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Assessing the Impacts of Water Diversion Project on Water Resource System Sustainability

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Keywords: reliability | resilience | sustainability assessment | vulnerability | water diversion project

ABSTRACT

Interbasin water diversion project has been considered as an effective way to assure water resource system sustainability. In order to assess the impacts of water diversion on sustainability, we propose a framework in terms of reliability, resilience, and vulnerability. The estimated water availability from hydrological models and the projected water demand are input to a water resource allocation model. The water resource allocation model allocates the two available water sources (i.e., the local and the diverted water) in the water-receiving areas. The differences of the allocated water resources between these two water sources are figured out to quantify the impacts of water diversion on water resource system sustainability. The water-receiving area of Bailong River Water Diversion Project, located in Gansu, China, was selected as a case study. The results show that compared to the reference planning years, the runoff in future planning years will be reduced, while their water demands will almost increase under all scenarios. Although the current designed water diversion scheme is effective in increasing resilience, there is still potential for increasing resilience through optimizing the designed scheme. Further, the more unfavorable the water supply and demand conditions are, the larger the space for optimizing the system sustainability. This study can help understand the impacts of water diversion on water resource system sustainability in a changing environment.

1 | Introduction

The sustainability of regional water resources is of great significance for ensuring socioeconomic development and ecological environment protection (Meng et al. 2022; Rosely and Voulvoulis 2024). However, as climate change alters the hydrological cycle, the hydrological series have been found to become nonstationary, posing challenges to the sustainable planning and management of water resource systems (Milly et al. 2008; Borgomeo et al. 2014). Several studies have found that the spatiotemporal distribution of water resources will become more uneven in the future, thereby increasing the risk of water shortage (Chen et al. 2017; Yin et al. 2018, 2021). Thus, the variation of available water resources caused by climate change hinders the sustainability of water resource systems. Furthermore, with the rapid development of industry and agriculture, the demand for water will increase, and the supply–demand contradiction of water resources will become more prominent in the future (Rockstroem et al. 2009). The sustainability of water resource systems in supporting regional socioeconomic development has been challenged.

The interbasin water diversion project is an effective way to improve the sustainability of water resource systems (Liu

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Summary

- Greater water resource system sustainability can be improved in the areas with more unfavorable conditions for water supply due to the impacts of the Bailong River Water Diversion Project.

et al. 2015; Wang, Liu, and Sun 2022; Wu, Su, and Zhang 2023). For example, the South-to-North Water Diversion Project diverts water from the Yangtze River to the northern regions of China. This project significantly alleviates water resource pressures and promotes sustainable social and economic development in water-receiving areas (Liu, Yu, and Kendy 2001). In addition, the California State Water Project, a major water infrastructure project in the state of California, USA, plays a pivotal role in ensuring water resource sustainability and in providing critical support in addressing the challenges posed by climate change and population growth (Diffenbaugh, Swain, and Touma 2015). The impact of water diversion project on a water resource system is a hot topic in the field of water resources research. Veena et al. (2021) found that inappropriate management frameworks during the project design phase could have adverse effects on the entire system. Water diversion can cause ecological and environmental problems in the donor area, such as river disconnection (Grant et al. 2012) and salinization problems (Zhuang 2016). Ming et al. (2017) found that water diversion could increase water and energy demands, resulting in unsustainable population growth and urban expansion. However, there is a lack of research on the impact of water diversion on water resource system sustainability although water diversion has raised concerns about the sustainability, especially in a changing environment. Assessing the impacts of the water diversion project on water resource system sustainability are also essential for decision-makers to develop adaptive water diversion plans to improve water resource system sustainability in a changing environment (Bormann, Ahlhorn, and Klenke 2012; Yang et al. 2024).

The important prerequisite for assessing the sustainability of water resource systems is to develop a sustainability indicator. Existing studies have proposed various sustainability indicators that incorporate a wide range of variables and metrics to assess the various aspects of sustainability (Attari, Mojahedi, and Sarraf 2014; Srdjevic and Srdjevic 2017; Odjegba et al. 2020; Mvongo, Defo, and Tchoffo 2023). Morris (2019) discussed the development of a sustainability indicator to measure the efficiency and effectiveness of water resource utilization in supporting social sustainable development. Da Silva et al. (2020) compiled the scientific and technical literature to form a list of indicators that reflected various aspects for water sustainability assessment and then proposed a river basin water sustainability indicator. Kumar, Kumar, and Gupta (2022) proposed a sustainability indicator based on Artificial Neural Networks (ANNs) and globally accepted parameters and applied it to a rural water management system for curbing water shortage risk. Although these indicators provide comprehensive descriptions of sustainability, most indicators consist of 10–20 variables, and some indicators even combine more than 60 variables, hindering the application of indicators (Jarzebski et al. 2024). The more variables there are, the more comprehensive the sustainability assessment provided, but they are at the cost of reducing data accessibility and implementation feasibility. Although some indicators (e.g., agricultural water poverty index (Forouzani and Karami 2011) and crop water stress index (Khan et al. 2022)) are outstanding in their applications, they are restricted in their specific domains and thus not suitable for assessing the sustainability of the water resource system across different water use areas.

One of the key issues for sustainable water resource management is to make the performance of water resource systems acceptable under a wide range of possible future demands and hydrological conditions. To achieve sustainability, Hashimoto, Stedinger, and Loucks (1982) proposed reliability, resilience, and vulnerability (RRV) indicators for assessing the different aspects of a water resource system performance. Specifically, the RRV indicators attempt to assess the likelihood of a system performing acceptably, the rate of its performance recovering from an unacceptable state, and the expected consequences of being in an unacceptable state (Hashimoto, Stedinger, and Loucks 1982). These three performance indicators are some aspects of the concept of sustainability and can be used to measure the sustainability (Kay 2000; Zou et al. 2020). In the earliest 1997, Loucks (1997) expressed sustainability as the product of RRV. Further, the sustainability indicator based on RRV has been widely applied in water resource system assessment (Kay 2000; Kjeldsen and Rosbjerg 2001; Hammad and Chung 2024). Different from the other sustainability evaluation systems where there are often more than 10 indicators, the sustainability indicated by RRV only requires the resistance sequences of the system rather than more index and their weights. It is easy to apply and understand by decision-makers and stakeholders. Furthermore, as the sustainability indicated by RRV focuses on the system failure, the application of its indicators can be flexibly extended to various domains, such as the water supply system (Asefa et al. 2014), natural river system (Hammad and Chung 2024), and water–energy–food–society nexus system (Zeng et al. 2024). Therefore, the sustainability embraces different aspects of water resource systems and can be assessed across different domains. This assessment can help understand the system performance in a changing environment and then analyze various scenarios that incorporate strategies and measures (e.g., water diversion) to adapt to the changing environment (Asefa et al. 2014; Zeng et al. 2024).

This study aims to propose a framework to assess the impacts of water diversion on water resource system sustainability based on RRV. A water resources allocation model is developed to allocate the local available water and the diverted water to the water users in receiving areas. The sustainability of water resource systems is reflected by RRV. Taking a typical water diversion project in China as an example, we will demonstrate how this framework can help understand the effectiveness of RRV in assessing sustainability, as well as the role of water diversion in water resource system sustainability for current and future planning years. The remainder of this paper is organized as follows: Section 2 presents the details of the proposed framework. Section 3 introduces the characteristics of the case study area. Section 4 illustrates the results and discussions of the numerical modeling based on the framework. Section 5 summarizes the main contributions of this study.

2 | Methodology

In order to quantify the RRV, water availability and water demand should be estimated or projected first. Then, a water resource allocation model will be developed to figure out the performances of water resource systems in terms of RRV and the impacts of water diversion on water resource system sustainability (as shown in Figure 1).

2.1 | Water Availability Estimation Module

The available water resource depends on climate, as climate determines the precipitation patterns which directly dominate available water. Warming climate can increase the evaporation from soil and water bodies, which reduces the amount of available water. Global Climate Models (GCMs) have been taken as a useful modeling tool to simulate and project historical and future climate conditions under various shared socioeconomic pathways (Abramowitz and Bishop 2014; Ebtehaj and Bonakdari 2023). As GCM outputs are too coarse to conduct climate change impact assessment at the regional scale, bias correction is used to improve the applicability of GCM for regional water resource systems. The Daily Translation (DT) method has been used worldwide. The DT method assumes that there are equal biases across quantiles between future and historical climate variables, and then it reduces the biases (Mpelasoka and Chiew 2009). The corrected climate variables from the DT method are input into a hydrological model, the Community Water Model (CWatM), to estimate water availability. The CWatM can simulate the hydrological processes of the nature–society system for estimating the natural runoff that is not affected by human activities. The CWatM estimates the water balance for different types of land use and then summarizes the flux and storage at the grid scale according to the percentage of each land use type, following a bottom-up paradigm (Burek et al. 2020). The CWatM has been used for regional water resource assessment and management under the impacts of human activities and climate change (Kushwaha et al. 2021; Guillaumot et al. 2022; Cheng et al. 2024); it will be deployed here for estimating the available water resource.

