Potential risk to water resources under eco-restoration policy and global change in the Tibetan Plateau

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Abstract

Water shortage is a core problem that has hindered sustainable development worldwide. The Tibetan Plateau feeds ten main rivers on which almost 20% of the world’s population depends. However, the plateau has suffered serious environmental deterioration from global warming. Since the 1980s, the Chinese government has supported ecological restoration in the Tibetan Plateau, mainly by promoting large-scale afforestation and grassland conservation. To identify the impact of global change and ecological restoration policy on the plateau, we used geographic information system (GIS) methodologies to study changes to the water supplies in the region as a result of implemented restoration programs. Moreover, we also used GIS to assess the potential risks of these changes for the long-term sustainability of water supplies. Our findings show that the quantity of water supplies in the Tibetan Plateau has increased over the last 36 years; this was attributed to an increase in precipitation as well as increasing glacial meltwater due to global warming. We also found that the water consumption associated with afforestation projects reduced the water yield, in that it was altered by the artificial establishment of plant communities, with different afforestation projects variously impacting water consumption. The potential risk areas in the plateau were mainly distributed in areas with dense human populations and villages, and intensive human activities around forest shrubs where ecological restoration programs had been largely implemented. We highlight the need for ecosystem management and monitoring within larger afforestation programs, which should include the planting of vegetation with low rates of water consumption.

1. Introduction

Many countries currently face the problem of increasing water scarcity, and it is expected that in the 1st quarter of the 21st century, one quarter of the world’s population will suffer from severe water shortages (Haddeland et al 2014). The Tibetan Plateau has suffered serious environmental deterioration from both climate change and human interventions (Xiong et al 2019). Although most of its glaciers have retreated and increased river water flow in the short term (Parmesan 2006, Jacobs et al 2016), as glaciers continue to shrink, glacial meltwater will inevitably decrease so that rivers dominated by this meltwater replenishment will undergo a gradual drying process. Any changes in glacier flow and melting rates...
could affect freshwater supplies to hundreds of millions of people in surrounding countries, namely India, Pakistan and China. Furthermore, restrictions on available water in a given region often increase competition for available water by species within an ecosystem and between the natural ecosystem and human needs (Cao and Zhang 2015).

The Tibetan Plateau is located in the Tethyan domain, one of the three major tectonic domains in China, and is composed of several (Phanerozoic) orogenic belts and suture zones (Cao and Zhang 2015). The Plateau has the highest elevation mean among the world’s recognized major plateau areas, and it is still rising due to tectonic activity. It is the source of ten rivers, including five major rivers: the Yangtze, Yellow, Mekong, Indus, and Brahmaputra (Luo et al 2018, Gao et al 2019). Because these ten rivers affects the lives of people in China and neighboring countries, in providing sufficient water resources to sustain more than 1.4 billion people (more than 20% of the global population; Gao et al 2019), the Tibetan Plateau is regarded as Asia’s Water Tower. However, because of the high altitude and harsh environmental conditions, it possesses the most fragile alpine ecosystem in the world (Xiong et al 2016, Dakhil et al 2019). Therefore, it is urgent to know the temporal and spatial changes of water supplies in the Tibetan Plateau.

For the last 30 years, the Tibetan population on the Tibetan Plateau has suffered from scarce water supplies; however, most of the meltwater has not been utilized effectively. In a global warming context then, glacial recession has accelerated, and the runoff into the seven major rivers in the Tibetan Plateau has shown unstable changes (Wang et al 2009). However, we still know little about the actual water resources changes on the Tibetan Plateau under global warming will be in the long term. Moreover, researchers have shown that if the temperature further increases, the plateau’s area under permafrost will be reduced and then the growth of vegetation will increase (Yi et al 2012). However, the impact of these vegetation changes on the distribution of water supplies across the plateau has not yet been fully studied.

