Applied Geography 160 (2023) 103101

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Integrating water quantity- and quality-related ecosystem services into water scarcity assessment: A multi-scenario analysis in the Taihu Basin of China

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ARTICLE INFO

Handling Editor: J Peng

Keywords:
Ecosystem services
Supply and demand
Water scarcity
Water quality
Climate change
Land use change

ABSTRACT

Water scarcity is a growing global concern, resulting from drastic climate and societal changes witnessed over the past few decades. Previous attention has predominantly focused on inadequate water quantity as the main cause of water scarcity, but pollution-induced water scarcity has been largely overlooked. Furthermore, there is a lack of understanding about the effectiveness of policy interventions in mitigating water scarcity and its social impact. To address these knowledge gaps, we developed an ecosystem service-based approach to measure quantity- and quality-related water scarcity by comparing supply of and demand for water provision and water purification services. We also developed several water and land management scenarios to examine their potential in alleviating water scarcity under different climate conditions and water quality requirements. Our case study in the Taihu Basin of southeastern China identified four types of water scarcity status across different sub-basins, including quantity-based, quality-based, quantity- and quality-based, and no water scarcity. The degradation of water quality in the Taihu Basin has exacerbated the scarcity of clean water supply. Water conservation measures effectively alleviated quantity-based water scarcity, while nitrogen reduction and grain for green (i.e., conversion of cropland into forest land) exhibited similar efficacy in alleviating quality-based water scarcity. Integrating these measures contributed to alleviating both quantity- and quality-based water scarcity. However, the effectiveness of these measures decreased under drier climate conditions and higher water quality requirements, highlighting the importance of climate and water quality in determining the magnitude, extent, and severity of water scarcity. The approaches and findings presented here provide new insights into the sustainable management of water resources in the Taihu Basin and other similar basins worldwide.

1. Introduction

Water scarcity is a significant issue affecting an increasing number of human populations worldwide. It refers to a shortage of water resources available for human use in a specific region over a particular period of time (Liu et al., 2017). In the 2000s, severe water scarcity conditions affected two-thirds of the global population, equivalent to approximately 4 billion people (Mekonnen & Hoekstra, 2016). Between 1970 and 2010, water scarcity has worsened, primarily in the downstream areas of the world's major river basins affecting over 60% of the global population, while improving elsewhere for less than 10% of the population (Huang et al., 2021; Veldkamp et al., 2017). A recent study revealed that the 10% most water-stressed basins worldwide accounted for 19% of the global population and 35% of irrigated crop yield

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https://doi.org/10.1016/j.apgeog.2023.103101
Received 4 May 2023; Received in revised form 28 August 2023; Accepted 18 September 2023
Available online 24 September 2023
0143-6228/

between 2012 and 2016, indicating disproportionate impacts on livelihoods and agriculture (Qin, Mueller, et al., 2019). Furthermore, climate and societal changes are expected to exacerbate water scarcity in many regions worldwide, particularly in urban areas (Greve et al., 2018). He et al. (2021) recently projected that the proportion of the global urban population facing water scarcity could increase from one-third in 2016 to nearly half by 2050, with 91 additional large cities worldwide expected to experience water scarcity. In China, the expanding urban areas face increasing risks of water scarcity, with the number of affected urban populations projected to double from 159 million in 2016 to a maximum of 315 million by the mid-21st century (Liu & Wu, 2022).

Various metrics have been developed to quantify the severity of water scarcity from the lens of water shortage (low availability on a per capita basis), water footprint, and water stress (high consumption relative to availability) (Kummu et al., 2016). The per capita water availability is a simple metric that identifies the population with difficulties in fulfilling their water needs (Jiang, 2009), with a threshold value of 500 m^3/person/year proposed as a measure of absolute water scarcity (Liu et al., 2017). On the other hand, water footprint-based metrics calculate the ratio of consumptive water use for socio-economic sectors to water availability to determine overuse of water resources (Hoekstra et al., 2012). Further, the water stress index, which measures the ratio of total water withdrawals (including consumptive water use and return flow) to water availability, is another widely used indicator of water stress levels (Qi et al., 2022). A value of 0.4 is commonly used to distinguish between low and high water stress (Li, Liu, et al., 2017), while a value greater than 1.0 has a clear physical meaning indicating water scarcity (He et al., 2021).

While the aforementioned metrics and case studies have been successful in identifying water scarcity issues and quantifying their patterns, they have largely focused on water quantity, overlooking the equally important factor of water quality (Li et al., 2022). In fact, a recent survey of the global water sector identified water quality degradation and its impact on water scarcity as one of the top 100 research priorities (Mdee et al., 2022). In China, for example, excessive nitrogen discharge from anthropogenic sources has led to widespread water pollution (Yu et al., 2019), exacerbating water scarcity issues in some areas, despite sufficient water quantity (Ma et al., 2020; Shu et al., 2021).

To account for both water quantity and quality in water scarcity assessments, researchers have proposed two methods. The first calculates blue water and gray water footprints to measure the severity of quantity-related and pollution-induced water scarcity, respectively (Liu et al., 2016; Zeng et al., 2013). Another approach, proposed by van Vliet et al. (2017), assesses water scarcity by comparing sectoral water withdrawals of acceptable quality to overall water availability. In this case, total water demand includes actual water withdrawals for socio-economic sectors and extra water needed for dilution to obtain acceptable water quality. van Vliet et al. (2021) applied this method to assess global water scarcity from 2000 to 2010 and found that 30% of the global population suffered from inadequate water quantity, while pollution-induced water scarcity affected an additional 10% of the world's population, primarily in eastern China and India.

Over the past decade, ecosystem services have become increasingly mainstreamed in water resource management (Liu et al., 2013), resulting in a growing number of studies attempting to incorporate water quantity-related ecosystem services into water scarcity assessments (Boithias et al., 2014). These studies focus on water provision service and compare its supply (e.g., quantified using annual water yield) and demand (e.g., water consumption or withdrawal) to identify regions where demand exceeds supply (Shaad et al., 2022), thus providing a clear indication of the level of water scarcity. However, similar to other water scarcity assessments, water quality-related services, such as water purification, have not been included due to obstacles in quantifying the supply-demand relationship based on a referenced water quality standard. Recently, Tao et al. (2023) developed a research framework to estimate the supply and demand budget of water purification service by comparing actual and allowable nutrient export with a clear indication of water quality status, thus presenting a promising basis for including water purification service in ecosystem service-based assessments of water scarcity. While many studies have examined the severity and impact of water scarcity using the approaches described above, only a few, including those of Qin, Liu, et al. (2019) and van Vliet et al. (2021), have explored the contributions of adaptive measures, including reduced water consumption and clean water technologies in alleviating water scarcity. The potential of other countermeasures and management strategies, such as land use regulation and water conservation, and their combined effects on water scarcity under varied climate conditions, remain poorly understood.

To address these knowledge gaps (e.g., the unclear impacts of and solutions to quantity- and quality-related water scarcity), we focus on the Taihu Basin in southeastern China as a typical case study and aim to answer three key questions: (i) How can water scarcity caused by deficient water quantity, degraded water quality, or both, be quantitatively measured? (ii) How does water scarcity vary spatially under different climate conditions and water quality requirements? (iii) How can alternative water conservation and land use regulation measures alleviate water scarcity? To answer these questions, we developed an ecosystem service-based approach to measure quantity- and quality-related water scarcity under varying climate conditions and water quality requirements. We also developed multiple scenarios to examine the effectiveness of individual and combined water and land-based measures in alleviating water scarcity in the Taihu Basin. Results from our work will inform other regions in China or globally that experience similar stresses from altered climate and accelerated urbanization on addressing water scarcity issues.