2.2 | Water Demand Projection Module

Socioeconomic water demand is impacted by various factors such as population growth, economic development, technological changes, and policy shifts. There have been many methods to project water demand including the trend analysis, quota method, scenario analysis, integrated resource planning, and so on. In-stream ecological water is for maintaining the ecological environment in stream, such as supporting the survival of aquatic wildlife. The methods for estimating in-stream ecological water demand generally refer to hydrological methods, water quality model, biological model, holistic methods, historical simulation methods, and so on. Due to the flexibility of the Tennant method (Tennant 1976), it can be used here for projecting the in-stream ecological water demand as Equation (1):

$$WD\_E_i^m = R_i^m \times \varepsilon \tag{1}$$

where $WD\_E_i^m$ is the in-stream ecological water demand in the i-th operational zone at the m-th month (m^3/s); R_i^m is the average annual runoff (m^3/s); ε is the proportion coefficient of minimum ecological in-stream water demand.

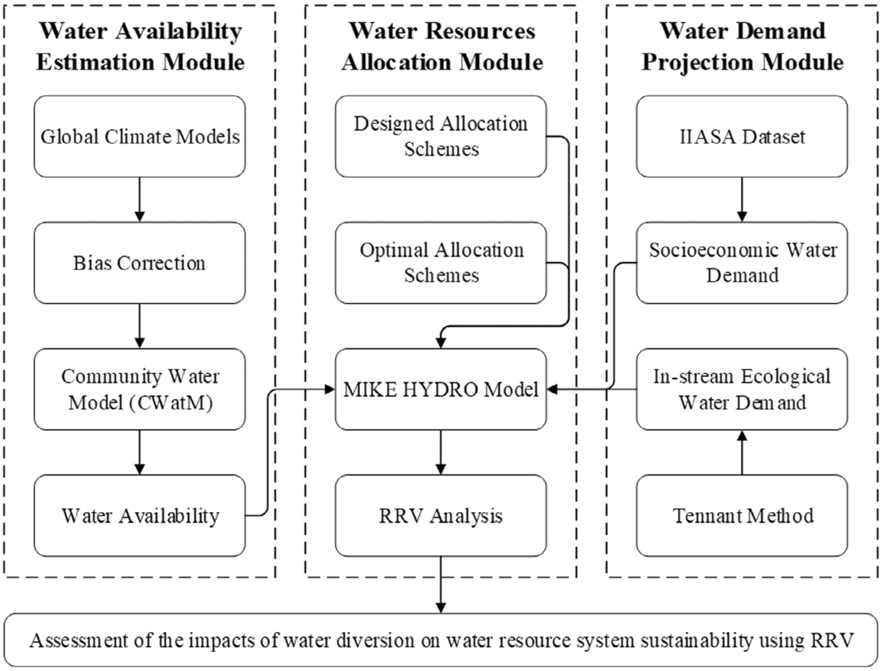

FIGURE 1 | Proposed framework for assessing the impacts of water diversion on water resource system sustainability using RRV.

2.3 | Water Resources Allocation Module

According to the amount of available water resource from the water availability estimation module and the amount of water demand from the water demand projection module, the water resources should be allocated to each water use sector to meet their water demand through predefined rules. Owing to the versatility and flexibility of MIKE HYDRO Basin developed by DHI (2017), it has been widely used in water resource planning and management (Ireson, Makropoulos, and Maksimovic 2006; Jaiswal, Lohani, and Galkate 2021; Tra et al. 2023). Thus, MIKE HYDRO Basin is selected as an effective water resource allocation module and can be used to assess the impacts of water diversion on water resource system sustainability.

To allocate water resources, MIKE HYDRO Basin constructs a basin system diagram with rivers as the branches, water user sectors, engineering, and diversion/convergence points as the nodes, and then implements system-dynamic simulations based on the attributes of the above elements. The model can automatically track and generate rivers based on the Digital Elevation Model (DEM) through spatial analysis, thereby establishing a river network. Further, catchments can be then divided based on the locations of the user-defined catchment outlet points in the river network. The natural runoff data simulated by the CWatM is input into the divided catchments to generate the spatiotemporal distribution of natural water resources. Water resources from water diversion projects are input into MIKE HYDRO Basin by adding confluence points and channels to the river network. The water use sectors are generalized as nodes, and each node establishes hydraulic connections with the river network through a water intake and return branch. Each water user node corresponds to a water demand that can be obtained from the water demand projection module. The cumulative water shortage ratio in a water user node is expressed as follows:

$$D'(t+1) = D(t+1) + f(t) \times \mathrm{WS}(t) \tag{2}$$

where $D'(t+1)$ is the effective water demand at time $t+1$ (m^3/s); $D(t+1)$ is the water demand at time $t+1$ (m^3/s); WS (t) is the water shortage at time t (m^3/s); $f(t)$ is the cumulative proportion at time t; When $f=0$, the conventional solution of the model is obtained, while $f=1$ represents a "perfect memory" for water shortage.

To improve the efficiency of diverted water, an optimal allocation scheme is developed by setting objective function, constraints, and optimal algorithm (Liu et al. 2018; Zou et al. 2020). The genetic algorithm (GA) is a search-based optimization technique and has been widely used for single objective optimization problems in water resource systems (Holland 1992; Jahandideh-Tehrani, Bozorg-Haddad, and Loaiciga 2019). The GA is employed to help optimally allocate water to the ith operational zone in the tth month (represented by x_i^t). The optimal allocation scheme can be expressed as Equations (3–5):

$$F = \max Sus \tag{3}$$

Subject to:

$$x_i^t \le D_i^t \tag{4}$$

$$0 \le \sum_{t=1}^{T} \sum_{i=1}^{n} x_i^t \le \mathrm{TDW} \tag{5}$$

where F is objective function; *Sus* is sustainability indicators, and the details of determining *Sus* can be found in Section 2.4; D_i^t is the water demand of the ith operational zone in the tth month (m^3/s); TDW is the total amount of diverted water (m^3/s).

2.4 | Sustainability Indicators Using RRV

The water resource system sustainability is measured by RRV indicators. The driving factor for system failure refers to the load (λ), while the system's ability to avoid failure refers to the resistance (ρ). As for a water resource system, water demand represents λ, while water availability represents ρ. If $\lambda > \rho$, the water resource system is at a state of water shortage (i.e., failed state), F; otherwise, the water resource system is at a normal state, S. The reliability of the water resource system (*Rel*) refers to the probability of the system being in a normal state and can be represented by Equation (6):

$$Rel = P(\lambda \le \rho) = P\left(X_t \in S\right) \tag{6}$$

where X_t is the state variable of the water resource system at time t. Using the series of water availability and water demand, Equation (6) is quantified as Equation (7):

$$Rel = \frac{1}{T} \sum_{t=1}^{T} I_t \tag{7}$$

where T is the number of time steps; $I_t = 1$ if $X_t \in S$, otherwise, $I_t = 0$ if $X_t \in F$.

The resilience of the water resource system (*Res*) refers to the probability of the system transmitting from a failed state to a normal state and can be represented by Equation (8):

$$Res = P\left(X_t \in S \mid X_{t-1} \in F\right) \tag{8}$$

According to the total probability formula, *Res* is rewritten as Equation (9):

$$Res = \frac{P\left(X_t \in S, X_{t-1} \in F\right)}{P\left(X_{t-1} \in F\right)} \tag{9}$$

Using the series of water availability and water demand, *Res* can also be further quantified as Equation (10):

$$Res = \frac{\sum_{t=1}^{T} Y_t / T}{\sum_{t=1}^{T} \left(1 - I_t\right) / T} = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} \left(1 - I_t\right)} \tag{10}$$

$$\begin{cases} Y_t = 1, \text{if } X_{t-1} \in F \text{ and } X_t \in S \\ Y_t = 0, \text{otherwise} \end{cases} \tag{11}$$

If $\sum_{t=1}^{T} Y_t = 0$, the water resource system will remain in a failed state after a failed event, and $Res = 0$. If $\sum_{t=1}^{T} Y_t = \sum_{t=1}^{T} (1 - I_t)$, the water resource system will definitely become a normal state in the next time step after a failed event, and $Res = 1$.

