (Table S4). Compared with the household wastewater pollution discharge, COD loadings from industrial wastewater went from 367.81 thousand tons in 2003 to 29.69 thousand tons in 2020, while NH₄ went from 27.5 thousand tons in 2003 to 1.37 thousand tons in 2020, both...
decreased by 11.39- and 19.07-fold, respectively, indicating that cleaner production technology in NWC has achieved much success. It is worth noting that the slower decline trend in domestic pollution loadings is mainly due to NWC’s continuously increased urbanization.

4.5.2. Water Quality of Rivers

The quality standards for surface water in China are divided into five grades [73]. The highest grades I and II denote very good and good water quality, respectively, suitable for national nature reserve areas and as drinking water sources. Grade III poses no risk to aquatic life or human health, and is usually recommended as the target for current regional water quality management [74]. Grade IV reflects poor quality, where water is useable for general industrial water applications, but is harmful to human health when there is direct contact. Grade V is very poor and the river water can only be used for landscaping, while a grade worse than V means that it cannot be used at all.

Due to the considerable progress in the WWT capacity, remarkable river water quality improvement has occurred in NWC from 2003 to 2020. Overall, the annual percentage of river water quality at grades I + II + III increased notably by 0.6% per year (Figure 9). In 2020, rivers with water quality better than grade VI accounted for 94.9% of the total evaluation river length, and worse than grade VI only accounted for 3.5% (Figure 9a). The improvement of surface water quality at the national level [18,75] also indicates the positive outcomes of the pollution control measures in NWC. The focus on such measures is important, as the NWC is the less developed region of China. In addition, the positive correlation between the investments in wastewater control and the percentage of river water quality at grades I + II + III, as well as the negative correlation between the percentage of river water quality at grades VI + V and worse than V both indicate that WWT capacity expansion efforts have led to significant improvements in river water quality in NWC (Figure 9b,c). These findings provide further evidence of the effectiveness of the water environmental investments in reducing water pollution in NWC.

![Figure 9](image-url)  
*Figure 9. The evaluation results of river water quality according to the evaluation river length of NWC (a) and the quantitative relationships between the investment in control of wastewater and corresponding river water quality (b): at grades I + II + III; and (c) at grades VI + V and worse than V during 2003–2020.*
5. Concluding Remarks

This study revealed the spatiotemporal pattern of water sustainability considering the water quantity and quality status and challenges in NWC, as they have evolved, based on 18-year (2003–2020) datasets. Unavoidably, all studies reporting the situation in large-scale areas based on multiple datasets are accompanied by the uncertainties included in the input data. Such uncertainties may refer to the water demand reported for each crop type and industrial use, and the hydrological information (e.g., evapotranspiration) of the inland river basins. We assume, however, that the data used in this paper are based on accurate official reports and databases. In any case, and despite any limitations, the purpose of such assessments is highly valuable; to our knowledge, this is the first study thoroughly assessing both water quantity and quality in NWC, putting them in a broader frame considering the socio-economic development across different sectors and resources sustainability. Another limitation of this paper is that although we presented the water management efforts to improve the situation in NWC (e.g., the policies of Table S3), it was not feasible to provide a detailed analysis regarding their objectives, specific regions of implementation, institutional framework, and a thorough evaluation of the results they caused in a finer spatial resolution. Although this is currently beyond the scope of this paper, it can certainly be the next step for future research in the region. The results revealed that although total water use in NWC has significantly increased as a result of the region’s expansion, water use efficiency has improved. Agricultural and industrial water-use intensities have decreased over the studied period due to stringent water saving and conservation policies. However, there is still significant water scarcity, especially in Xinjiang, Ningxia, and Gansu, and there are inequalities in water availability for use among provinces. The recent decreases in water use and major water pollutants loadings and the improvement in river water quality reflect the efforts that have been put in place in NWC. Compared to water quality, water shortages due to high WSI are clearly the most severe issue in NWC.

Overall, the large number of water-saving measures and efforts have not played a significant role in the broader sustainability of the area: Although water use has declined and water quality indicated some improvements, the use of water resources of adequate quantity and of sufficient quality for all sectors’ use falls short in serving and supporting a degree of socio-economic development. The results of this study reveal that NWC’s water scarcity and quality issues have not been alleviated.