2. Materials and methods

2.1. Study area

The Taihu Basin (119°3'1"–121°54'26"E, 30°7'19"–32°14'56"N) is situated in southeastern China and is at the heart of the Yangtze River Delta. The region spans approximately 36,900 km^2 and is bordered by the Yangtze River to the north, the Qiantang River to the south, the East China Sea to the east, and the Maoshan and Tianmu Mountains to the west (Fig. 1a). Despite receiving sufficient annual precipitation (1200 mm) and being located within the subtropical monsoon climate zone, the Taihu Basin faces water scarcity risks due to two main reasons. First, the basin encompasses the city of Shanghai, southern Jiangsu province, and northern Zhejiang province and is one of the most densely populated and economically developed regions in China. As of 2020, the basin supported 4.8% of the nation's population and produced 9.8% of its GDP, despite occupying only 0.4% of China's total land area (Taihu Basin Authority of Ministry of Water Resources, 2020). This has resulted in a significant demand for water resources from different sectors and tensions related to local water supply. According to the water resources bulletin (Taihu Basin Authority of Ministry of Water Resources, 2020), each resident in the Taihu Basin has access to only 400 m^3 of water resources annually, which is less than one-fifth of the amount of water resources per capita (2200 m^3) averaged for China and lower than the threshold of 500 m^3 recommended to fulfill basic human water needs. The low availability of local water resources in the basin is also sensitive to climate change, resulting in shortfalls in local water supply during dry seasons or years (Taihu Basin Authority of Ministry of Water Resources, 2020). Second, plains comprise more than two-thirds of the Taihu Basin, which is one of the most agriculturally productive regions in China, with half of its territory covered by cropland and aquaculture ponds (Fig. 1a). Such intensive agricultural production has led to the consumption of large quantities of water resources, exports of virtual water (e.g., through agricultural trade), and the exportation of significant amounts of nitrogen into water bodies, exacerbating water scarcity in the basin

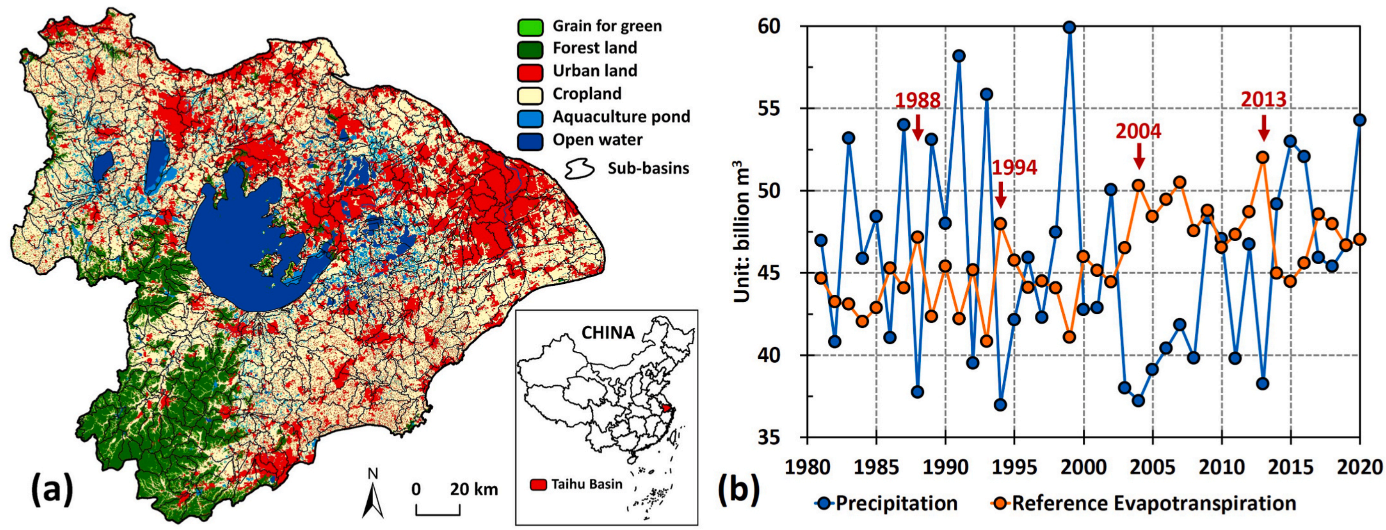

Fig. 1. An overview of the study area. Lake Taihu is the large circular water body in the center of the map. (a) Land use in the Taihu Basin as of 2020. Bright green grid cells represent potential grain for green locations under alternative land use scenarios as described in Table 2. (b) Annual precipitation and reference evapotranspiration during the period of 1981–2020. The orange arrowheads highlight the four driest years (2013, 2004, 1994, and 1988) with the largest deficit between precipitation and reference evapotranspiration.

through degraded water quality. For example, and according to the National Development and Reform Commission (2022), algae blooms covered over 40% of Lake Taihu in June 2020 due to its high nitrogen and nutrient concentrations.

2.2. Data sources

This study relied on ten major datasets, each with distinct parameters and sources. First, land use data for the Taihu Basin in the year 2020 were obtained at 30-m resolution from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences (http://ids.ceode.ac.cn/). This data was acquired through the interpretation of Landsat 8 OLI images and had an overall accuracy of 85%. Different land uses were classified into five categories, including urban land, cropland, forest land, aquaculture pond, and open water (Fig. 1a). Second, mean annual precipitation and reference evapotranspiration data from 1981 to 2020 were obtained at 1-km resolution from the National Ecosystem Science Data Center (http://rs.cern.ac.cn/) through spatial interpolation of meteorological observations. The third dataset, a soil map with information on soil depth and composition, was derived at 1-km resolution from the Harmonized World Soil Database (Food and Agriculture Organization of the United Nations, 2008). The fourth dataset was a Digital Elevation Model (DEM) at 30-m resolution, derived from the China Geospatial Data Cloud (www.gscloud.cn) for hydrological modeling. The boundaries of the 490 sub-basins (Fig. 1a) were delineated using the DEM and corrected with the distribution of ditches, dikes, and dams by the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (http://wsgs.niglas.cas.cn/). Additionally, the amount of water withdrawals for irrigation, aquaculture, industries, and domestic use in the Taihu Basin as of 2020 was obtained from the water resources bulletin (Taihu Basin Authority of Ministry of Water Resources, 2020). Net primary productivity product in 2020 was downloaded from the MODIS website (https://modis.gsfc.nasa.gov) at 1-km resolution for estimating water withdrawals for irrigation in each cropland grid cell. Nighttime light intensity image in 2020 was provided by NOAA's National Centers for Environmental Information (https://ngdc.noaa.gov) at 1-km resolution for allocating basin-wide water withdrawals for industries and domestic use to each urban grid cell. Gridded population data in 2020 were obtained from the LandScan Program initiated at Oak Ridge National Laboratory (https://landscan.ornl.gov) at 1-km resolution for estimating the number of populations affected by water scarcity in the Taihu Basin. Finally, the biophysical parameters used in the ecosystem service models, such as plant evapotranspiration, nitrogen load and retention efficiency of various land uses (Table 1), were derived based on relevant literature (Han et al., 2021; Wang et al., 2017) and calibrated with gauged datasets in the basin.

2.3. Water scarcity assessment

This study presents an ecosystem service-based approach to assess water scarcity in each sub-basin of the Taihu Basin, which involves three key steps as depicted in Fig. 2. First, water scarcity resulting from deficient water quantity was evaluated based on the supply-demand budget of water yield service. Inadequate water quantity available for human uses due to a lower supply of water yield and higher demand for water withdrawal leads to quantity-based water scarcity. Second, water scarcity due to degraded water quality was assessed based on the supply-demand budget of water purification service. A lower nitrogen retention supply and higher nitrogen load demand indicate that the water quality is insufficient to meet human water usage requirements, resulting in quality-based water scarcity. Thirdly, the quantity- and quality-based results from the previous two steps were synthesized for a comprehensive assessment of water scarcity. This final step results in categorization of basins into different water-scarce situations that are subject to deficient water quantity, degraded water quality, or both (Fig. 2). Further details on this three-step approach are elaborated below.

2.3.1. Assessment of quantity-based water scarcity

To assess quantity-based water scarcity, we compared the supply of

Table 1
Calibrated biophysical parameters in the water yield and nitrogen retention models for the Taihu Basin.

LULC	Kc	root_depth	load_n	eff_n	LULC_veg
Urban land	0.3	500	10	0.05	0
Cropland	0.7	2000	25	0.25	1
Forest land	1	7000	5	0.75	1
Aquaculture pond	1	1000	15	0.05	0
Open water	1	1000	0	0.05	0

LULC: land use and land cover; *Kc*: plant evapotranspiration coefficient; *root_depth*: maximum root depth (mm); *load_n*: annual nitrogen load (kg·ha^{-1}); *eff_n*: maximum nitrogen retention efficiency; *LULC_veg*: 1 for vegetated land use types and 0 for other land use types.