The vulnerability of the water resource system (Vul) describes the expected severity of system failure and can be represented by Equation (12):

$$Vul = E(S) = \sum_{i=1}^{\mathrm{NF}} P_i \times S_i \tag{12}$$

where P_i and S_i are the probability and severity of the i-th failed event, respectively; NF is the number of failed events. S can be represented by the water shortage rate (WSR) for a water resource system. Assuming that the probabilities of every failed event are equal, Vul can be further represented by Equation (13):

$$Vul = \frac{1}{\mathrm{NF}} \sum_{i=1}^{\mathrm{NF}} \mathrm{WSR}_i \tag{13}$$

The sustainability indicator (Sus) is the cubic root of the product of Rel, Res, and (1–Vul) and represented by Equation (14). Its value ranges from 0 to 1. The larger the value of Vul, the more likely the water resource system at a normal state is and the more likely the water resource system recovers after a failure, while the less severe the failure is, more sustainable the water resource system is:

$$Sus = \sqrt[3]{Rel \times Res \times (1 - Vul)} \tag{14}$$

3 | Case Study

3.1 | Study Area

The sustainability of the water resource in Gansu Province is facing serious challenges due to the influence of climate and terrain conditions, as shown in Figure 2. For example, the water consumption per capita in Pingliang and Qingyang cities is 142 and 132 m^3/person, respectively, accounting for only 32.1% and 29.9% of the provincial average (442 m^3/person), as well as 10.3% and 9.5% of the world average (1385 m^3/person) in 2021 (Koncagül, Tran, and Connor 2021). The water shortage in Pingliang City will reach around 300 million m^3 by 2030 according to the projection. Thus, the regional water resource system fails to sustainably support the socioeconomic development. To ensure the sustainability of the water resource system, the Bailong River Water Diversion Project (BRWDP) is currently under planning and will be operated in 2040. After the implementation of the BRWDP, the Yellow River system in Gansu Province will be connected to the Yangtze River system for optimizing the spatial and temporal distribution of regional water resources. Therefore, the BRWDP can be taken as a typical water diversion project to evaluate its impacts on the sustainability of regional water resource systems.

As shown in Figure 2, Tianshui, Qingyang, and Pingliang cities in Gansu Province, China are the water-receiving areas of the BRWDP. There are 20 districts or counties denoting the green line and the blue line that are located in the Wei River Basin (WRB) and the Jing River Basin (JRB), respectively. The regional water resource system is sketched as a node diagram as shown in Figure 3.

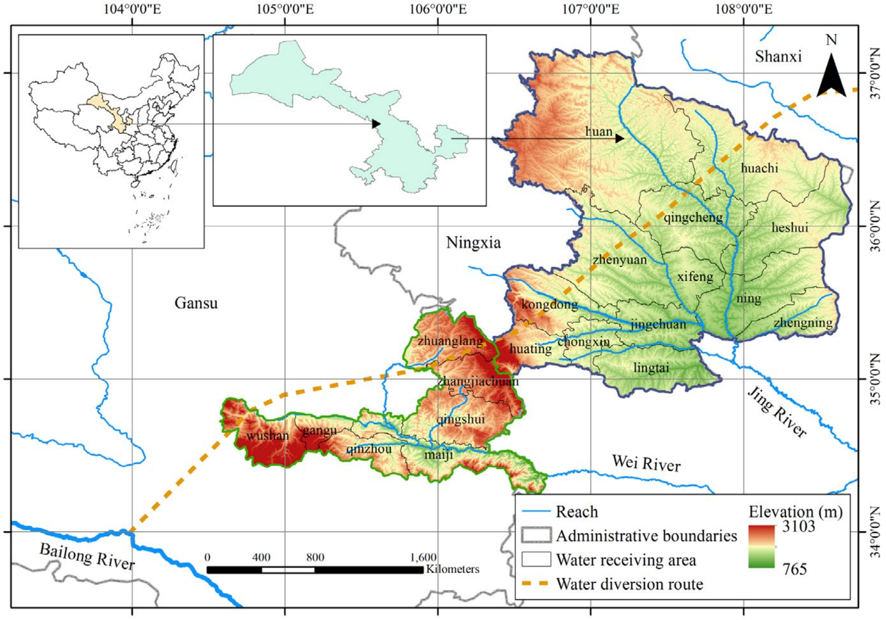

FIGURE 2 | Location of water-receiving area of the BRWDP. The administrative areas within the green and blue lines are located in the Wei River Basin and Jing River Basin, respectively.

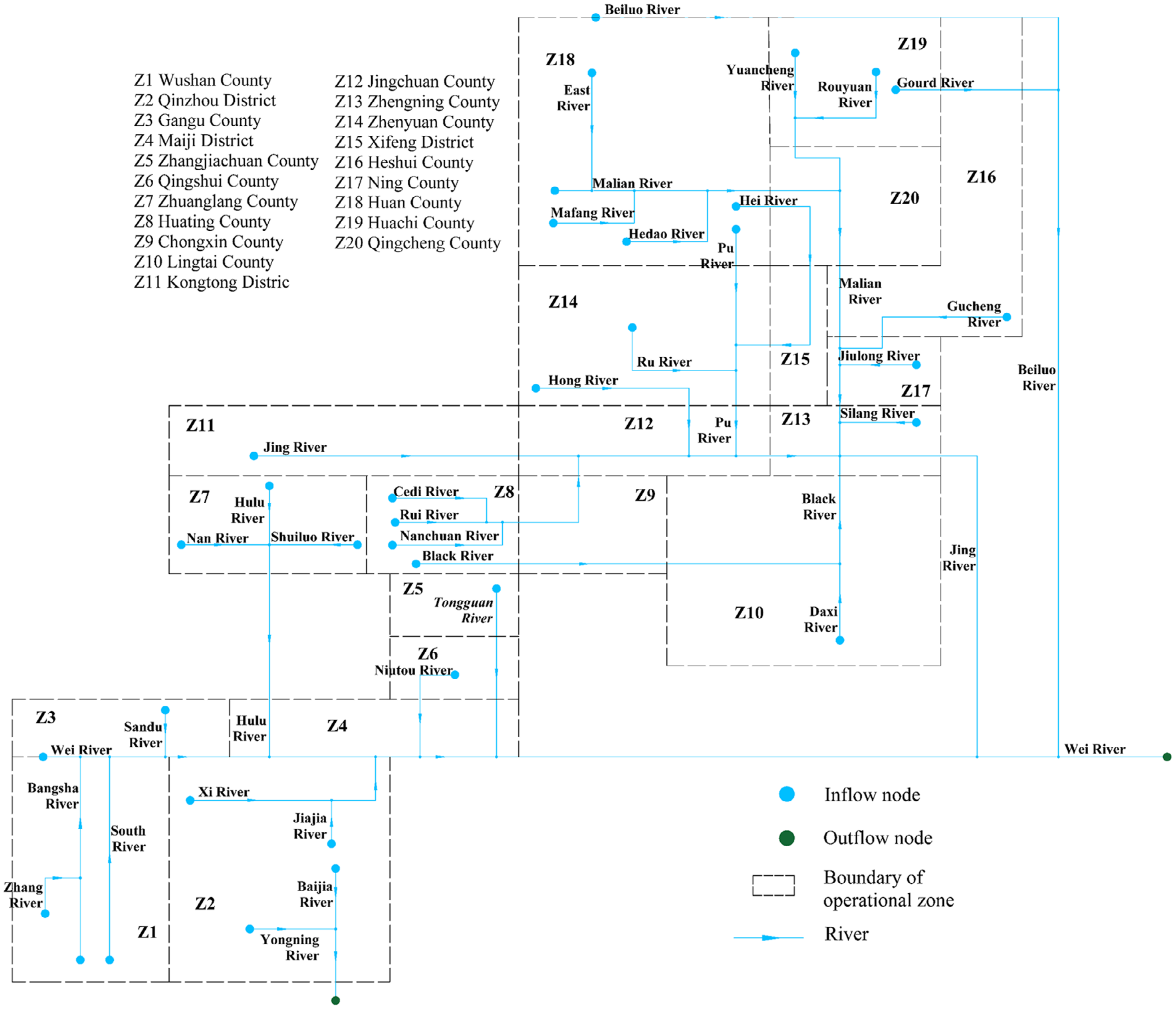

FIGURE 3 | Schematic diagram of water resource system for the water-receiving area of the Bailong River Water Diversion Project.

3.2 | Dataset

The World Climate Research Program (WCRP)-Coupled Model Intercomparison Project, Phase 6 (CMIP6) data from the IPSL-CM6A-LR model output (IPSL-CM6A-LR) of Institute Pierre-Simon Laplace (IPSL) was used to project the future climate. The IPSL-CM6A-LR has important scientific value and can provide strong support for climate change impact assessment and decision-making in China and thus was selected to project the future climate in our case study area (Boucher et al. 2020; Wang et al. 2022; Li et al. 2024). Two Shared Socioeconomic Pathways (SSPs), SSP 126 and SSP 585, represent the minimum greenhouse gas emission path for sustainable development and the maximum greenhouse gas emission path for rapid economic development, respectively. The two SPPs were selected to reflect the uncertainty of future socioeconomic development. The data required to construct the CWatM includes meteorological, topographic, land use, and soil data (see Table 1 for details). The observed runoff from hydrological stations was used to calibrate the CWatM parameters.

