Research Article

Calculation of targeted eco-environmental water requirements in a dry inland river: a case study of the Yarkand River Basin, Xinjiang, China

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Abstract

Analysis of eco-environmental water requirements along a dry inland river under extreme drought conditions can provide a theoretical basis for the sustained utilization and management of water resources in arid regions. This paper uses the Yarkand River Basin in Xinjiang, China, as a case study to determine and assess a method to calculate targeted eco-environmental water requirements (TEEWR) for different ranges of ecological protection of inland riparian forests. The proposed method is intended to comprehensively analyze the water resources along arid inland rivers. Specifically, the ranges of ecological protection were gradually expanded at intervals of 1 km (or multiples of the smallest distance) away from the river course while the TEEWR was determined as a function of the ecological water demand of riparian forest vegetation (Y_{ec}) and its corresponding river loss (X_{loss}). The developed method was shown to be feasible for analyzing TEEWR in the Yarkand River Basin and thus provides a novel and effective approach for the rational utilization and management of water resources in inland river basins in arid regions.

Article Highlights

- Zones of ecological protection were gradually expanded at intervals of 1 km (or multiples of the smallest distance) away from the river course on both sides of the dry inland river
- The targeted eco-environmental water requirement, defined as the ecological water demand of riparian forest vegetation (Y_{ec}) and its corresponding river loss (X_{loss}), was determined for a dry inland river basin
- The developed methods for calculating targeted eco-environmental water requirements are useful, but have limitations.

Keywords Ecological protection · Ecological red line · Inland river basin · Riparian forests · Targeted eco-environmental water requirement

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1 Introduction

Water resources in inland river basins in arid regions are mainly derived from the alpine melting of snow and precipitation, which are consumed in oasis and desert areas [1, 2]. Water supply and demand in inland river basins are strongly affected by climate change and human activities [1, 2]. With the warming of global and regional climates, the inflow of water in mountainous areas initially increases before decreasing [3, 4]. Moreover, with increasing population, the amount of water used for production and domestic requirements has increased significantly, which has seriously impacted the quantity of ecological water available for surface vegetation. This increasing water demand has resulted in major ecological degradation and large-scale decline of surface vegetation. Land desertification is also aggravated, which in turn restricts the stability and development of oases, hindering the achievement of sustainable ecological, economic, and social development in the basin [3]. Therefore, it is urgent to rationally allocate limited water resources in arid basins for production, living, and ecological maintenance, and to maximize the major benefits of water in the basin.

Environmental water requirements are necessary to ensure the basic functional health of ecosystems [5]. The specific ecological–environmental water requirements of rivers refer to the water demand for the eco-environment in and outside of the river course [6]. The water demand for a river can be divided into two components: basic water requirements (the minimum amount of water that is needed in the river [7]) and targeted water requirements (the water needed to meet the protection goals of ecosystems outside of the river [8]).

Previous studies have focused on the minimum ecological–environmental water requirements [9–11], the minimum ecological flow [12, 13], and the reasonable ecological flow [14] of agricultural, industrial and ecological water use in a basin [15–17]. The basic eco-environmental water requirement (BEEWR) is the minimum amount of water that needs to be retained in the river to maintain the eco-environmental function of the river. The targeted eco-environmental water requirement (TEEWR) is the amount of water retained along a river course for the protection of riparian forests and vegetation in a dry inland river basin for a specific area. However, previous studies have yet to consider TEEWRs. In arid and hyper-arid inland river basins, river waters are not only used to ensure the health and stability of riverine ecosystems, but also are used for agriculture and to supply the ecological water demand of riparian vegetation. Therefore, BEEWR, TEEWR and the agricultural water use in a river need to be simultaneously considered. BEEWR has been calculated using several different methods [12, 13, 18–20], whereas agricultural water use can be determined using local monitoring data published in Chinese Statistical Year Books in the study area. However, at present there is no relevant research on how to calculate TEEWR. It is thus critical to systematically obtain different reasonable scales of river targeted ecological environmental protection, and to determine their ecological water demand, in order to calculate TEEWR.