Table 2
Descriptions of alternative scenarios for alleviating water scarcity through combining water and land management measures.

Scenario	Description
Water Conservation (WC)	Water use efficiencies in the industrial, domestic, and agricultural sectors are all improved by 20%. This improvement results in a 20% decrease in total water withdrawals in the Taihu Basin, compared to the current status quo (Taihu Basin Authority of Ministry of Water Resources, 2014).
Nitrogen Reduction (NR)	Nitrogen fertilizer usage for agriculture and aquaculture are reduced by 20% (Qiao et al., 2012; Tian et al., 2012; Xu et al., 2021). Accordingly, the nitrogen load values for cropland and aquaculture pond decrease by 20% from 25 kg ha^{-1} and 15 kg ha^{-1} to 20 kg ha^{-1} and 12 kg ha^{-1}, respectively in the InVEST model.
Grain for Green (GG)	To reduce nitrogen loads and enhance nitrogen retention, croplands with slopes greater than 6° and those within the 30-m riparian zone of water bodies (including open water and aquaculture ponds) are converted into forest land (Taihu Basin Authority, 2013; Sun et al., 2022). These land use change policies result in a 15% increase in forest land and a 4% decrease in cropland compared to 2020 (Fig. 1a).
Integrated Management (IM)	This scenario encompasses the implementation of all measures, including water conservation, nitrogen reduction, and grain for green initiatives, taken under the three aforementioned scenarios.

and demand for water yield service for each sub-basin. The supply of water yield service (WY_S) was determined by summing the annual water yield for each grid cell within the sub-basin, estimated using the principle of water balance as follows.

$$WY_S = \sum_{x=1}^{N} \left(1 - \frac{AET_x}{P_x}\right) \bullet P_x$$

where N is the number of grid cells in a sub-basin; P_x is annual precipitation in grid cell x; and AET_x represents actual annual evapotranspiration in grid cell x, which is a function of reference evapotranspiration, plant evapotranspiration coefficient, root depth, and seasonality factor.

The InVEST water yield model was used to calculate the equation (Natural Capital Project, 2022). First, the model was run with annual precipitation, reference evapotranspiration, and land use data in 2020. The estimated annual water yield was calibrated with the gauged volume of water in the Taihu Basin as of 2020 (31.3 billion m^3) (Taihu Basin Authority of Ministry of Water Resources, 2020). Our calibrated model estimated 31.1 billion m^3 of annual water yield, which demonstrated an overall accuracy of 99%. Using this calibrated model (Table 1), we estimated annual water yield with land use data in 2020 under average and dry climate conditions to evaluate the influence of climate change on water yield (Boithias et al., 2014). For the average climate condition, mean annual precipitation and reference evapotranspiration during the 1981–2020 period were used. For the dry climate condition, water yield was estimated using the four driest years (2013, 2004, 1994, and 1988) that have the largest deficit between precipitation and reference evapotranspiration. Fig. 1b shows that mean annual precipitation during these four driest years was 18% lower than during 1981–2020, while mean reference evapotranspiration was 9% higher during these four driest years than over the past four decades.

To calculate the human demand for water yield service (WY_D) of a sub-basin, the total amount of water withdrawals in each grid cell of that sub-basin was determined. This was calculated using the following formula.

$$WY_D = \sum_{x=1}^{N} (IRG_x + AQU_x + IND_x + DOM_x)$$

where N is the number of grid cells in a sub-basin; and IRG_x, AQU_x, IND_x, and DOM_x represent water withdrawals in grid cell x for irrigation, aquaculture, industries, and domestic use, respectively. The environmental water requirement in each grid cell was not included in calculating WY_D because it was already subtracted from WY_S as actual annual evapotranspiration.

In this study, we estimated WY_D of each sub-basin using statistical and geospatial datasets collected in 2020, including water withdrawal, land use, nighttime light, and net primary productivity. First, we obtained the total water withdrawals for irrigation, aquaculture, industries, and domestic use from the water resources bulletin for the entire Taihu Basin (Taihu Basin Authority of Ministry of Water Resources, 2020). Secondly, the total water withdrawals for industries and domestic use were spatially allocated to urban grid cells weighted by nighttime light intensity (Sun et al., 2023), total water withdrawals for irrigation were allocated to cropland grid cells weighted by net primary productivity (Li, Liu, et al., 2017), while total water withdrawals for aquaculture were equally allocated to each aquaculture pond grid cell (Qin, Liu, et al., 2019). These grid cell-level estimates of water withdrawals were then totaled for each sub-basin to obtain WY_D. Finally, we compared WY_S and WY_D, and any sub-basin with WY_D higher than WY_S was deemed to have insufficient water quantity, and consequently identified as being subject to quantity-based water scarcity.

2.3.2. Assessment of quality-based water scarcity

Quality-based water scarcity is a consequence of deteriorating water quality, which can be evaluated in each sub-basin by comparing the supply of and demand for water purification service. In the Taihu Basin, nitrogen discharged from urban and agricultural sources poses a significant threat to surface water pollution within the basin (National Development and Reform Commission, 2022). To measure the supply of water purification service (WP_S) in a given sub-basin, we calculated the total nitrogen retention in each grid cell using the InVEST nitrogen delivery ratio model (Natural Capital Project, 2022) as follows.

$$WP_S = \sum_{x=1}^{N} (ALV_x - Exp_x)$$

where N is the number of grid cells in a sub-basin; ALV_x is annual nitrogen load in grid cell x adjusted by its annual water yield; and Exp_x represents the amount of nitrogen exported from any upstream grid cell x that eventually reaches downstream water bodies, which can be estimated based on the following equation.

$$Exp_x = ALV_x \prod_{y=x+1}^{X} (1 - R_y)$$

where R_y is nitrogen retention efficiency of each downstream grid cell y; and X represents the number of downstream grid cells.

In this study, we first ran the InVEST nitrogen delivery ratio model to estimate nitrogen concentration (i.e., nitrogen export divided by water yield) for each sub-basin using actual annual water yield and land use data from 2020. We calibrated our estimates based on gauged nitrogen concentration in the Taihu Basin, which is known to have surface water quality requirements for nitrogen concentration lower than 1 g m^{-3}. Our calibrated results show that over 82.3% of the basin had nitrogen concentrations below this limit, a proportion comparable to the reported 82.5% by the National Development and Reform Commission (2022), indicating the robustness of our model estimates. Then, using this calibrated model (Table 1), we estimated nitrogen retention in each sub-basin with land use data in 2020 and water yield estimates respectively under the average and dry climate conditions as described in Section 2.3.1.

The demand for water purification service (WP_D) can be characterized as the quantity of nitrogen load in a landscape that must be intercepted and retained before entering water bodies to preserve a predetermined level of surface water quality (Tao et al., 2023). To calculate WP_D, we determined the excess amount of nitrogen load in