The socioeconomic water demand was projected from the Water Future and Solutions (WFS) project. Specifically, the WFS conducted by the International Institute for Applied System Analysis (IIASA) added the hydro-economic system classes to the SSPs for describing a country or region's ability to respond to water and climate risks. Further, three global water models H08, PC Raster Global Water Balance (PCRGLOBWB), and Water—Global Assessment and Prognosis (WaterGAP) were then used to predict the socioeconomic water demand from 1961 to 2050 under different SSPs based on population, Gross Domestic Product (GDP), technological and economic growth rates, and so on. The predicted socioeconomic water demand was extracted and corrected as domesticity, industry, and livestock water demand in the case study. The irrigation water demand was simulated by CWatM based on land cover, crop type, soil moisture, and irrigation mode. The comparison between the projected water demand and the water consumption from the Gansu Province Bulletin of water resources in 2020 is shown in Table 2. The total water demand is slightly higher (17.3% higher)

TABLE 1 | Data required to construct the CWatM.

Type	Parameters	Source
Meteorological data	Precipitation, average temperature, maximum temperature, minimum temperature, wind speed, absolute humidity, longwave radiation, shortwave radiation, ground pressure	Global Soil Wetness Project Phase 3—Water Watch Global Meteorological Forcing Dataset (v5.5) (GSWP3-W5E5)
Topographic data	Absolute elevation, relative elevation, standard deviation of elevation, grid area, flow direction, slope, river slope, river length, river width, river depth, and river roughness	Multi-Error-Removed Improved-Terrain Hydrography—Inter-Hydro Unit (MERIT Hydro IHU)
Land use	Crop type, land cover ratio, crop coefficient, minimum soil depth ratio, interception capacity, maximum root depth, root area ratio	United States Geological Survey—Global Land Cover Characterization (USGS-GLCC)
Soil data	Saturated hydraulic conductivity, groundwater regression constant, groundwater permeability coefficient, groundwater storage coefficient, proportion of permeability area, soil depth, saturated soil moisture content, residual soil moisture content, soil pore size index, soil air intake value	Harmonized World Soil Database (HWSD)

TABLE 2 | Projected water demand ($10^8\,m^3$) and the water consumption ($10^8\,m^3$) from Gansu Province Bulletin of water resources in 2020.

Water use sector	Agriculture	Industry	Domesticity	Total
Water use from Gansu Province Bulletin of water resources	5.54	1.09	2	8.63
Predicted water demand	5.23	2.11	2.78	10.12

than the total water consumption, suggesting that the water demand from the WaterGAP is reliable in the case study.

According to the design and operation plan of BRWDP, the annual amount of the designed water is 684.45 million m^3/year that is diverted from the Daigu Temple Water Control Reservoir Project. The annual temporal distribution of designed water diverted to the 20 water-receiving areas is shown in Table 3.

4 | Results and Discussion

4.1 | Water Availability and Demand for the Planning Years

To ensure the reliability of water availability estimation, the CWatM parameters were calibrated by the observed runoff from 2010 to 2017 and were validated by the observed data during the period of 2018–2019. Kling–Gupta efficiency (KGE) was selected as a performance criterion as it can comprehensively evaluate the model performance by combining the correlation, the time delay, and the change amplitude of the runoff series. The calibration and validation results are shown in Figure 4. KGE is 0.81 for the calibration period and 0.75 for the validation period in Beidao Station that is located in the outlet of WRB, and KGE is 0.42 and 0.11 for the calibration and validation periods in Yangjiapin Station located in the outlet of JRB, respectively. During the validation period, the deviation of the simulation results in the flood season is greater than that in the non-flood season. However, as the failure of water supply in water resource systems often occurs during non-flood seasons, the deviation of the simulation results in the flood season will have nonsignificant effects on the water supply.

The runoffs from 1961 to 2010 and from 2021 to 2050 were simulated to represent the water availability for the different planning years, respectively. The annual average runoff at the outlets of basins is summarized in Table 4. The average annual runoff in WRB is 3 times more than that in JRB, indicating that there may be higher water shortage risks in the districts/counties located in JRB. Due to the precipitation decreases and the temperature increases, the runoff in these two basins will decrease to varying degrees in the future. As BRWDP is expected to operate in 2040, 2040 was selected as one of the future planning years, and 2020 was selected as the reference planning year to estimate the water demand for the three cities (see Table 5). The results show that except for Qingyang, the water demand has increased even under SSP 126. The water demand in Tianshui has increased more prominently than the other two cities. Overall, due to the decrease in runoff and increase in water demand in the future, the sustainability of the water resource system in the study area will be a big challenge.

4.2 | Impacts of Water Diversion on Water Resource System Sustainability for the Reference Planning Year

To assess the impacts of water diversion on water resource system sustainability in our study area, the reliability, resilience,

TABLE 3 | Annual temporal distribution of designed water diverted to the 20 water-receiving areas of the Bailong River Water Diversion Project ($10^4\,m^3$).

Receiving area	1	2	3	4	5	6	7	8	9	10	11	12
Qinzhou	414	417	181	535	538	538	466	470	461	450	430	426
Maiji	96	97	42	124	125	125	108	109	107	104	100	99
Wushan	202	204	88	261	263	263	228	229	225	220	210	208
Gangu	208	210	91	269	271	271	234	236	231	226	216	214
Zhangjiachuan	179	181	78	232	233	233	202	203	199	195	186	185
Qingshui	152	154	66	197	198	198	171	173	169	165	158	157
Zhuanglang	210	212	92	272	274	274	237	239	234	229	219	217
Huating	294	297	128	380	383	383	331	334	328	320	306	303
Chongxin	171	172	75	221	222	222	192	194	190	186	177	176
Lingtai	147	148	64	190	191	191	165	167	163	160	153	151
Kongdong	611	616	267	790	795	795	688	694	680	664	635	630
Jingchuan	275	277	120	355	358	358	310	312	306	299	286	283
Zhenyuan	409	412	179	528	532	532	461	464	455	445	425	421
Xifeng	544	549	237	703	708	708	613	617	605	591	565	560
Heshui	186	187	81	240	241	241	209	211	207	202	193	191
Ning	285	288	125	369	371	371	321	324	318	310	296	294
Zhengning	114	115	50	148	149	149	129	130	127	124	119	118
Qingcheng	312	314	136	403	406	406	351	354	347	339	324	321
Huan	267	269	117	345	348	348	301	303	297	290	278	275
Huachi	241	243	105	311	313	313	271	273	268	262	250	248

vulnerability, and sustainability were estimated for each district/county in the receiving area of the BRWBP without water diversion (see Figure 5). Figure 5a shows that the reliability of districts/counties located in WRB is generally higher than those located in JRB. The reliability is greater than 96.93% in all the districts/counties of WRB. Compared to JRB, there are more water resources in WRB, and thus the local water demand can be satisfied with a high reliability. In JRB, the reliability of water resource systems varies from 50.87% to 95.03%. The reliability of water supply in a district/county is impacted by the local water availability and water demand and the transit water relating to the river system. The reliability of districts/counties located upstream of the river system is lower than that located downstream of the river system. For example, the four districts/counties with the lowest reliability in JRB (i.e., Kongdong, Huachi, Huan, and Huating) are all located at the upstream of the river system. This finding is consistent with the conclusion of Zou et al. (2020). There is an overall positive correlation between resilience and reliability, as shown in Figure 5b. But the range of variation in resilience (29.84%–100%) is larger than that in reliability (50.87%–100%). The resilience of water supply in a district/county is always lower than its reliability. However, if the reliability of water resource systems is at a higher level, the corresponding decrease in resilience compared to reliability is relatively small, and vice versa. For example, the reliability in Qinzhou (97.90%) is only 1.65% higher than its resilience (96.25%), while the reliability in Huan (69.63%) is 32.63% higher than its resilience (37.00%). If the reliability of water resource systems is low, their failure states are likely to occur continuously, resulting in lower resilience. The vulnerability of water resource systems is negatively correlated with their reliability and resilience, as shown in Figure 5c. If a water resource system often fails to supply enough water to meet the water demand, it is very likely that the available water resources are much lower than the water demand, indicating that low reliability often accompanies high vulnerability. Although these three indicators assess the different aspects of water resource systems by complementing each other, the results of the assessments of the water supply system performance exhibit consistency.