In this paper, a method to calculate TEEWR for different spatial scales of ecological protection of inland riparian forests in arid areas is proposed. In addition, the Yarkand River Basin is used as a case study to assess the feasibility and limitations of the method of calculating TEEWR. The approach provides a theoretical basis for the rational utilization and management of water resources in inland river basins in arid areas. In this paper, a method to calculate TEEWR for different spatial scales of ecological protection of inland riparian forests in arid areas is proposed. In addition, the Yarkand River Basin is used as a case study to assess the feasibility and limitations of the method of calculating TEEWR. The approach provides a theoretical basis for the rational utilization and management of water resources in inland river basins in arid areas.

2 Study area and data

2.1 Study area

The studied inland river basin (the Yarkand River) is located in an arid area, and the local community's production, living, and ecological water use mainly depend on the inland river. Due to the region's natural droughts, the occurrence of sand, salt and alkali, and human activities including the unreasonable use of water resources, the original ecological balance has been substantially altered, forming a fragile ecological environment. The landscape exhibits a macroscopic pattern of wetland-forest (grass)-desert vegetation that forms a spatial matrix along river corridors. In general, the most obvious ecological characteristics of inland river basins in arid zones are their vulnerability and variability; they are sensitive to external disturbance factors and are prone to changes that are not conducive to human utilization. The lack of water resources has restricted the development of the region and affected the entire basin ecosystem. To rationally use water resources, it is necessary to put forward a well-defined plan for the use of water for production, living, and ecological purposes in river basins. Therefore, it is crucial to accurately determine the amount of water used for these purposes and, in particular, the EWRs of riparian forest vegetation attached to the specific inland river.

This paper uses the Yarkand River Basin in Xinjiang (Fig. 1) as an example of a typical inland river that is characterized by extreme drought in China. The Yarkand River originates in the Karakoram Mountains and is supplied primarily by snow and ice meltwater. Seasonal in river flow is significant and extremely uneven; large flows occur in summer, while smaller flows occur in winter. Importantly, the Yarkand River supplies water for more than 1.96 million people in southern Xinjiang. Moreover, its incoming water needs to meet the water requirements of approximately 0.60 million ha of irrigation agriculture. Irrigation in the area uses traditional flood irrigation methods. Since the efficiency of water use is extremely low, agricultural water use seriously crowds out ecological water use [21]. The Yarkand River is also one of the main sources of water to the Tarim River. In recent decades, with an increase in the population and irrigated areas in the basin, the diversion of water from irrigation areas has increased. As a result, water has not been discharged into the Tarim River since 1986 [20]. Consequently, the Yarkand River has lost its surface water replenishment function as a source stream of the Tarim River. There are also large areas of desert riparian forest vegetation distributed on both sides of the Yarkand River. Due to the large amount of water diversion to irrigated areas, the rivers on which natural vegetation depends have been cut off, resulting in a large-scale decline of desert riparian forests, soil erosion, and desertification [22]. Indeed, the function of the riparian ecosystem has been seriously diminished. Consequently, the Yarkand River not only needs to meet the requirement of water diversion in irrigated areas of the basin, but must also meet an EEWR in the river to fulfill its function as a water supply to the Tarim River as well as meet the requirements of natural desert forest vegetation. Overall, it is necessary to control water diversion in irrigation areas, and maintain BEEWR in the river. This requires a rational allocation of the remaining water resources to achieve the ecological protection of the river basin.

2.2 Data

Runoff data and the annual average river loss ($\overline{X}_{\text{loss}}$) during the past 50 years (1969–2018) were obtained from the local watershed water authority. The area, length, and maximum and minimum distribution widths of inland riparian forests were determined by analyzing recent Landsat TM images and through field work. By consulting the Kashi Administration of the Tarim River Basin in Xinjiang, $\overline{X}_{\text{loss}}$ from Kaqun to Heiniyazi in the Yarkand River Basin (Fig. 3) was found to be 15.07×10^8 m^3. In order to effectively control the diversion of water from river basins, the Chinese government issued 'The Most Stringent National Water Resources Management System and the Ecological Protection Red Line Policy' [23], which requires all regions to demarcate the maximum total amount of surface water use in river basins as soon as possible. The maximum usable total amount of surface water used in the ecological red line policy in the Yarkand River Basin was calculated to be 51.43×10^8 m^3.