Moreover, resources in these cold high-altitude areas are generally scarce, so residents often use rare plant species as fuel, putting the unique biodiversity of the area under multiple pressures (Scheffers et al 2016). The Chinese government has launched some massive eco-restoration projects in the Tibetan Plateau, intending to mitigate or reverse this environmental deterioration and protect local water supplies—for example the Sloping Land Conversion Program, Grazing Forbidden Conversion Project targeting grassland restoration—along with those targeting forest restoration: the Natural Forest Protection Program, the Three Rivers Headwater Region Program, and the Yangtze River Shelterbelt Project, among others (Wang et al, 2018, Xiao et al 2019). Although the indices related to vegetation cover of the Tibetan Plateau have increased in recent years, few people have considered the potential risk brought about by those well-intended ecological restoration plans to the water resources of this region. Reductions in water availability may occur with increases in regional evapotranspiration as a consequence of these increased afforestation effects (Liu et al 2014), which could be seen as ‘a ticking time bomb’ for the preservation of water supplies in this region.

In this study, we examined the potential impact of these changes to the water supplies of the Tibetan Plateau. To do this, we analyzed the average annual precipitation, evapotranspiration, precipitation, temperature, and increasing glacial meltwater over the last 36 years (1980–2015). We further assessed the trends in water supplies of this region, the drivers of the changes, its vegetation growth, and the potential risks looming behind the increases of total volume of water. Our study’s main objective was to tackle three key questions that need to be addressed:

(a) How have the water supplies changed on the Tibetan Plateau over the past 36 years?
(b) How did climatic changes, conservation policies, or development activities change water resources among different regions on the plateau?
(c) Where are the potential high-risk regions for water resources? What puts those areas at greater risk for their water resources?

2. Materials and methods

2.1. Study area

The Tibetan Plateau is the largest plateau in China and the highest in the world. It lies at 26°00’ N–39°47’ N and 73°19’ E–104°47’ E, covering a total land area of approximately 2.5 million km² (figure 1). Because of its high elevation, the Tibetan Plateau has cold winters and mild summers, featuring a large diurnal temperature variation. Its annual average temperature is approximately −5 °C–8 °C. As warm and humid air current from the south is blocked by multiple mountains, the annual precipitation is correspondingly reduced from 2000 mm to less than 50 mm, decreasing from southeast to northwest. The sunshine on the plateau is sufficient to sustain vegetation communities. The total annual solar radiation is 140–180 kcal cm⁻², and the total annual sunshine period is 2500–3200 h. The main river systems of the plateau can be divided into the Yellow River, Yangtze River, Lancang River (i.e. the Mekong River), Nujiang River (i.e. the Salween River), Yarlung Zangbo River (i.e. the Brahmaputra River), and the Indus.

2.2. Data sources

Land cover and land use data from 1980 to 2015 were obtained from the Data Sharing Infrastructure of the Earth System Science, at the Chinese
Figure 1. (a) Location and ecosystems' distribution of the Tibetan Plateau, China (note: 1. Indus; 2. Ganges; 3. Inner; 4. Brahmaputra; 5. Qaidam; 6. Yangtze; 7. Salween; 8. Hexi; 9. Yellow; 10. Mekong). (b) Land view of the water chain and eco-environment in Tibetan Plateau.
Academy of Science (www.geodata.cn). These data were produced at a resolution of 1 km, by using the visual interpretation of the Landsat Thematic Mapper/Operational Linescan System images, with an average overall accuracy >94% (Liu et al 2014). Meteorological data from 1980 to 2015 were obtained from the Chinese National Meteorological Information Center (http://data.cma.cn). Digital elevation model data were extracted from the Shuttle Radar Topography Mission, at a resolution of 90 m. The administrative divisions were provided by the Data Sharing Infrastructure of the Earth System Science (www.geodata.cn). The continental Global Inventory Modeling and Mapping Studies normalized difference vegetation index (NDVI) dataset (spatial resolution 8 km, covering the period from 1982 to 2015) was obtained from the Ecological Forecasting Laboratory at the National Aeronautics and Space Administration Ames Research Center (https://ecocast.arc.nasa.gov). Since these products may be affected by cloud cover, atmospheric conditions, or ice–snow cover, we first used the asymmetric Gaussian function filter to reconstruct the NDVI time-series dataset to reduce the noise and improve overall data quality. This data preprocessing procedure was carried out based on the TIMESAT 2.3 program (Ekblad and Jönsson 2015). The watershed data were obtained from the Institute of Tibetan Plateau Research Chinese Academy of Sciences (www.tpedatabase.cn). Glacier data mainly included The Second Glacier Inventory Dataset of China (http://westdc.westgis.ac.cn), and the glacier data for the Tibetan Plateau in 1976, 2001, and 2013 (www.tpedatabase.cn; Ye et al 2017).