Combined with the reliability, resilience, and vulnerability, the sustainability of the water resource system can be estimated, as shown in Figure 5d. There are significant differences in water resource system sustainability in the case study area. The sustainability of districts/counties located in WRB is higher than 0.94 as a result of the abundant available water resources. However, the sustainability of water supply in Kongdong, Huachi, and Huan is only 0.43, 0.53, and 0.56, respectively, since there are fewer available water resources in these districts/counties located upstream of Jing River. Although Ning, Xifeng, and Jingchuan districts/counties are located downstream of Jing River, their water demands are higher than those of surrounding districts/counties

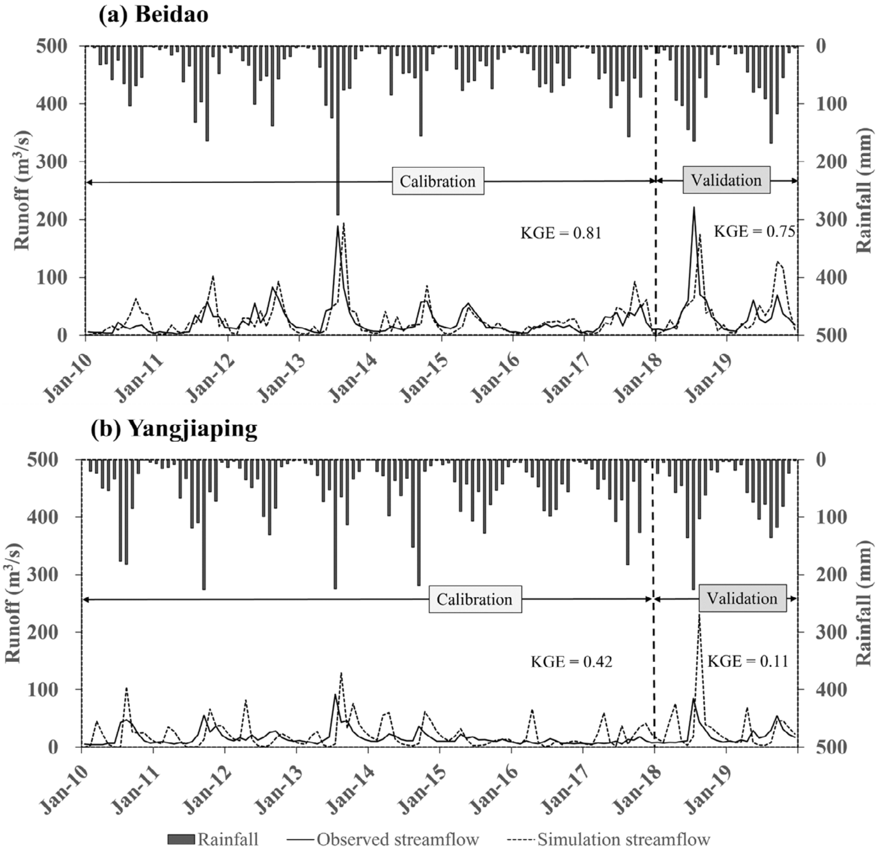

FIGURE 4 | Calibration and validation results for the runoff from CWatM at: (a) Beidao and (b) Yangjiaping.

TABLE 4 | Annual average runoff (m^3/s) in Wei River Basin (WRB) and Jing River Basin (JRB) for the reference and the future planning years.

Basins	Runoff from 1961 to 2010	Runoff from 2021 to 2050 under SSP 126	Runoff from 2021 to 2050 under SSP 585
WRB	180.25	162.46	165.79
JRB	51.75	43.55	40.60

TABLE 5 | Water demand ($10^8 m^3$) in Tianshui, Pingliang, and Qingyang for the reference and the future planning years.

Cities	Water demand in 2020	Water demand in 2040 under SSP 126	Water demand in 2040 under SSP 585
Tianshui	2.66	4.70	5.00
Pingliang	2.61	3.34	3.35
Qingyang	4.84	3.46	5.02

and bring low sustainability. For example, Ning county is located downstream of Heshui, but its water demand (i.e., 101.55 million m^3) is 85.55 million m^3 higher than that of Heshui (i.e., 15.70 million m^3). Furthermore, there is uniform sustainability across different water user sectors, except for Huating county. The unique characteristics of local water demand have led to uneven sustainability among its various water user sectors in Huating county. Huating county is one of China's important coal production bases, and its huge industrial water demand makes it difficult to sustain water supply. In contrast, the low demand for agricultural water and the high priority of water supply for the domestic sector can bring the sustainability of water supply.

Based on the water supply results without the water diversion project (taken as H1 scenario), the designed (taken as H2 scenario) and the optimal (taken as H3 scenario) allocation schemes for the diverted water were simulated for assessing the impacts of water diversion on water resource system sustainability (see Figure 6). The results show that water diversion with the designed allocation scheme can increase the reliability of the water resource system by an average of 9.69%, increase its resilience by an average of 19.21%, decrease its vulnerability by an average of 9.32%, and thus improve its sustainability by an average of 0.10. However, even if the diverted water has been allocated as the designed plan, the sustainability of water supply in six districts/counties still cannot reach 0.90. By optimizing the allocation of diverted water, the sustainability of water supply in all districts/counties can reach 0.90 except for Kongdong. As shown in Figure 6, the region in green represents the improvement for the performance of the designed allocation scheme after optimizing the allocation of the diverted water. The performances of the H3 scenario improve those of the H2 scenario by 85.50%, 252.18%, and 101.66% in terms of reliability, resilience, and vulnerability accumulated in all operating zones, respectively. Although water diversion with the designed allocation scheme

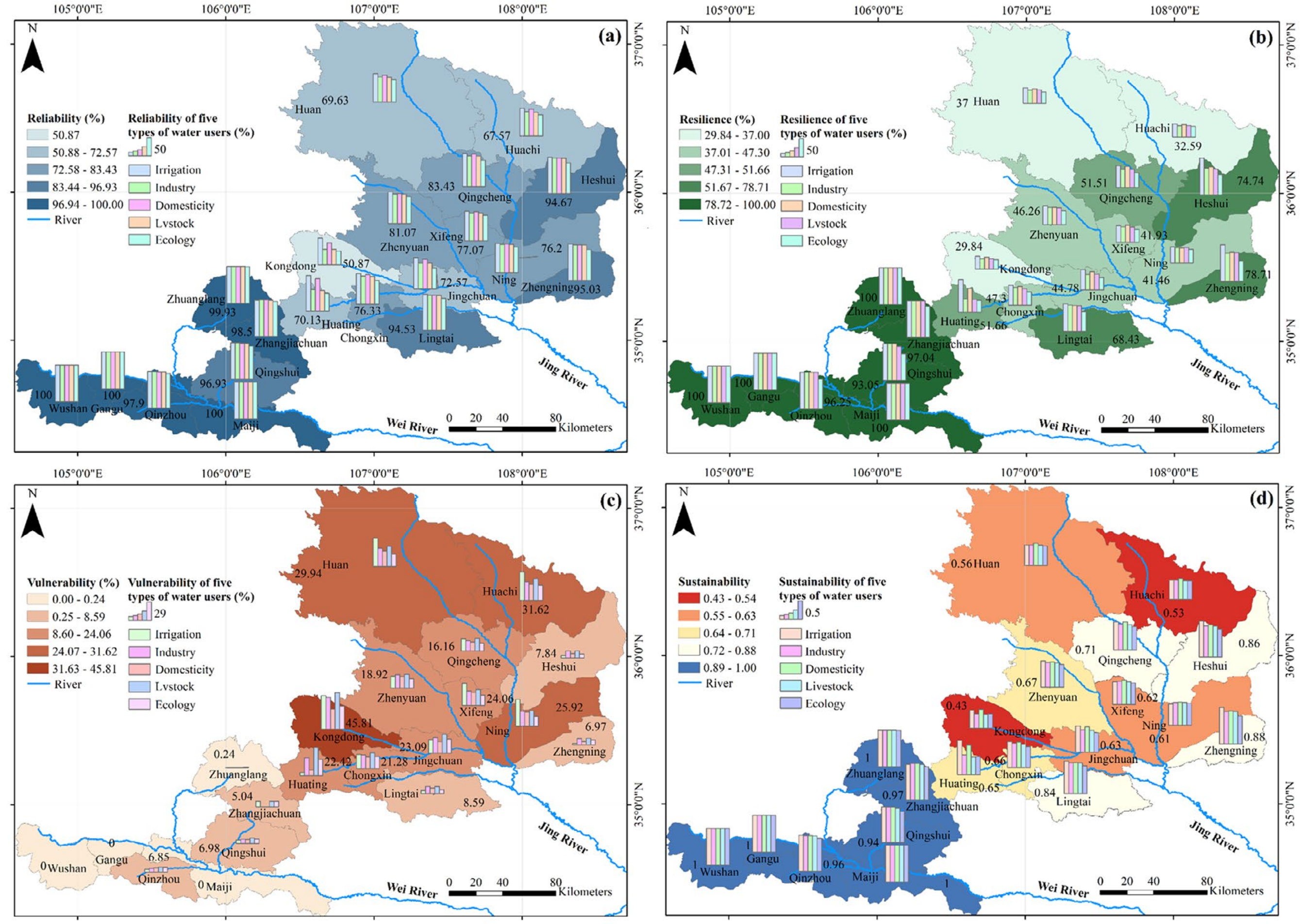

FIGURE 5 | (a) Reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project without water diversion for the reference planning year.

has the greatest improvement in resilience among the three indicators, the designed allocation scheme has the greatest potential and space for improvement in terms of system resilience. For example, the larger green region in Figure 6a compared to Figure 6b indicates that the designed allocation scheme fails to consider the resilience of the water resource system. The water resource system will be in a long-term state of failure, even if its reliability has been increased. Similar results can also be obtained from the comparison of Figure 6c and Figure 6d.

The practical lessons from the results are that priority should be given to improving the system's ability to quickly recover after a failure if the water diversion strategy needs to be modified. To improve system resilience, it is recommended to establish a comprehensive hydro-meteorological monitoring network to collect real-time data on rainfall, water level, and discharge and then develop emergency plans to ensure rapid response in case of emergencies.