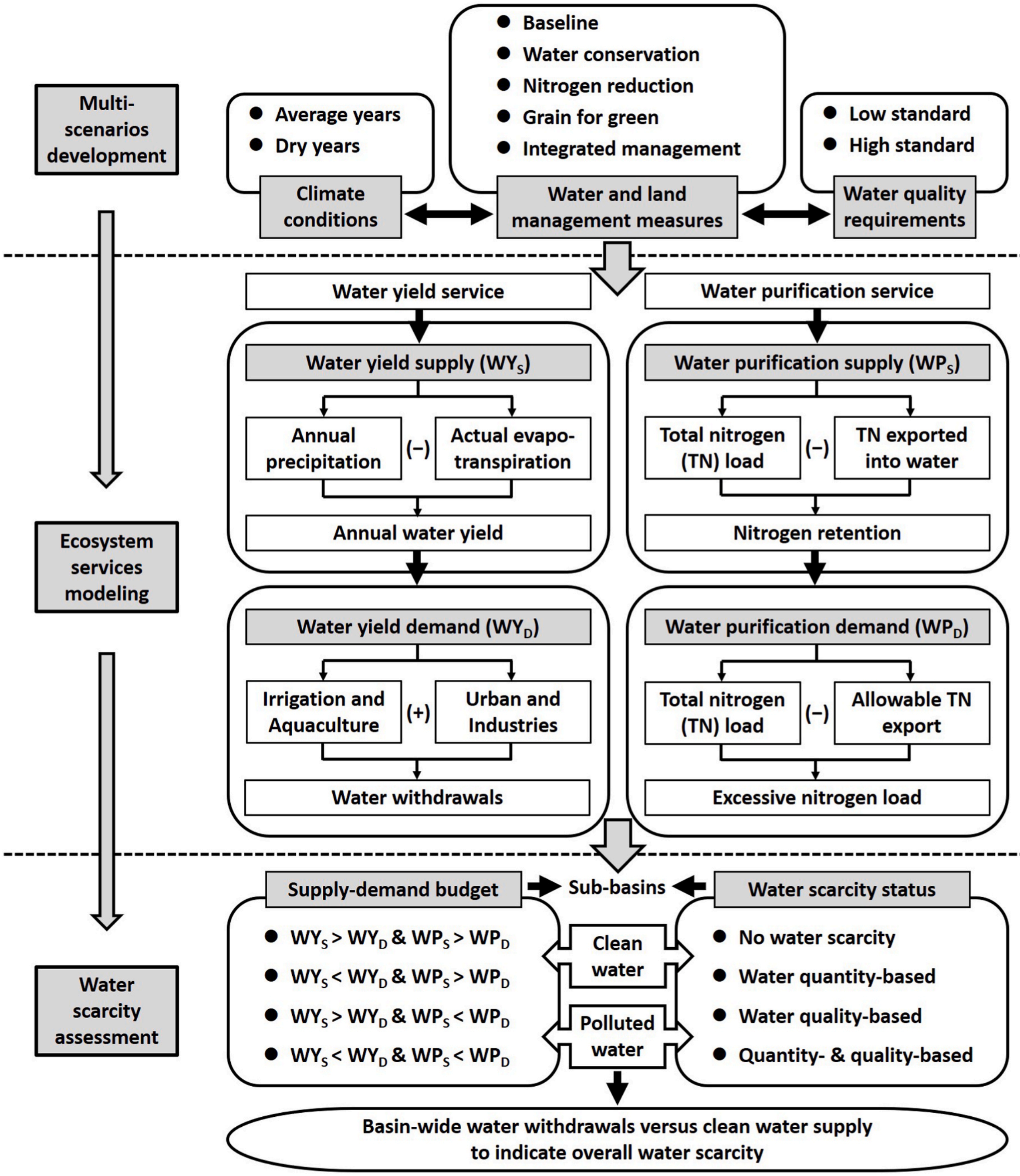

Fig. 2. The workflow of an ecosystem service-based approach to assess water scarcity.

each sub-basin. This was done by subtracting the sub-basin's allowable amount of nitrogen export under the specific water quality requirement from its total nitrogen load, as indicated below.

$$WP_D = \sum_{x=1}^{N}(ALV_x - Y_x \bullet \rho)$$

where N is the number of grid cells in a sub-basin; ALV_x is annual nitrogen load in grid cell x; Y_x is annual water yield in grid cell x; ρ is the threshold concentration of nitrogen in the runoff, which can be specified based on the surface water quality standard of China; and correspondingly, $Y_x \cdot \rho$ represents the allowable amount of nitrogen export in grid cell x.

This study utilized the calibrated model presented in Table 1 and land use data as of 2020 to estimate WP_D for each sub-basin based on high ($\rho = 1$ g m^{-3}) and low ($\rho = 1.5$ g m^{-3}) surface water quality standards, as recommended by the State Environmental Protection Administration of China (2002), and under both average and dry climate conditions as previously described. Subsequently, by comparing the WP_D to the WP_S for each sub-basin, any sub-basin with a WP_D exceeding its WP_S was classified as having degraded water quality, and consequently identified as being subject to quality-based water scarcity.

2.3.3. Comprehensive assessment combining water quantity and quality dimensions

This final step of the assessment comprehensively diagnosed one of the four categories of water scarcity for each sub-basin of the Taihu Basin based on the supply-demand budget of water yield and water purification services, as quantified in the previous two steps (Fig. 2). Category I included any sub-basin with WY_D greater than WY_S but WP_D lower than WP_S. Category I sub-basins were only subject to quantity-based water scarcity, because they had insufficient water quantity but adequate water quality. Category II encompassed sub-basins with WY_D lower than WY_S but WP_D greater than WP_S. Category II basins were only subject to quality-based water scarcity, because they had sufficient water quantity but degraded water quality. Sub-basins falling into Category III had WY_D greater than WY_S and WP_D greater than WP_S, and were subject to both quantity- and quality-based water scarcity. Sub-basins that fell outside of these three categories were not subject to any form of water scarcity and were placed into Category IV. Using these assessment results, we calculated the areal proportion, land-use composition, and population distribution across the four groups of sub-basins to respectively infer the characteristics, potential causes, and consequences of water scarcity in the Taihu Basin.

On the basin-wide scale, water scarcity was assessed using two different algorithms. The first algorithm assumed that every drop of water yield in the basin, regardless of its water quality status, should be counted for comparison with water demand. As such, we measured water scarcity simply based on the budget (WY_B) between the total water withdrawal (WY_{D_basin}) and total water yield (WY_{S_basin}) of the Taihu Basin, as shown in the equation below.

$$WY_B = \frac{WY_{S\_basin} - WY_{D\_basin}}{WY_{D\_basin}}$$

The second algorithm assumed that only water yield with adequate water quality was suitable for water use in the Taihu Basin. With this assumption, we measured the water budget (WY_B) by comparing the total water withdrawal (WY_{D_basin}) in the basin to the sum of water yield in the sub-basins where WP_S exceeded WP_D (i.e., sub-basins of types I and IV) as follows.

$$WY_B = \frac{\sum_{j=1}^{M} WY_{Sj} - WY_{D\_basin}}{WY_{D\_basin}}, \text{if } WP_{Sj} \geq WP_{Dj}$$

where WY_{Sj} represents water yield in the jth sub-basin; WP_{Sj} and WP_{Dj} represent water purification service supply and demand in the jth sub-basin, respectively; and M is the number of sub-basins where WP_{Sj} exceeds WP_{Dj}.

In both equations above, a negative value of WY_B indicates the severity of water scarcity as the proportion of unmet water demand, whereas a positive value of WY_B indicates the proportion of surplus water supply in the Taihu Basin.

2.4. Scenario development for alleviating water scarcity

Based on the assessment models developed in Section 2.3, several water and land management measures could be implemented to alleviate water scarcity in the Taihu Basin, but their potential individual and interactive effects remain unclear. This study examined the effectiveness of four such scenarios, as described in Table 2. The Water Conservation (WC) scenario aimed to reduce water withdrawals and alleviate only quantity-based water scarcity through improved water use efficiencies. On the other hand, the Nitrogen Reduction (NR) scenario targeted only quality-based water scarcity by reducing nitrogen input and output from cropland and aquaculture ponds through improved land management. The Grain for Green (GG) scenario aimed to primarily alleviate quality-based water scarcity by reforesting hilly and riparian croplands to reduce nitrogen export and enhance retention. The Integrated Management (IM) scenario combined all the measures proposed under the former three scenarios and was expected to alleviate both quantity- and quality-based water scarcity compared to the baseline scenario (i.e., actual land and water use as of 2020). In summary, this study assessed water scarcity for the Taihu Basin and its sub-basins by crossing the two climate conditions (average vs. dry) and the two water quality standards (i.e., high with $\rho = 1$ g m^{-3} and low with $\rho = 1.5$ g m^{-3} for nitrogen concentrations) with the five alternative scenarios (including the baseline scenario), resulting in a total of 20 combinations of results illustrated in Fig. 3.