Human population density and village settlements, which may convey the influence of human activities on changes to water resources, were obtained from the Data Sharing Infrastructure of the Earth System Science at the Chinese Academy of Science (www.geodata.cn). The afforestation data across the Tibetan Plateau were obtained from China’s annual Forestry Statistics Yearbooks (1981–2016). All cartographic data were converted into the same coordinate system (Albers conical equal area) with the same spatial resolution (1 km).

2.3. Methods

2.3.1. Quantification of water yield

To quantify the water resources (water yield), we applied a water balance equation to the hydrological series spanning 1980–2015, for which it was assumed that surface water and groundwater interactions were negligible. The water balance for a catchment can be described as follows:

\[ Q = P - ET + \Delta G, \]

where \( Q \) is the water yield (mm), as a proxy for the water yield; \( P \) and \( ET \) represent the precipitation (mm) and actual evapotranspiration (mm), respectively, and \( \Delta G \) (mm) is the water change in each watershed arising from glacier melt (mm), which is equal to the changed volume \( V \) of the glacier.

2.3.1.1. Evapotranspiration factor

Following the assumption similar to that made by Budyko (1974), the actual evapotranspiration can be estimated according to Yang et al (2014):

\[ ET = \frac{P \times ET_p}{(P + ET_p)^{1/n}}, \]

where \( ET \) is the actual evapotranspiration (mm) and \( n \) is the model-controlling parameter that determines the shape of the Budyko curve, which primarily represents the integrated effects of the catchment's land cover characteristics upon its water balance (Yang et al 2014). \( ET_p \) is the potential evapotranspiration and can be estimated by the Priestley and Taylor (PT) equation (Priestley and Taylor 1972), as follows:

\[ ET_p = \alpha \times \frac{\Delta}{\Delta + \gamma} \times (R_n - G), \]

\[ \Delta = 4098 \times (0.6108 \exp\left(\frac{17.27 T}{T + 237.3}\right)), \]

\[ \gamma = 0.665 \times 10^{-3} \times 101.3 \times \frac{293 - 0.0065H}{293} \times 5.26, \]

where \( \alpha \) is the PT coefficient of 1.26 for open water and saturated land (Priestley and Taylor 1972); \( \Delta \) is the slope of the saturated vapor pressure curve (kPa °C⁻¹); \( \gamma \) is the psychrometric constant (kPa °C⁻¹); \( R_n \) is the net absorbed radiation at the surface, expressed in MJ m⁻², which can be estimated using the calibrated radiation part of the FAO56-PM model (Yin et al 2008); \( G \) is the downward soil heat flux, also in MJ m⁻²; \( H \) is the elevation above sea level (m).

2.3.1.2. Glacier and frozen soil meltwater factor

The area of glaciers and frozen soil usually shows a significant statistical correlation with their volumes (Radié et al 2008). The statistical model relating glacier area to volume can be expressed this way:

\[ V = C \times A^\gamma, \]

where \( V \) is glacier volume and \( A \) is glacier and frozen soil area. \( \gamma \) is an exponential factor, and \( C \) is the proportionality constant. To establish this non-linear model for the plateau, the data of the Second
China Glacier Survey were used (Liu et al. 2014, Guo et al. 2015). According to the parameter estimation requirements of the model, the glacier catalog data were processed and divided into the main basins of the plateau (figure 1). In addition, the relationship between the area and volume of sampled glaciers in each basin was analyzed, and their C and gamma parameters derived accordingly (figure 2).