3 Calculation of TEEWR

3.1 Delineation of different targeted ecological protection zones of riparian forests

Riparian forest vegetation typically occurs on both sides of inland rivers in arid areas and is generally sparse and scattered. The transverse distribution of riparian forest varies as a result between locations. The vegetation near the river is greatly affected by water in the river, while vegetation far from the river is less affected by it. Different ecological protection ranges were therefore delineated as a function of distance from the river. The delineation of different ecological protection zones was defined on the basis of the maximum and minimum distribution of vegetation perpendicular to the river on both sides of the channel. The maximum and minimum distributions of vegetation on one side of the river were defined as '*a*' km and '*b*' km, respectively, and the maximum and minimum distributions on the other side were defined ad '*c*' km and '*d*' km, respectively. When defining the ecological protection of vegetation on both sides of the river, the minimum width perpendicular to the river should be fully considered. When the minimum width of vegetation on both sides of the river was less than 1 km, the vegetation on both sides of the river was divided into an equal-difference series of '*b*' km and 'd' km. The distribution width was '*b*' km and 'd' km, '2 *b*' km and '2 'd km, and '$(n-1)$ b' km and '$(n-1)$ *d*' km, where n is an integer, and the distribution width of the farthest point from the river is '*a*' km and 'c' km, respectively; '$a-(n-1)$b' can be less than 'b' km, and '$c-(n-1)d$' can be less than '*d*' km. When the minimum range of vegetation on both sides of the river is more than 1 km, the vegetation on both sides of the river is divided into an equal-difference series of 1 km, and the width after division is 1 km, 2 km, … $1 \times (n-1)$ km, where n is an integer, and the distribution width of the farthest point from the river is 'a' km and '*c*' km, respectively. Among them, both '$a-1 \times (n-1)$' and '$c-1 \times (n-1)$' can be less than 1 km.

As shown in Fig. 1, starting from the edge of the river, the scope of ecological protection is gradually expanded parallel to the river on both sides of the river. The minimum extent of ecological protection is the sum of '*b*' km