3. Results

3.1. Basin-wide scale water scarcity assessment

Table 3 shows that under the baseline scenario, total water supply slightly exceeded total water demand in the Taihu Basin by less than 5% under average climate conditions, regardless of water quality status. However, when polluted water sources were excluded, clean water supply fell short of total water demand by 29% and 75% under low ($\rho = 1.5$ g m^{-3}) and high ($\rho = 1$ g m^{-3}) water quality requirements, respectively. In contrast, total water supply and clean water supply were less than 70% and 20% of total water demand, respectively under dry climate conditions. The effects of climate were the strongest under low water quality requirements, as the proportion of unmet water demand for the baseline scenario nearly tripled from 29% to 81% under drier climate conditions. Similarly, each of the four water and land management scenarios (i.e., WC, NR, GG, and IM) showed a consistently higher proportion of unmet water demand under drier climate conditions and higher water quality requirements.

Table 3 also compares the water budget values under four water and land management scenarios to those under the baseline scenario. Without considering water quality requirements, WC increased the proportion of surplus water supply by 26% under average climate conditions and decreased the proportion of unmet water demand by 17% under dry climate conditions. However, NR and GG had limited effects on water supply and demand budget under both climate conditions. When considering the low water quality requirement, WC decreased the proportion of unmet water demand by 5–18% under both climate conditions, while NR and GG had a greater impact with a decrease of 13–28% and 12–24%, respectively. IM led to a fundamental transition from water deficit to surplus, increasing water budget values from a negative 29% to a positive 31% under average climate conditions. When considering the high water quality requirement, WC, NR, and GG reduced the proportion of unmet water demand by no more than 15% and 3% under average and dry climate conditions, respectively. However, IM led to a significant reduction in unmet water demand of over 50% under average climate conditions and a modest decrease of 7% under dry climate conditions.

3.2. Sub-basin scale water scarcity assessment

For each sub-basin of the Taihu Basin, we identified one of four types of water scarcity status: quantity-based, quality-based, quantity- and quality-based, and no water scarcity (Fig. 3). In general, sub-basins in the northeastern region with high levels of urbanization experienced quantity-based water scarcity (depicted in light red). Agricultural sub-basins distributed throughout the Taihu Basin experienced quality-based water scarcity (depicted in yellow), while the forested sub-basins in the southwestern hilly region were largely free from water scarcity (depicted in cyan) under most conditions. However, under dry climate conditions and high water quality requirements, the northern part of the basin experienced both quantity- and quality-based water scarcity (depicted in dark red). For instance, in the baseline scenario (Fig. 3a–d), the proportion of sub-basins subject to both types of scarcity increased by 14–20% under higher water quality requirements and 45–51% under drier climate conditions.

Of the four water and land management measures, WC was shown to be the most effective in addressing quantity-based water scarcity. Under average climate conditions with low water quality requirements, the WC scenario resulted in a 13% reduction in sub-basins previously impacted

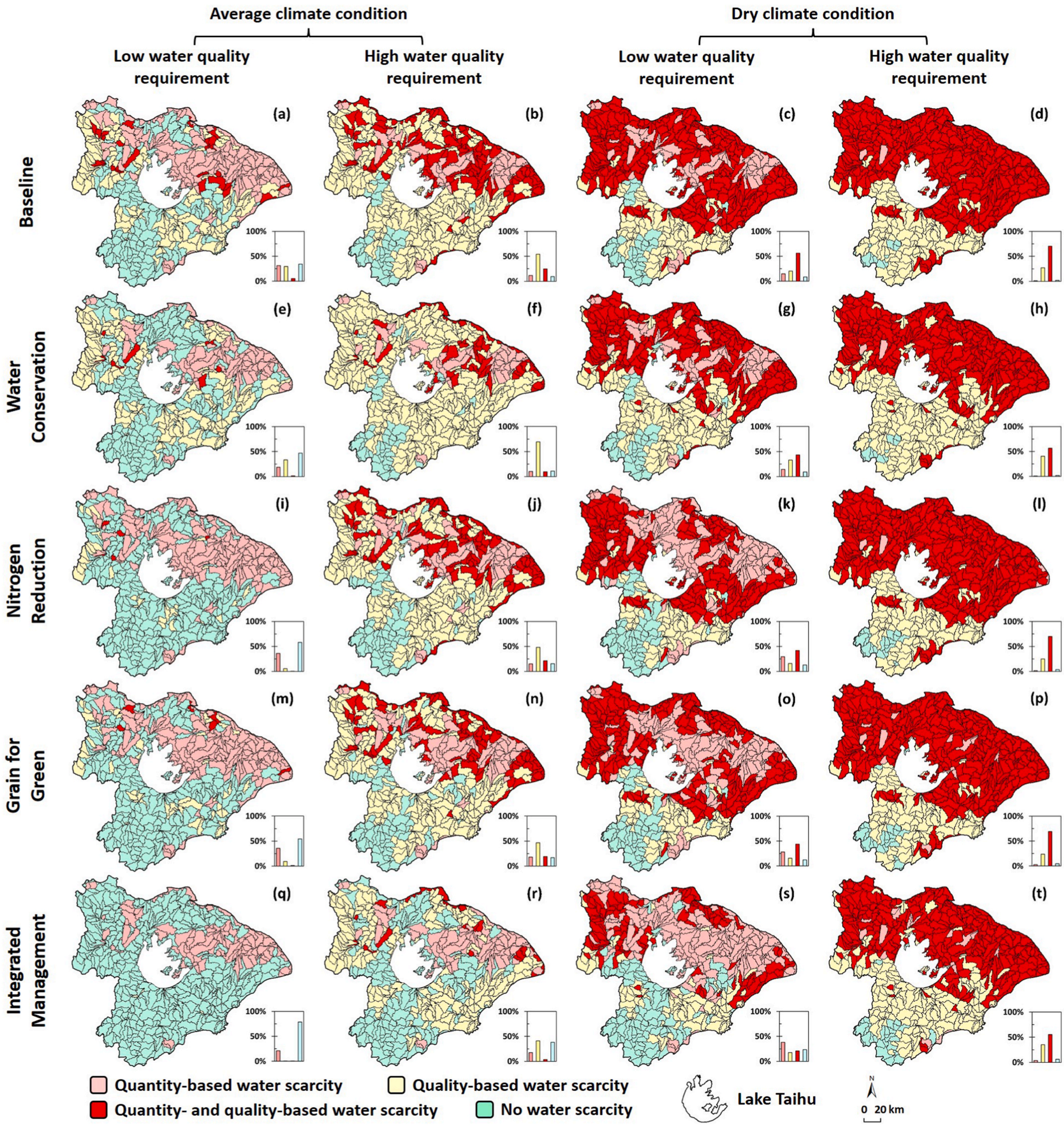

Fig. 3. The four types of water scarcity status identified for each sub-basin under different scenarios. The accompanying bar charts illustrate the proportion of sub-basins that fall into each of these four categories.

by quantity-based water scarcity (Fig. 4a). For the remaining three conditions, 12–15% of sub-basins affected by both quantity- and quality-based water scarcity under the baseline scenario experienced an improvement in their water scarcity status, shifting to being only subject to quality-based water scarcity under the WC scenario (Fig. 4b–d).

NR and GG scenarios exhibited similar efficacy in mitigating quality-based water scarcity. Under average climate conditions with low water quality requirements, NR and GG scenarios led to 24% and 21% reductions, respectively, in the area of sub-basins impacted by quality-based water scarcity, as demonstrated in Fig. 4e and i. In the case of dry climate conditions with low water quality requirements, the NR and GG scenarios respectively resulted in 14% and 13% of sub-basins previously impacted by both quantity- and quality-based water scarcity shifting to being only subject to quantity-based water scarcity, as shown in Fig. 4g and k. However, both NR and GG were found to be less effective in mitigating quality-based water scarcity under higher water quality requirements, as illustrated in Fig. 4f, h, 4j, and 4l.

Integration of WC, NR, and GG into the IM type proved to be highly

Table 3
Water supply and demand budget in the Taihu Basin under different climate conditions, water quality requirements, and water and land management scenarios. Positive and negative percentages indicate excess supply and demand, respectively.