2.3.2. Spatial-temporal analyses
The 'Spatial Analyst' tools in ArcGIS 9.3 were used to identify the spatial characteristics (i.e. total amounts and mean capacities) of the water yield in the different provinces and river basins. To examine the variation in trends of water yield and NDVI during the study period (1982–2015), we used a least-squares linear regression model to obtain the trend of every pixel change by fitting a linear equation of water yield variables as a function of time (year). This regression approach is one of the most commonly used methods in the trend analysis of variation, and it can be described as follows (Cao and Pan 2014).

The slope (trends) and p values (significant) were calculated by programming in the Interactive Data Language 4.8 (Harris Corporation, Melbourne, FL, USA).

2.3.3. Potential risk assessment for water supplies construction
Using questionnaires, we surveyed 36 counties in Tibetan Plateau in 2017. The questionnaires were given to the experienced staff in those counties, who had worked in the county weather stations for many years. The survey response information included that of water runoff in the rivers, as well as of vegetation growth between 1990 and 2015. These questionnaires’ data served as supporting material for devising a risk assessment definition.

To objectively assess the risk to water supplies in the Tibetan Plateau, our study developed a unified risk assessment system. Based on questionnaire results, previous research (Cao et al. 2014, Xiong et al. 2019), and the trend analysis of water supplies and NDVI, this study reasoned that if a region had strong vegetation expansion (i.e. high NDVI value yr$^{-1}$) and its water yield showed a decreasing trend and water consumption showed an increasing trend, then it could be deemed as a potential risk region for water yield. Yet even if the vegetation in the area was seriously degraded (i.e. low NDVI value) but its water yield showed a decreasing trend and water consumption showed an increasing trend, it too is a potential risk region. NDVI less than −0.5 or more than 0.75, then it is under high risk; NDVI from −0.5 to 0 or from 0.25 to 0.75 then it is under moderate risk; NDVI from 0 to 0.25 then it is under low risk.

2.3.4. Correlation and regression
We used Pearson correlation analyses to investigate the relationships between the water yield change and its driving forces. A stepwise regression model of water yield change and driving factors (climate, ecological programs, social and economic factors) was used to identify their relative contribution to influencing the spatial characteristics of water supplies (Hernandez et al. 2018). All these statistical analyses were done using SPSS 20.0 (IBM Corp., Armonk, NY, USA).

2.3.5. Validation
To verify the reliability of the calculated water yield, we cross-checked these results against the observed data, which were available from China’s Water yield Bulletin from 1998 to 2015 (State Water Agency, 1998–2015). The calculation of water yield was consistently within the corresponding estimates (the r-values ranged from 0.64 (Tibet) to 0.87 (Qinghai), n = 18 (years), p < 0.01). The data from Tibet’s Water Resources Statistical Yearbook considered other types of water resources (total volume of glacial solid water, not the glacier melt water). So, the water supplies simulated by the water balance equation were lower than the observed data, but the results were still acceptable.

3. Results

3.1. Overall water supplies and NDVI trends of the Tibetan Plateau
Water supplies of the Tibetan Plateau have fluctuated over time, but the pattern is one of a general rising trend from 1980 to 2015 (rate of increase: 0.42 mm yr$^{-1}$). Because adequate water supplies are conducive to vegetation growth, the NDVI and evapotranspiration data also showed a similar trend of increasing over time. At the continental scale, maximum levels of water supplies and NDVI occurred in 2010 (figure 3), in part due to increased rainfall and temperature in the plateau (figure 3).

3.2. Increasing regional water supplies in the Tibetan Plateau
At the regional scale, almost all parts of the Tibetan Plateau underwent an increase in water yield from 1980 to 2015 (figure 4), but this was particularly pronounced in the middle part of the plateau, especially in the headstream conservation area (Three Rivers Headwater Region) of the three rivers (the Yellow, Yangtze, and Mekong). By contrast, water supplies decreased overall in the Shannan and Ali regions of the Brahmaputra River.