4.3 | Impacts of Water Diversion on Water Resource System Sustainability for the Future Planning Years

Due to the climate change and socioeconomic development in the future, it is necessary to assess the sustainability of water resource systems and the impact of water diversion on their sustainability under varying water availability and water demand. Thus, the reliability, resilience, vulnerability, and sustainability were estimated for each district/county in the receiving area of the BRWBP in the future planning years. Figures 7 and 8 present the changes of the sustainability of water resource systems from the reference planning year to the future planning year. There is great spatial heterogeneity in the changes of various indicators, as shown in Figure 7. There are 10, 10, and 12 operational zones with decreased reliability, decreased resilience, and increased vulnerability, respectively. The number of districts/counties with increased and decreased indicators are similar. However, the decrease in reliability and resilience is greater than their increase, and the increase in vulnerability is greater than its decrease. Therefore, different from one indicator for the performance assessment of water resources allocation schemes, the sustainability indicator will result in more operational zones with decreased performance since the sustainability is formed by multiplying the three indicators. The sustainability of most districts/counties in Tianshui and Pingliang cities has decreased due to the decreased runoff and the increased water demand. Further, the sustainability of most districts/counties in Qingyang City has increased due to the decreased water demand under SSP 126. Compared to SSP 126, there are more operational zones with decreased reliability, resilience, and sustainability, and

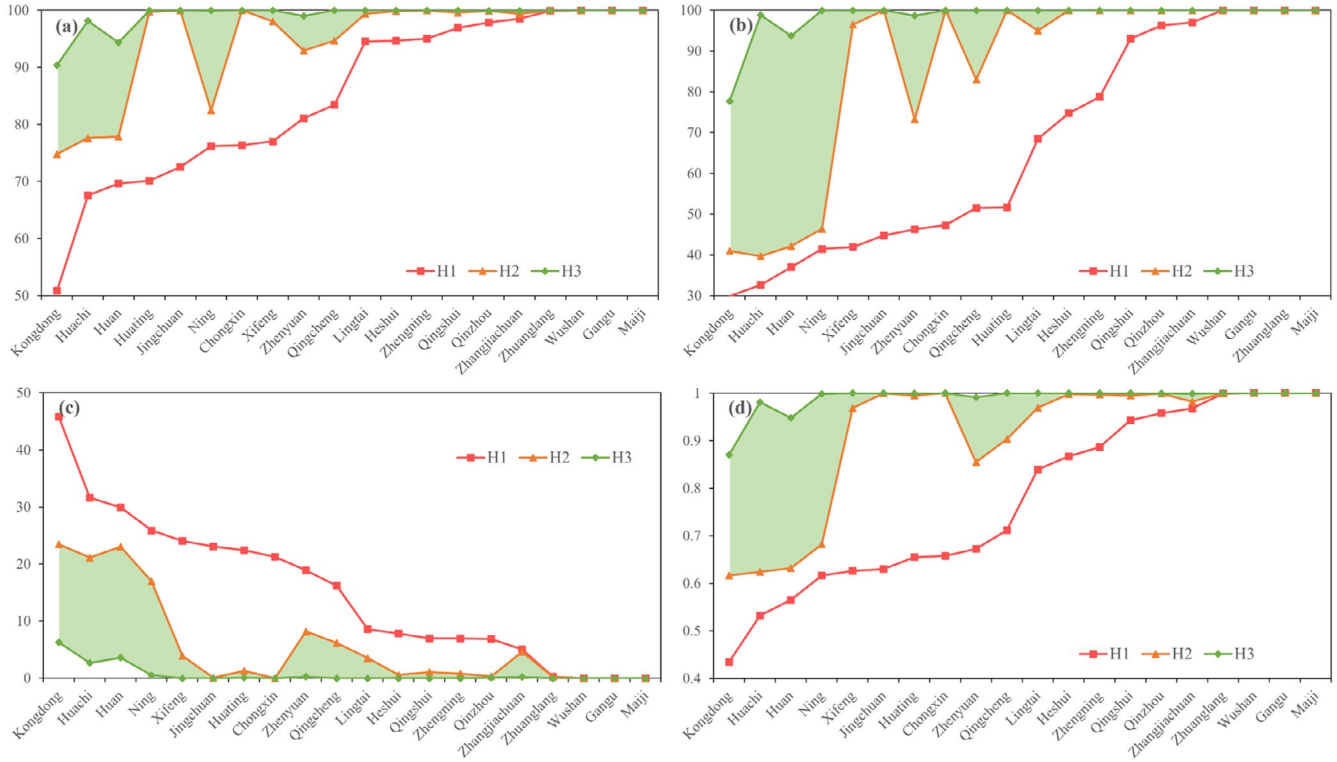

FIGURE 6 | (a) Reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project under H1 (without water diversion), H2 (with designed allocation scheme), and H3 scenarios (with 23 optimal allocation schemes) for the reference planning year.

increased vulnerability in the future under SSP 585, as shown in Figure 8. The rapid economic development with maximum greenhouse gas emission is not conducive to the sustainability of water resource systems as expected. For example, 14 out of 20 operational zones are experiencing a decline in sustainability, and there are no operational zones with sustainability increasing by more than 0.1. The average sustainability value of the water resource system only slightly drops from 0.778 for the reference planning year to 0.763 for the future planning year of SSP 126, but it rapidly drops to 0.719 for the future planning year of SSP 585. In general, the sustainability of the water resource system has changed dramatically for the future planning year, and it is important to assess the impacts of water diversion project on the sustainability, especially for the future planning year under SSP 585.

The reliability, resilience, vulnerability, and sustainability of the water resource system were estimated for each district/county in the water-receiving area of the BRWDP for the future planning year under SSP 126 with and without BRWDP, as shown in Figure 9. The water diversion with its designed allocation scheme can increase the reliability of the water resource system by an average of 11.85%, increase its resilience by an average of 20.75%, and decrease its vulnerability by an average of 11.69%, and finally its sustainability can be improved by an average of 0.15. The improvement in these three indicators and their corresponding sustainability for the future planning year are all better than those for the reference planning year. Even if the sustainability has decreased by 0.015 under SSP 126 compared to the reference planning year due to climate change and socioeconomic development, allocating diverted water resources with the designed scheme can still improve the sustainability by 0.135 for the future planning year. Further, allocating diverted water resources with its designed scheme can only improve sustainability by 0.10 for the reference planning year. Therefore, if the water diversion project is implemented according to the designed plan, the sustainability of the water resource system for the future planning year is actually higher than that for the reference planning year even if the water availability and water demand conditions become more unfavorable for the future planning year. It should be noted that there still are four districts/counties whose water supply sustainability cannot reach 0.90 after the diverting water project with the designed plan. However, the sustainability of water supply in all districts/counties can reach 0.90 through optimizing water resources allocation. Consistent with the result of Section 4.2, the improvement degree for the performance of the designed plan in all operating zones is the highest for resilience (240.45%), followed by vulnerability (116.70%), and finally reliability (81.28%) after implementing the optimal water allocation scheme.

The sustainability of the water resource system has sharply declined in the future planning year under SSP 585. Thus, it is valuable to assess the impacts of the water diversion project on sustainability under this scenario. Figure 10 shows that the water diversion project with the designed allocation scheme can change the reliability, resilience, vulnerability, and sustainability of the water resource system by an average of 12.12%, 22.01%, 13.39%, and 0.17%, respectively. Although this