Scenario	Average climate condition			Dry climate condition		
	No water quality requirement	Low water quality requirement	High water quality requirement	No water quality requirement	Low water quality requirement	High water quality requirement
Baseline	4.5%	−28.6%	−75.2%	−30.7%	−80.6%	−98.8%
Water Conservation	30.6%	−10.8%	−69.0%	−13.3%	−75.8%	−98.4%
Nitrogen Reduction	4.5%	−1.1%	−64.3%	−30.7%	−67.5%	−97.3%
Grain for Green	5.2%	−5.1%	−60.2%	−30.3%	−68.6%	−95.5%
Integrated Management	31.5%	31.3%	−24.7%	−12.8%	−44.1%	−91.5%

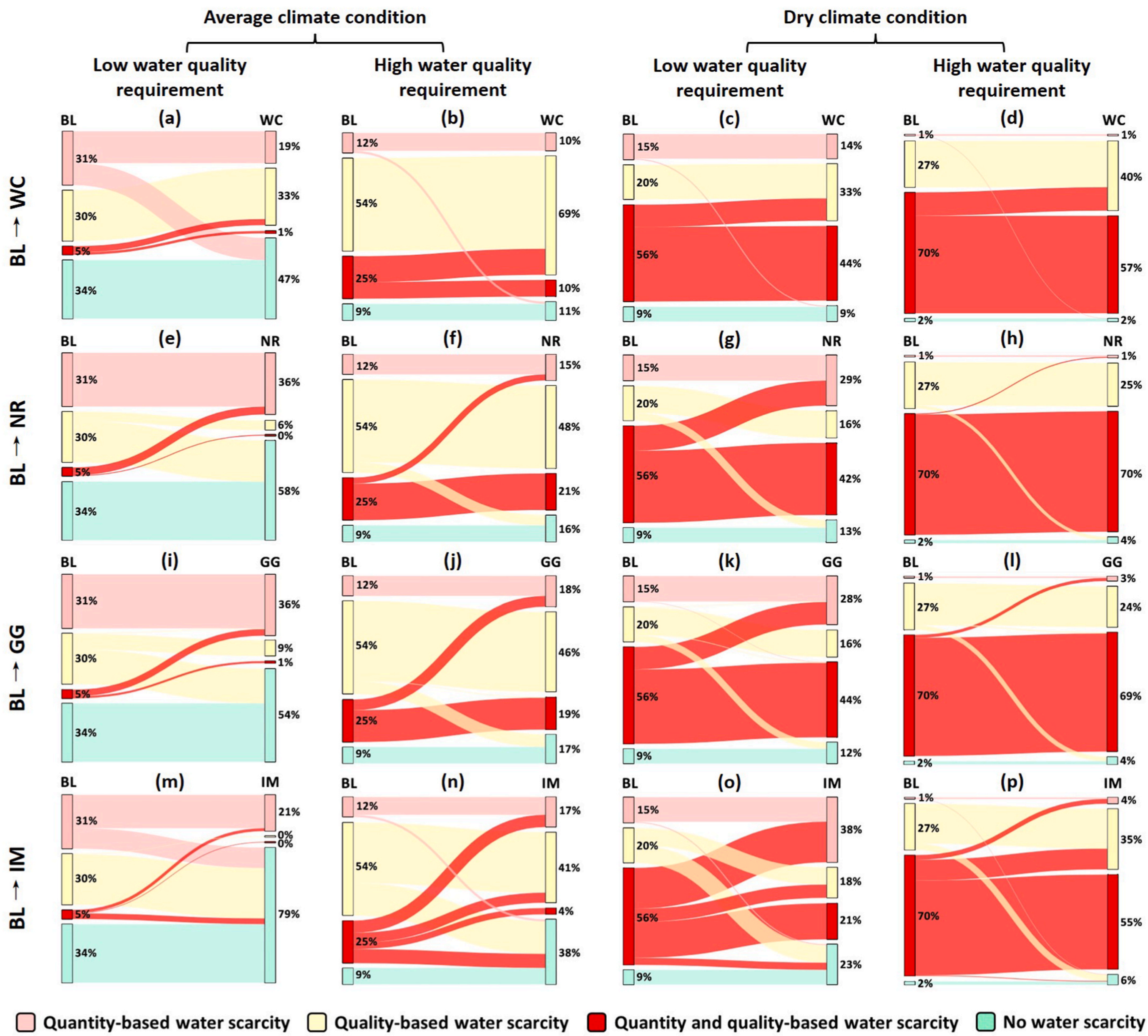

Fig. 4. Conversions between the four types of water scarcity status under the baseline and four water and land management scenarios (BL: baseline, WC: water conservation, NR: nitrogen reduction, GG: grain for green, IM: integrated management).

effective in addressing both quantity- and quality-based water scarcity. As compared to the baseline scenario, IM resulted in a significant decrease in the proportion of water-scarce areas (including quantity-based and quality-based) by 29–45% under average climate conditions, as depicted in Fig. 4m and n. Additionally, IM considerably reduced the proportion of quality-based water scarcity by 37%, and moderately reduced the proportion of quantity-based water scarcity by 12% under dry climate conditions with low water quality requirements (Fig. 4o). However, IM had a relatively mild impact under dry climate conditions with high water quality requirements, reducing the proportion of water-scarce areas by only 4% (Fig. 4p).

3.3. Land-use composition among the four types of sub-basins

The distribution of land-use types across the four types of sub-basins subject to varying degrees of water scarcity is depicted in Fig. 5. Sub-basins with only quantity-based water scarcity (type I) had a higher proportion of urban land compared to the other three types of sub-basins. Type II sub-basins, which were solely subject to quality-based water scarcity, were dominated by cropland, covering over half of the area. Aquaculture ponds constituted a small proportion of land use across all four types of sub-basins, with the exception of type III sub-basins, where both quantity- and quality-based water scarcity co-occurred under average climate conditions with low water quality requirements. Here, aquaculture ponds covered a substantial one-fifth to one-third of the total land area (Fig. 5a, e, 5i, and 5q). Finally, forest land