To solve the water problem in NWC, it is crucial to tackle the shortage of water quantity. NWC still needs more, more diverse and flexible regional water management strategies to cope with its water shortage. Both water storage (supply) and demand management should be enhanced. Such measures can include the consideration of alternative crops, less water-demanding crops, investments in the water distribution and transport networks, and the application of many efficient irrigation methods to reduce losses [76], combined with adequate investments in water storage works (e.g., local reservoirs) to increase the water availability in critical (dry) time periods [58]. Optimal water allocation among different water uses, and other sector-specific best management practices (BMPs) should also be applied, following similar successful examples from other regions of the world [18,77,78]. The creation and enhancement of farm water rights, water market-based strategies, and water demand-side management capacity building from local governments must also be considered, in a local-scale that will allow the optimal balance and trade-off between the agricultural and industrial sectors, particularly in the Xinjiang and Ningxia Provinces, to achieve sustainable and equitable growth. In any case, all water quantity management efforts should be accompanied by nonpoint source pollution measures (given that the point source pollutants have been controlled in principle), and measures to further restore the rivers’ water quality.

This study provides useful insights combining different datasets for the holistic assessment of large-scale areas experiencing human–environmental changes in varying paces and degrees. Centralized management approaches should take into account such differences
in the environmental capacity of large areas (in our case, their water availability, demand and quality), along with the human (socio-economic and technological) development. Furthermore, the core idea of the implementation of any water management measures should be broader sustainable development considering the coverage of the future water needs without undermining the current uses.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su151411017/s1: This paper is accompanied by a ‘Supplementary Material’ file, that includes: Figure S1. Spatial patterns of Population (a), GDP (b), and land use type (c) in 2015 and the temporal socio-economic development (d) in Northwest China. Figure S2. Trends of the agricultural WUI in Northwest China (a) and its relationship between water saving irrigated area (b), and the corresponding regional primary industry GVA and the agricultural water use (c). Figure S3. The annual precipitation in Northwest China during the period of 2003 to 2020. Figure S4. Trends of the industrial WUI in Northwest China (a) and its relationship between recycled industrial water use (b), and the corresponding regional industrial GVA and the industrial water use (c). Figure S5. The national investment (100 million CNY) in facilities for domestic and industrial wastewater treatment in Northwest China. Table S1. Mann-Kendall trend and Pettitt test results of the total water use in Northwest China. Table S2. Mann-Kendall trend and Pettitt test results of the water use in different departments of Northwest China Table S3. Timeline of key policy interventions of China’s water-related laws and regulations and comprehensive plans for water saving and conservation since 2002 (Table S3 is supplemented based on the work of Zhou et al. (2020) [7]. Table S4. Recent laws, plans, guidelines, and regulations related to improving China’s water quality (Table S4 is supplemented based on the work of Huang et al. (2019) [18] and Tong et al. (2017) [66].

Author Contributions: Conceptualization, D.D., W.C., Q.S. and L.R.; methodology, D.D., A.A. and L.R.; writing—original draft preparation, D.D., A.A. and W.C.; writing—review and editing, D.D., A.A., W.C., Q.S. and L.R. All authors have read and agreed to the published version of the manuscript.

Funding: D.D. was supported by the National Natural Science Foundation of China (grant number 42207548).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used in this paper are cited in the main text and Supplementary Materials, and can be accessed from the respective citations.

Conflicts of Interest: The authors declare no conflict of interest.

References


30. Garcia, J.A.; Alamanos, A. Integrated Modelling Approaches for Sustainable Agri-Economic Growth and Environmental Improvement: Examples from Greece, Canada and Ireland. *Land* 2022, 11, 1548. [CrossRef]


46. Xia, J.; Qiu, B.; Li, Y. Water Resources Vulnerability and Adaptive Management in the Huang, Huai and Hai River Basins of China. Water Int. 2012, 37, 523–536. [CrossRef]
52. Fu, J.; Kang, S.; Zhang, L.; Li, X.; Gentine, P.; Niu, J. Amplified Warming Induced by Large-Scale Application of Water-Saving Techniques. Environ. Res. Lett. 2022, 17, 034018. [CrossRef]


70. Tang, W.; Pei, Y.; Zheng, H.; Zhao, Y.; Shu, L.; Zhang, H. Twenty Years of China’s Water Pollution Control: Experiences and Challenges. Chemosphere 2022, 295, 133875. [CrossRef]


72. Han, D.; Currell, M.J.; Cao, G. Deep Challenges for China’s War on Water Pollution. Environ. Pollut. 2016, 218, 1222–1233. [CrossRef]


Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.