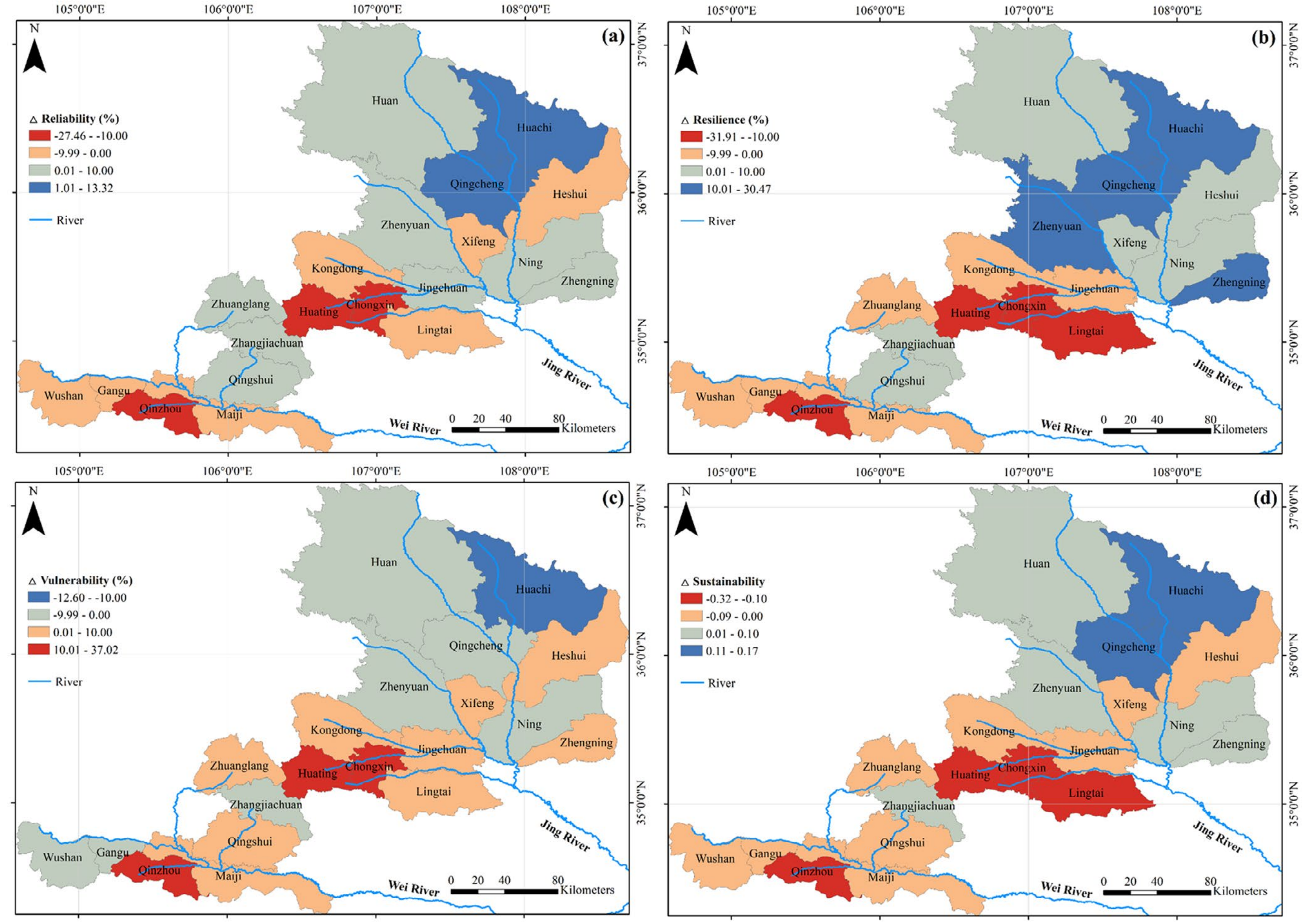

FIGURE 7 | Changes of (a) reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project without water diversion in the future planning year (SSP 126) compared to the reference planning year.

improvement effect is more significant than that under SSP 126, these improvements of sustainability cannot compensate for the reduction of sustainability from the climate change and the socioeconomic development. Even after implementing the water diversion project with the designed allocation scheme, nearly half of the districts/counties (9 out of 20) still cannot achieve a sustainable level of 0.90. However, implementing the optimal water allocation scheme can increase the reliability and resilience of the water resource system in all districts/counties to above 0.90, decrease their vulnerability to below 0.10, and ultimately improve the sustainability of all districts/counties to above 0.90. Implementing the optimal allocation scheme of diverted water resources can increase the average sustainability of the water resource system to the upper bound (i.e., 0.99) for both the reference and the future planning years. Furthermore, the area of green regions for the future planning year under SSP 585 is larger than that for the future planning year under SSP 126 and for the reference planning year. After implementing the optimal water allocation scheme under SSP 585, the improvement degree for the performance of the designed plan can reach 101.94%, 335.27%, 136.79%, and 0.27% in terms of reliability, resilience, vulnerability, and sustainability in all operating zones, respectively. These four improvement degrees are obviously higher than the corresponding improvement degrees for other schemes. Therefore, the more unfavorable the water availability and water demand conditions are, the more is the improvement from implementing the optimal water resources allocation scheme of the water diversion project.

If water diversion is implemented in a low carbon emission way and adheres to a sustainable development path, the sustainability of water resource systems for the future planning year will be higher than that for the current planning year with the water diversion project. Therefore, water diversion should be in conjunction with macro policies that control carbon emissions in practice. If the carbon emission target cannot be achieved, it is recommended to improve the monitoring system, regularly evaluate the water diversion effect, and dynamically update and optimize the water diversion scheme to adapt to complex and unfavorable changing environments.

5 | Conclusions

A framework for assessing the impacts of the water diversion project on water resource system sustainability is proposed by reliability, resilience, and vulnerability indicators. A typical

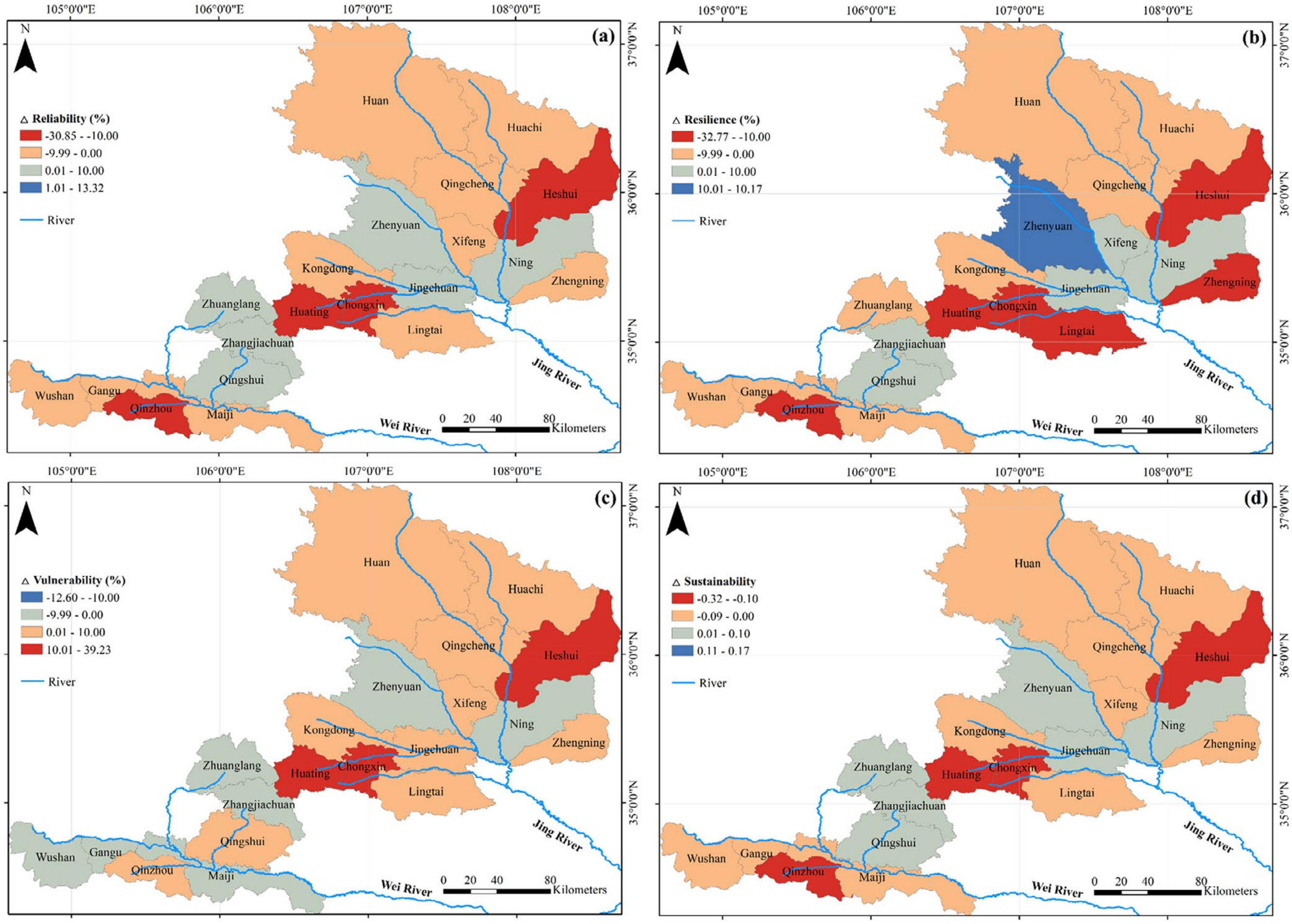

FIGURE 8 | Changes in (a) reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project without water diversion in the future planning year (SSP 585) compared to the reference planning year.

water resource system facing unsustainable water supply in China and its implementation of water diversion projects have been selected as a case study. These comprehensive indicators provide valuable insights into the performance of the water resource system and the role of water diversion project on water resource system sustainability in a changing climate and socioeconomic development conditions.

The case study results show that the reliability of water resource systems is positively related to their resilience and negatively related to their vulnerability. The resilience of water resource systems (29.84%–100%) is usually lower than their reliability (50.87%–100%), indicating that their failure states are likely to occur continuously. The designed water diversion project has the greatest improvement in resilience among these three indicators. However, there is still the greatest potential for improving resilience by optimizing the designed allocation scheme, accumulating 252.18%, 240.45%, and 335.27% increase in resilience in all counties/districts for current planning years, future planning years of SSP 126, and future planning years of SSP 585, respectively. Optimizing the designed allocation scheme can increase the water resource system sustainability to the upper bound (i.e., 0.99) regardless of the climate change and socioeconomic development. Further, the more unfavorable water availability and water demand conditions are, the larger is the improvement from optimizing the designed allocation scheme.