3.3. Assessment of changes in water yield
Regression results showed that six parameters significantly affected the water yield changes from 1980 to 2015 (table 1). Increasing precipitation contributed the most to water yield increase (accounting for
Figure 2. Power function-fitting results for the relationship between glaciers’ area and volume of each basin in the Tibetan Plateau.
Figure 3. Interannual variation in the precipitation, temperature, evapotranspiration, water resources, NDVI, and glacial area in the Tibetan Plateau. Black dashed lines indicate a linear fit to the data for the period of 1980–2015 (the rise or decline of the black line indicates an increasing trend or a decreasing trend).
Figure 4. Spatial-temporal pattern of water resources in the Tibetan Plateau from 1980 to 2015, with crosses indicating those areas that underwent significant changes over time ($p < 0.05$).

Table 1. Regression results for the relationships between various driving forces and water yield of the Tibetan Plateau from 1980 to 2015. Contributions (%) represent the proportion of the total change in water yield accounted for by a given driving factor. The driving forces including the trend of precipitation, the trend of temperature, the trend of evapotranspiration, elevation, slope and village density.

| Independent variable       | Contribution (%) |
|---------------------------|------------------|
| Precipitation             | 0.893∗∗          |
| Temperature               | 0.505∗∗          |
| Evapotranspiration        | −0.337∗∗         |
| Elevation                 | 0.535∗∗          |
| Slope                     | −0.369∗∗         |
| Village density           | −0.009           |
| $R^2$                     | 0.545            |
| $N$                       | 797              |

Parameters with significant contributions to the regression were identified by repeated-measures analysis of variance. ∗∗ $p < 0.01$.

33.72% of the total change, followed by increasing elevation (20.2%), increasing temperature (19.07%), decreasing slope ($-13.94$%), and decreasing evapotranspiration ($-12.73$%).

3.4. Increased vegetation cover and potential risks: water consumed by afforestation in risk regions

In comparing the linear and nonlinear regressions, the polynomial regression (significance) usually performed better than linear regression (non significance) for quantifying the relationship between the variation in NDVI and water yield change in the plateau. NDVI variability, as an indicator of vegetation growth or vegetation degeneration (infertile soil, vegetation reduction, natural environment erosion and desertification), was significantly ($p < 0.01$) correlated with the water yield change. As figure 5 shows, water supplies gradually increased as the NDVI increased from vegetation degeneration region (NDVI $< -0.5$), to the vegetation region with a slight expansion, reaching a maximum ($0 <$ NDVI $< 0.25$), but then gradually decreased with further increases in the NDVI (NDVI $> 0.75$; i.e. vegetation significantly expanded to become high abundant of biomass of vegetation.

These risk areas were found distributed in areas with abundant water supplies formed mainly by glacial meltwater, low altitude, dense human populations and villages, and intensive human activities (table 2). The risk areas in the plateau were mainly distributed around forest shrubs where ecological restoration programs had been largely implemented (figure 5). The planted area of shelter forest accounted for 85.94% of the total afforestation area in the Tibetan Plateau (figure 6(a)). The water consumed by these afforested areas reached 1.17 billion m$^3$ in 2015, which was 10.21% of the annual water supplies (absolute average value) from 1980 to 2015 (figure 6(b)).
Figure 5. Regression analysis of the relationship between (a) NDVI variation and water resources change, and (b) risk characteristics between NDVI variation and water resources change. (c) The spatial distribution of risk regions of water supplies in the Tibetan Plateau.
Table 2. Characteristics of the background and change in the risk regions for various driving factors and water supplies in the Tibetan Plateau.

| Background characteristics | Water resource (mm km$^{-2}$) | Elevation (m) | Slope ($^\circ$) | Village (Kernel Density) | Population (persons km$^{-2}$) |
|----------------------------|--------------------------------|---------------|-----------------|-------------------------|-------------------------------|
| Risk region                | 123.75                         | 3878.40       | 15.61           | 147.43                  | 10.12                         |
| Non-risk region            | 64.11                          | 4544.01       | 9.03            | 39.94                   | 2.36                          |

| Change characteristics | Water yield (mm yr$^{-1}$) | NDVI (NDVI yr$^{-1}$) | Precipitation (mm yr$^{-1}$) | Temperature ($^\circ$C yr$^{-1}$) | Evapotranspiration (mm yr$^{-1}$) |
|------------------------|-----------------------------|-----------------------|------------------------------|-----------------------------------|----------------------------------|
| Risk region            | −1.10                       | 0.33                  | −0.64                        | 0.05                              | 0.75                             |
| Non-risk region        | 0.59                        | 0.06                  | 0.98                         | 0.06                              | −0.25                            |