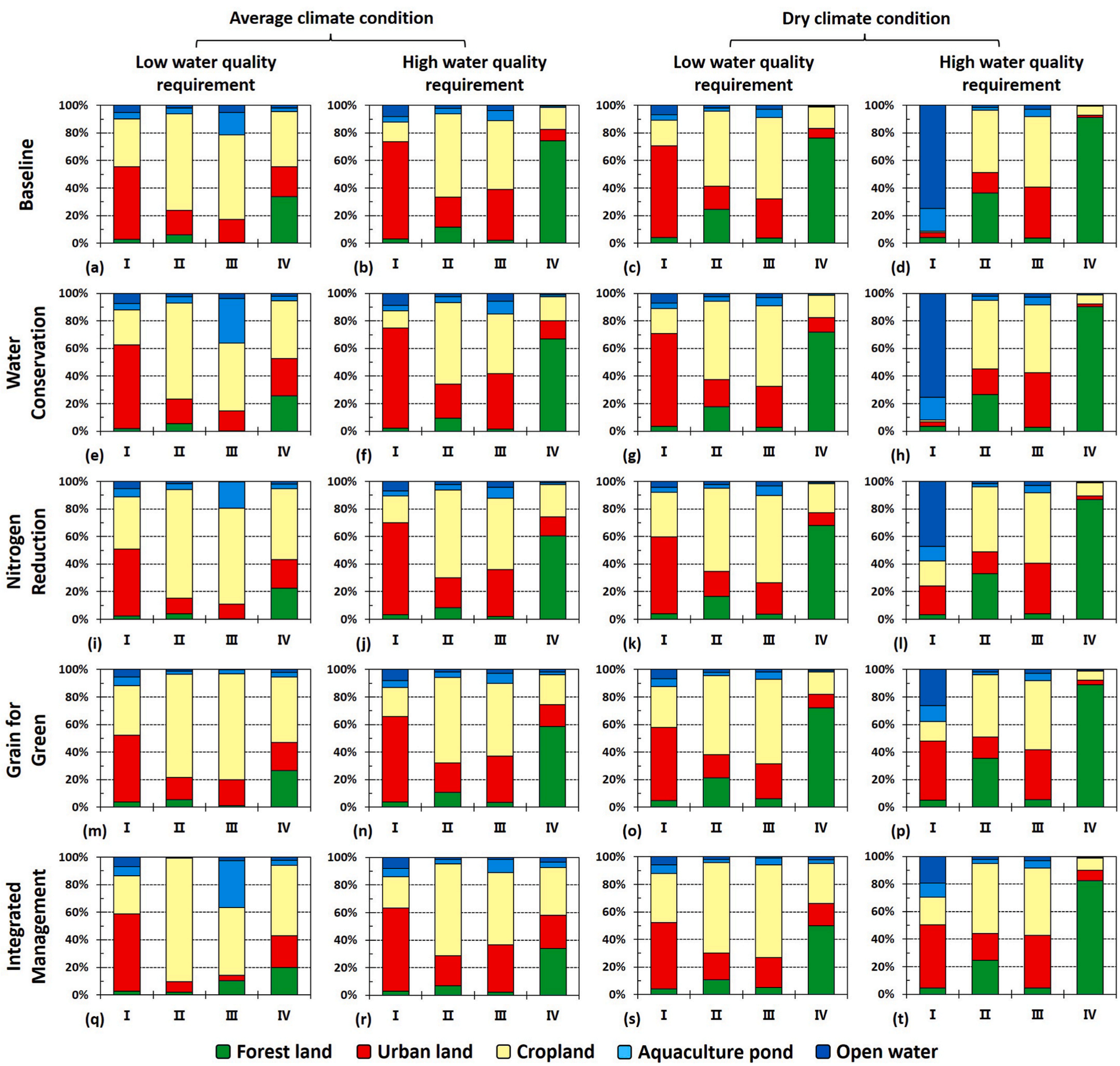

Fig. 5. Land-use composition across the four types of sub-basins under 20 combined scenarios. Type I sub-basins were only subject to quantity-based water scarcity, type II sub-basins were only subject to quality-based water scarcity, type III sub-basins were subject to both quantity- and quality-based water scarcity, and type IV sub-basins were not subject to any form of water scarcity.

was mainly concentrated in type IV sub-basins, which had no water scarcity problem.

Our observations reveal that the proportion of cropland in type II sub-basins decreased, while the proportion of forest land in type IV sub-basins increased under drier climate conditions and higher water quality requirements. For instance, under average climate conditions with low water quality requirements, cropland covered more than 70% of type II sub-basins, while forest land covered less than 40% of type IV sub-basins (Fig. 5a, e, 5i, 5m, and 5q). Conversely, under dry climate conditions with high water quality requirements, cropland covered less than 50% of type II sub-basins, while forest land covered more than 80% of type IV sub-basins (Fig. 5d, h, 5l, 5p, and 5t). Moreover, we found that under the IM scenario, the proportion of cropland in type II sub-basins increased by 6–20%, while the proportion of forest land in type IV sub-basins decreased by 9–40% as compared to the baseline scenario (Fig. 5a–d and 5q-5t). These findings suggest that land-use composition is strongly associated with water scarcity risks in the Taihu Basin. The association may strengthen during drier years or stricter water quality standards and weaken due to improved water and land management practices.

3.4. Populations potentially affected by water scarcity

By analyzing the population distribution across the four types of sub-basins in the Taihu Basin, we identified populations potentially facing water scarcity risks in the absence of adequate water transfer and treatment facilities. As shown in Fig. 6, under average climate conditions with low water quality requirements, the baseline scenario posed potential water scarcity risks to over 80% of the population (37 million), but the implementation of the IM scenario resulted in a reduction of almost 30% (13 million) of the affected population. Quantity-based water scarcity was the primary threat, affecting 51–68% of the population (23–31 million), whereas quality-based water scarcity impacted no more than 15% of the population (7 million) across all five scenarios. Under average climate conditions with high water quality requirements, quantity-based water scarcity remained a major threat to over half of the Taihu Basin's population, while quality-based water scarcity affected an additional 23–45% of the population (10–20 million) across all five alternative scenarios. Just less than a quarter of the population (11 million) was free from any form of water scarcity under the IM scenario. Under dry climate conditions with low water quality requirements, quantity-based water scarcity became the prevailing threat, potentially affecting 80–90% of the population (36–41 million), with less than 10% of the population (5 million) located in sub-basins with sufficient natural supply of clean water resources even under the IM scenario. Under dry climate conditions with high water quality requirements, the proposed water and land management measures (i.e., WC, NR, GG, and IM) were ineffective in reducing the number of affected people, leaving 75–90% of the population (34–41 million) potentially subject to both quantity- and quality-based water scarcity.

Our study also revealed that the proportion of affected population was notably higher than the proportion of unmet water demand in the Taihu Basin under alternative scenarios. For instance, under average climate conditions with low water quality requirements, clean water supply fell short of total water demand by less than 30% under the baseline scenario (Table 3). However, over 80% of the population was potentially affected by water scarcity across the basin (Fig. 6). Even under the IM scenario, where clean water supply exceeded total water demand by over 30%, more than half of the total population still faced potential water scarcity issues. Similarly, under average climate conditions with high water quality requirements, we estimated only a quarter of unmet water demand, but three-quarters of the affected population under the IM scenario. These results identify significant spatial mismatches between clean water supply and the distribution of the population (i.e., beneficiaries) across the Taihu Basin. This mismatch exacerbated the severity and impact of water scarcity, especially in densely populated sub-basins.

4. Discussions

4.1. Quality matters for water scarcity

Effective management of water resources for human use must consider both water quantity and quality (van Vliet et al., 2017), and therefore, water scarcity assessments should no longer be limited to water quantity issues. Instead, water quality should be explicitly integrated into the water scarcity assessments, such as the scarcity of clean water, which is most relevant for human use and consumption. Unfortunately, most previous studies have focused solely on water quantity, neglecting the effects of water quality degradation (Mdee et al., 2022). However, van Vliet et al. (2021) found that 30% of the world's population faced quantity-related water scarcity between 2000 and 2010, while an additional 10% experienced quality-related but not quantity-related water scarcity during the same period. In China, two previous studies indicated that northern arid regions suffered from severe quantity-based water scarcity, while pollution worsened quality-based water scarcity in the eastern and southern humid regions (Li et al., 2022; Ma et al., 2020). Using Beijing as an example, Zeng et al. (2013) estimated that the city's five major river basins faced both quantity- and quality-related water scarcity due to unsustainable water use and pollution.

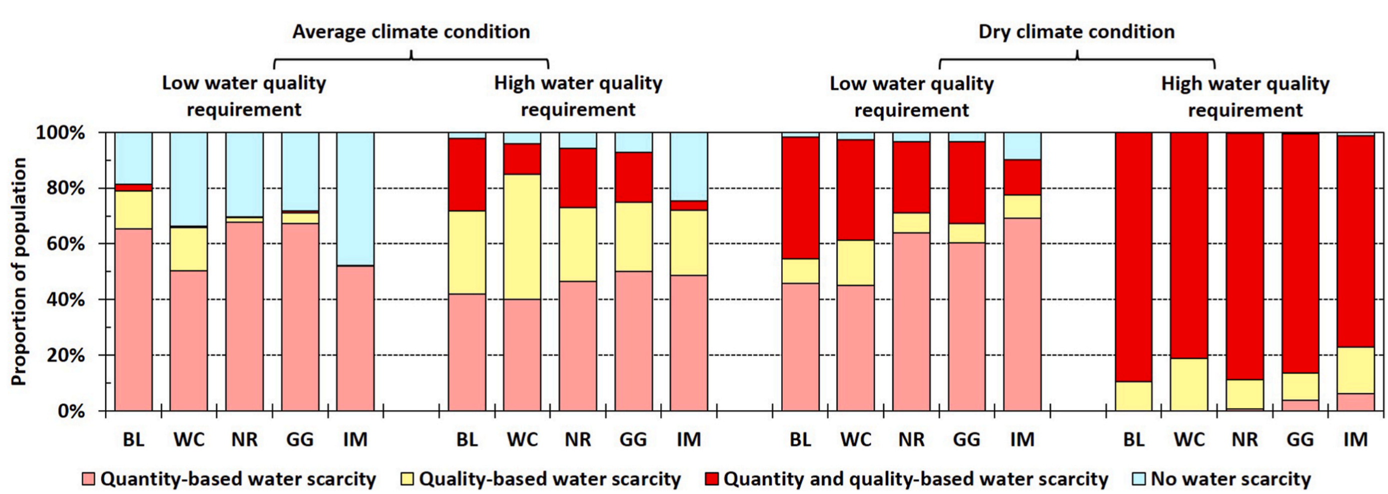

Fig. 6. The proportion of population distributed across the four types of sub-basins under alternative scenarios (BL: baseline, WC: water conservation, NR: nitrogen reduction, GG: grain for green, IM: integrated management).