Although our proposed framework can help us understand the impacts of the water diversion project on water resource system sustainability, there are significant uncertainties in GCM projections and future economic and social development (Zhang et al. 2021). Further, uncertainty analysis methods should be introduced to explore the impact of these uncertainties on the impacts of the water diversion project. The construction and operation of local water resource engineering will alter the spatial and temporal distribution of water resources. Exploring the joint implementation of water diversion and local water resource engineering will help us better understand the changes in the sustainability of water resource systems. Finally, the RRV method requires a subjective decision of defining a threshold that divides normal and failed states. The sensitivity of sustainable assessment results to the selection of this threshold needs to be further studied, especially at different spatiotemporal scales (Zeng et al. 2024).

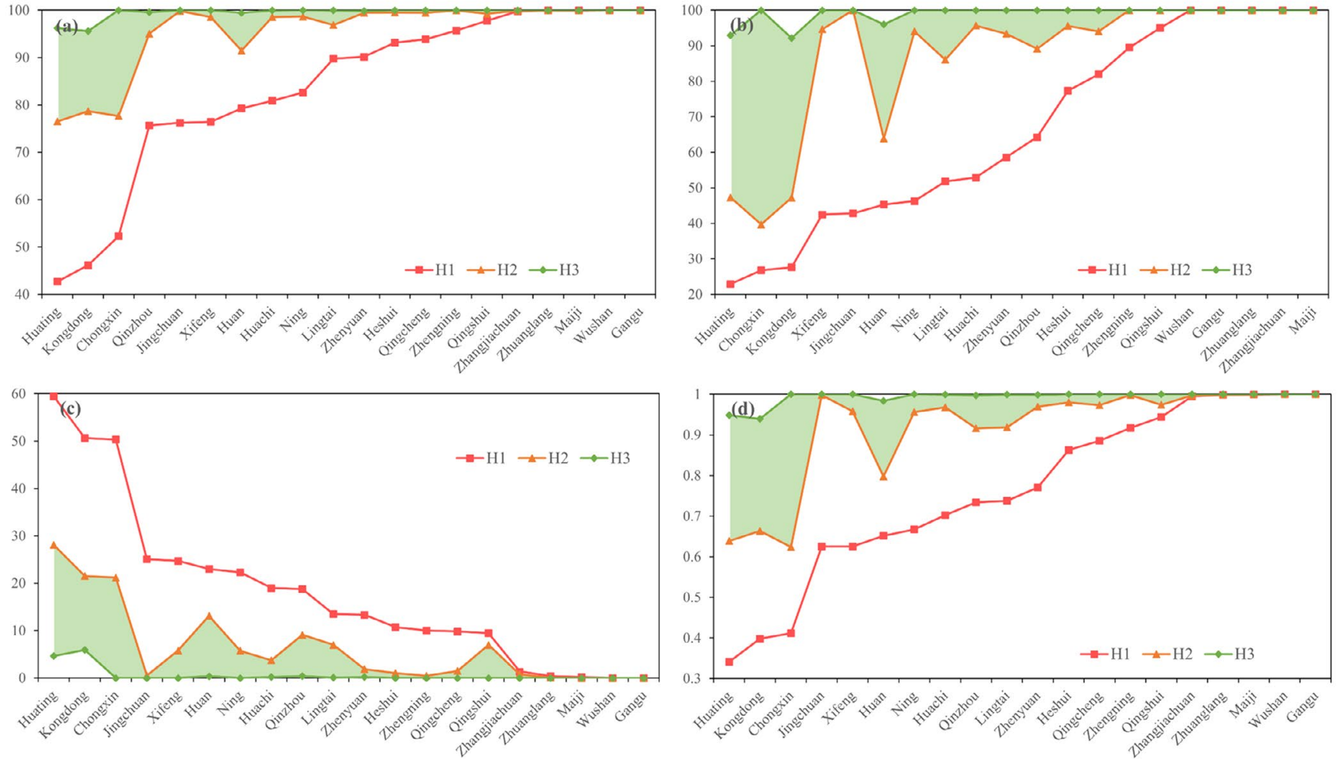

FIGURE 9 | (a) Reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project under H1 (without the water diversion project), H2 (with the designed allocation scheme), and H3 scenarios (with the optimal water resource allocation scheme) for the future planning year under SSP 126.

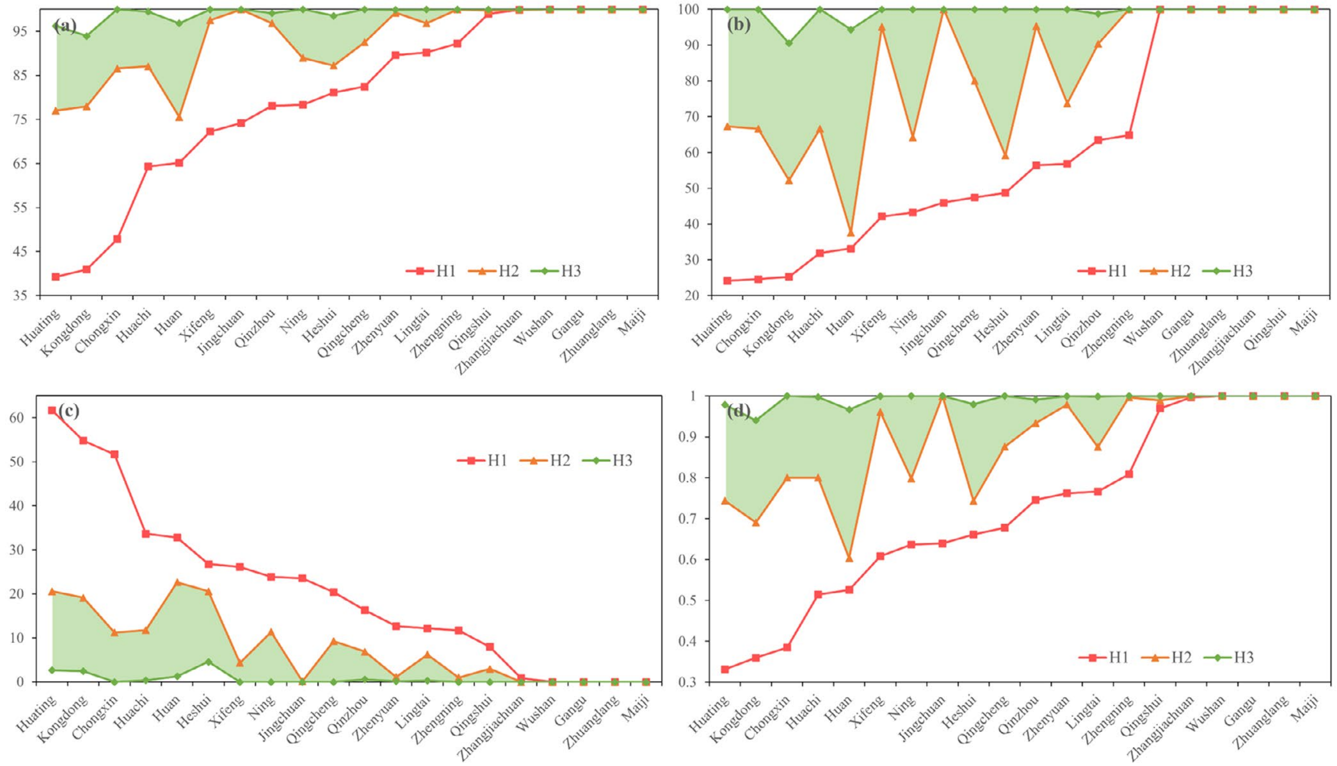

FIGURE 10 | (a) Reliability, (b) resilience, (c) vulnerability, and (d) sustainability of the districts/counties in the receiving area of the Bailong River Water Diversion Project under H1 (without the water diversion project), H2 (with the designed allocation scheme for the water diversion project), and H3 scenarios (with the optimal allocation scheme for the water diversion project) for 46 future planning years under SSP 585.

Author Contributions

Wen Chen: conceptualization, investigation, project administration, resources, validation. **Ruikang Zhang:** formal analysis, investigation, methodology, software, writing – original draft. **Dedi Liu:** conceptualization, data curation, funding acquisition, methodology, project administration, resources, supervision, validation. **Junde Wang:** investigation, project administration, validation, visualization. **Yufei Cheng:** conceptualization, data curation, investigation, project administration, resources, writing – review and editing. **Jie Chen:** conceptualization, data curation, methodology, project administration, resources, software.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its Supporting Information as we stated in Section 3.2. Some observed data can be accessed through email, and support to the findings of this study is available from the corresponding author upon reasonable request.

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