Figure 6. (a) Total area of afforestation in the Tibetan Plateau from 1980 to 2015. (b) Estimated water consumption by planted forest and natural forest or steppe vegetation.

4. Discussion

Mountain glaciers have melted by 21% in volume in the past 5 decades in the Tibetan Plateau; hence, the plateau's glaciers have entered into a full state of withdrawal (figure 1; Gao et al. 2019). Therefore, studying the water supplies of the Tibetan Plateau is a crucial step in protecting its environment, addressing 20% of the world’s population needs. Our results showed that changes to the water supplies of the plateau are mainly attributable to precipitation, which contributed to 33.72% of the increase in water volume over the study period (Stephens 2017). Additionally, the runoff into some major rivers originating in the Tibetan Plateau, such as the Brahmaputra River, has risen due to glacial melting resulting from global warming; in the short term, this will increase the potential demand for water to support human needs, economic development, and environmental protection (Su et al. 2016, Wu et al. 2018). For the Brahmaputra River, more than 50.0% of its total runoff increase was due to long-term increases in glacier melt (Su et al. 2016); however, this increased water input can only last as long as the glaciers themselves last (Cao and Zhang 2015). Since the glaciers are shrinking steadily (figure 3), these flows cannot continue indefinitely. Moreover, our observations revealed that potential evapotranspiration in this region can reach 650 mm yr$^{-1}$, far exceeding the average annual precipitation of approximately 360 mm over the last 36 years (figure 3). So, the mountain glacier provides the supply of perennial glacial meltwater that supports the evapotranspiration of local vegetation.

We found that water supplies in the central Tibetan Plateau have increased over the last 30 years, especially in the Three Rivers Headwater Region (figure 4). This fragile region is the source of several major rivers in Asia and is considered to be key ecological resource for eastern China (Xiong et al. 2019). This increase could be attributed to the implementation of the Three Rivers Headwater Region Program (Aredehey et al. 2018, Xiong et al. 2019),
which began in 2005 and mainly included artificial rainfall enhancement, grassland remediation, grazing prohibition, and ecological migration. Our results confirmed this ecological restoration project for the Tibetan Plateau has been effective. Further, to address environmental degradation and to improve human livelihoods, China also implemented a number of national afforestation policies, based on the paying for ecosystem services. These include the Natural Forest Protection Project (NFPP) and the Grain to Green Program (GTGP) (Cao et al. 2017). However, forest vegetation can reduce the runoff in a region, especially in arid and semiarid areas where the trees planted consume excessive amounts of limited water (Cao and Zhang 2015). The planted area of shelter forest accounted for 85.94% of the total afforestation area in the Tibetan Plateau (figure 6(a)). Moreover, the introduction of non-native tree species were generally encouraged in the GTGP and NFPP regions (Yang et al. 2018). In the present study, we found that the water consumed by afforested areas reached 1.17 billion m$^3$, which amounted to 10.21% of the annual water supplies from 1980 to 2015 (figure 6(b)). Water consumption by those artificial forests greatly exceeds that by natural vegetation in this area (Cao and Zhang 2015) and has exacerbated existing water shortages. Nonetheless, if the land had instead been conserved as natural forest—comprising the dominant, native natural vegetation in most of the afforestation areas—a large quantity of water would still have been consumed, as much as 0.85 billion m$^3$ in 2015 (9.13% of the annual water supplies). By contrast, if the land had been conserved as natural steppe, less water would have been consumed, reaching approximately 0.59 billion m$^3$ in 2015 (5.14% of the annual water supplies). This reduction in water consumption (0.58 billion m$^3$) vis-à-vis current land conditions would have eliminated the water deficit in the risk regions (0.21 billion m$^3$), generally reduced water risks, and provided a more sustainable life for people in the Tibetan Plateau region (Karlsen et al. 2018).