Our study on the Taihu Basin in southeastern China found that water quality degradation significantly contributed to water scarcity in three ways. First, degraded water quality reversed the basin's water budget from surplus to deficit under average climate conditions. Specifically, total water supply exceeded total demand by only 5% in the basin under the baseline scenario. However, once polluted water resources were excluded, the remaining clean water supply fell short of total demand by up to 75%, which likely will drive drastic shifts in water resources management and interventions (Table 3). Second, quality-based water scarcity affected large areas of the Taihu Basin. For example, under the baseline scenario with high water quality requirements, quality-based water scarcity affected 26–42% more of the area than quantity-based water scarcity (Figs. 3 and 4). This indicates that water quality degradation was the primary cause of water scarcity in the basin. Third, quality-based water scarcity potentially affected a significant population in the Taihu Basin. Under the baseline scenario and average climate conditions with high water quality requirements, 26% of the total population (12 million) faced both quantity- and quality-based water scarcity, and an additional 30% of the population (14 million) experienced quality-based water scarcity alone (Fig. 6). Hence, it is critical to consider the proportion of populations affected by water scarcity and their spatial variations, in addition to the percent of water deficit, in the water scarcity assessments. Overall, our findings underscore the need to consider the impact of water quality on water scarcity, especially in humid regions with severe water pollution.

It should also be noted that the nitrogen load values of different land uses in the InVEST nitrogen delivery ratio model were calibrated for the typical wet year of 2020. As in other studies (Han et al., 2021; Redhead et al., 2018), we employed these calibrated nitrogen load values to simulate nitrogen retention and export under average and dry climate conditions. Despite the InVEST model's adjustment of nitrogen load values based on the ratio of the annual water yield for each grid cell to the mean annual water yield for all grid cells in the basin (Natural Capital Project, 2022), our study found that the adjusted nitrogen load value was still insensitive to changes in precipitation and water yield under different climate conditions. Our estimation showed that while annual water yield in the Taihu Basin decreased significantly by 44% and 63% under average and dry climate conditions compared to 2020, the total nitrogen load only slightly decreased by 3% and 9%, respectively. However, a previous study identified strong positive associations between total nitrogen export and annual precipitation in the Taihu Basin during 2010–2019 (Lu et al., 2022). As a result, our findings might have exaggerated the severity of quality-based water scarcity in the Taihu Basin due to overestimation of nitrogen export with the InVEST model. In future studies, given the importance of water quality metrics in assessing water scarcity, nitrogen load values in the InVEST model or any other biophysical models should be carefully adjusted according to changes in precipitation and water yield under different climate conditions to improve the accuracy of nitrogen export simulations.

4.2. Policy implications for alleviating water scarcity

Our study demonstrated the effectiveness of water and land management measures, such as water conservation, nitrogen reduction, and grain for green, in alleviating quantity- and quality-based water scarcity in the Taihu Basin. To reduce water consumption and improve water use efficiency in urban areas, it is critical to implement measures such as the reuse of reclaimed water and the layout of green infrastructure such as rainwater harvesting and bioretention pools (Chang et al., 2021; Tao et al., 2019). In agricultural areas, water conservation can be achieved by improving irrigation efficiency, while the installation of buffer strips, reduction of fertilizer application, and wetland restoration can help control non-point source pollution and protect water quality through best management practices (Pueppke et al., 2019). The implementation of the "grain for green" policy (i.e., conversion of sloping and riparian cropland into forest land) should be prioritized in the water source areas of the Taihu Basin, such as the mountainous regions in the southwest, to ensure clean water supply to the local and downstream areas (Taihu Basin Authority of Ministry of Water Resources, 2013). Furthermore, we suggest that investments in water and sanitation facilities for wastewater treatment and water diversion from the Yangtze and Qiantang Rivers to the Taihu Basin are crucial for achieving water security and resilience in the face of rapid urbanization and climate change (Lin et al., 2021). More importantly, we argue that the countermeasures proposed for the Taihu Basin (i.e., water conservation, pollution abatement, and water diversion through coupled human and natural system interventions) are applicable to solving quantity- and quality-related water scarcity issues in other parts of China and the rest of the world.

4.3. Limitations and prospects for future research

While our ecosystem service-based approach provided a new and valuable perspective for assessing water scarcity, it does have several limitations. First and foremost, our approach assessed water scarcity separately for each sub-basin, which may have led to overestimation due to the exclusion of water inflows from upstream sub-basins. Previous studies have shown that interregional water flows significantly relieve water scarcity in downstream areas of typical dryland river basins in northern China (Li, Wu, et al., 2017; Sun et al., 2023). For the Taihu Basin, we encountered challenges in determining water inflows and outflows among sub-basins due to flat terrains and artificial disturbances (e.g., river diversion through ditches and dams). It is crucial to identify hydrologic connections between upstream and downstream sub-basins and quantify their inter-basin water flows to improve the accuracy of water budget calculations in each sub-basin. Therefore, the current approach of integrating the supply and demand budget of water-related ecosystem services (Fig. 2) can be improved by incorporating ecosystem service flows into water scarcity assessments in future studies.

Although we evaluated quality-based water scarcity by considering two different water quality requirements, we assessed each sub-basin under the same water quality requirement. However, in reality, maintaining water quality varies across sub-basins based on their locations and socio-ecological conditions (Taihu Basin Authority of Ministry of Water Resources, 2013). For instance, sub-basins located in forested water source areas should have higher water quality requirements than those in downstream urban and agricultural areas. Future studies should take a dynamic and spatially explicit approach to consider these spatial variations in water quality requirements when assessing water scarcity in various sub-basins.

Our proposed water and land management measures for alleviating water scarcity included a significant improvement in water use efficiency for all water-consuming sectors, a sharp reduction in nitrogen fertilizer use in all croplands, and the implementation of "grain for green" in hilly and riparian areas (Table 2). However, these measures may seem too radical for practical implementation. While previous studies have shown that a 20% reduction in nitrogen fertilizer use has limited negative impacts on crop yield (Tian et al., 2012), implementing such measures may be socially unfeasible in the Taihu Basin. Most farmers are not aware of this fact and may not want to risk their crop yield by reducing fertilizer use by that much for water quality protection, unless there are government incentives or payments for ecosystem services that compensate for such loss in crop yields. Moreover, our proposed "grain for green" measure converts only 4% of croplands to forest land (Table 2), but it may still conflict with local cropland protection policies (Xu et al., 2021). Therefore, more flexible water and land management measures should be explored to effectively alleviate water scarcity.

5. Conclusions

Our study utilized an ecosystem service-based approach to integrate the supply and demand budget of water provision and water purification services in the Taihu Basin. This approach enabled us to measure both the quantity- and quality-related water scarcity in the region. Our findings revealed a growing scarcity in water supply due to water quality degradation and drier climates. We identified four types of water scarcity status across the sub-basins, each with a diverse land-use composition. Water conservation measures significantly alleviated quantity-based water scarcity, while nitrogen reduction and grain for green initiatives had similar effects in alleviating quality-based water scarcity. Combining these three measures contributed to alleviating both quantity- and quality-based water scarcity. However, under drier climate conditions and higher water quality requirements, these measures became less effective in reducing water scarcity and the number of affected population. We concluded that the integration of ecosystem-based solutions, such as green infrastructure, best management practices, and grain for green, with artificial facilities such as water diversion projects and wastewater treatment plants, is crucial in securing sufficient clean water supply in the Taihu Basin under future climate changes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful to the anonymous reviewers and editors for their valuable comments and suggestions. This research was supported by the National Natural Science Foundation of China (42271304, 42271106, 41971230) and the Jiangsu Talent Program for Innovation and Entrepreneurship (JSSCBS20210282).

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