According to recent research, the total runoff of the Tibetan Plateau’s river basins would either remain stable or moderately increase by 2.7%–22.4% in the near-term future (Su et al. 2016). However, our study uncovered a potential risk to water supplies in the plateau, given the significant nonlinear correlations between its changed vegetation cover and the change in water supplies (figure 5). When water yields become scarce and evapotranspiration starts to increase, vegetation will be forced to extract belowground water to survive. This depletes the water near the surface, increasing the depth of the groundwater table and thereby reducing the water available to all vegetation, which will expand the potential risk area (Yang et al. 2009). Substantial increases in the agricultural, and afforestation activities augments the evapotranspiration of water and leads to a false green prosperity (Cao and Zhang 2015, Lu et al. 2018) in the arid and semi-arid areas of the Tibetan Plateau. Increased vegetation cover in these dense regions will result in evapotranspiration accounting for a greater fraction of the water budget (Xiong et al. 2019). If water is over-consumed in the plateau and precipitation is insufficient to compensate for water lost via evapotranspiration, the vegetation will begin to take up subsurface water, thereby generating dry conditions that lead to further losses of vegetation (Yu et al. 2018). Our results (table 2) also showed that these high risk regions correspond to low altitude areas with abundant water supplies, dense populations and villages, and intensive human activities. Large-scale tree planting and afforestation activities in the past decade were carried out around existing forest areas; this led to the simultaneous increase in NDVI and evapotranspiration intensity in the Tibet Plateau (Yu et al. 2018). However, with declining precipitation, water supplies in the plateau have shown a significant downward trend. Moreover, the risk regions, which have scarce water supplies, highly improved NDVI, high intensities of human activity, and increased evapotranspiration (table 2), were mainly concentrated around the forest–shrub land, indicating that large-scale plantations near the roads have already threaten regional water resources security (Pei et al. 2018). Other contributing factors such as the irrigation of shelter forests has driven water infiltration and hastened the drop in water levels (figure 6). So, it is not possible to restore the environment and water resources of the Tibetan Plateau by means of artificial afforestation.

Over 40 years have passed since the 1st Tibetan Plateau scientific expedition was launched in the 1970s. The environment (including water supplies) on the Tibetan Plateau has undergone massive changes. This study provides a reference map for water supplies’ investigation in the forthcoming 2nd Tibetan Plateau scientific expedition. Although our data resolution was insufficient to accurately calculate the distribution of water supplies in the whole plateau (Gao et al. 2019), our study was able to produce a map showing those suitable areas where the network of weather and isotope-monitoring stations should extend into the future.

Based on this study’s results, an ecological management mechanism for aquatic ecosystem resources in the Tibetan Plateau should be established to promote the effective use of water resources and to limit the degradation of the ecological environment.

5. Conclusions

Water supplies in the Tibetan Plateau have changed drastically in the past 36 years. Specifically, the quantity of water supplies has increased, largely because of
more precipitation as well as increasing glacial meltwater due to global warming. Conversely, ecological restoration activities to protect the Tibetan Plateau have augmented its water supplies, but some of these policy-driven activities have also exacerbated damage to water supplies. The water resources risk areas in the plateau were mainly distributed in areas with dense human populations and villages, and intensive human activities around forest shrubs where ecological restoration programs had been largely implemented. Although the objective of this afforestation is commendable, it highlights the need for better overall management that takes into consideration different aspects of restoration activities to avoid their negative consequences.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contribution

All authors worked together to design this study. Xiong Q L and Xiao Y contributed to initiating and conceiving the topic of this paper; Xiao Y collected the data. Xiao Y and Xiong Q L did the analysis; Xiong Q L, Xiao Y and Xiao Q wrote the draft of this paper; all authors contributed substantially to modify and revise this paper.

Conflicts of interest

The authors declare no conflict of interest.

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