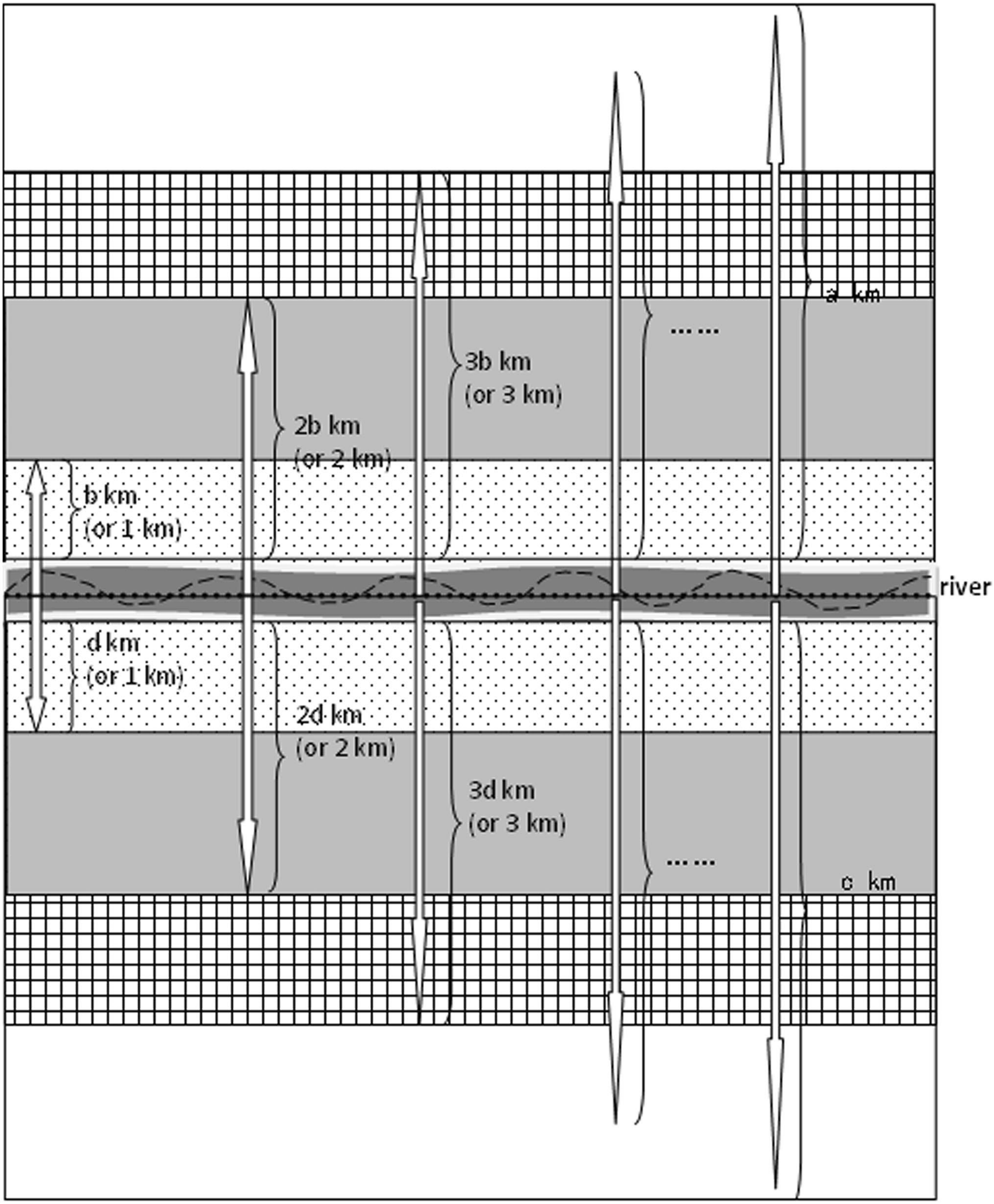

Fig. 1 Delineation of different ecological protection ranges

(or 1 km) from one side of the river channel and '*d*' km (or 1 km) from the other side of the river channel. The second ecological protection scale was defined by adding '2 *b*' km (or 2 km) from one side of the river channel to '2 *d*' km (or 2 km) from the other side of the river. The maximum range of ecological protection was defined by adding 'a' km from one side of the river to '*c*' km from the other side of the river.

The formula used to calculate the area of different distances of ecological protection (*A*) was:

$$A = (W_1 + W_2) \cdot L$$

where W_1 is the width of one side of the river perpendicular to the river for a specified distance; W_2 is the width on the other side perpendicular to the river for a specified distance; and L is the length of the river.

3.2 Calculation formula of TEEWR

The ecological water demand of natural vegetation in different ecological protection areas was calculated using the data obtained in Sect. 3.1 (above) and the calculation of ecological water demand for natural vegetation. In addition to satisfying the local community's production and living water uses, river flows also need to maintain the stability and health of the river's biological structure and function. This implies that the inland river should retain a minimum amount of water during a specified period of time, i.e., its BEEWR. There is also a certain amount of evaporation and leakage loss from the river itself, which is collectively termed river loss (X_{loss}). After the river flow is diverted to the irrigation areas, excess irrigation water in the irrigation area flows back into the river. The quantity is the amount of water withdrawn from the river. Because there is a large area of riparian forest vegetation on both sides of the river, it is necessary to retain a certain amount of water in the river to maintain the normal survival and growth of riparian forest vegetation, i.e., its TEEWR. Therefore, TEEWR mainly relies on residual water after meeting the local community's production and living water demand. The water in the river that is reserved corresponds to the ecological water demand of vegetation. Water resources utilization and a water balance map of inland river basins in arid areas is shown in Fig. 2. Because the residual water is unaffected by human activity is mainly used to meet $\overline{X}_{loss}$ and Y_{ec}, the ratio of residual water to $\overline{X}_{loss}$ is assumed to equal to the ratio of TEEWR to the corresponding X_{loss}, and TEEWR is approximately equal to the sum of Y_{ec} and the corresponding X_{loss}. TEEWR is calculated as:

$$\text{TEEWR} = Y_{ec} + (Y_{ec} \times \overline{X}_{loss})/(X - X_{live} - \overline{X}_{loss})$$

where Y_{ec} is the ecological water demand of the riparian vegetation; $\overline{X}_{loss}$ is the annual average river loss during the past 50 years; and X is the average annual runoff during the past 50 years, i.e., the arithmetic average annual runoff during the past 50 years, which is the annual runoff of the basin upstream of the monitoring site in a year. X_{live} is the surface water consumption for production and living.

4 Case study: Yarkand River Basin, Xinjiang, China

A map of the Yarkand River Basin and its main sections in Xinjiang, China, is presented in Fig. 3.

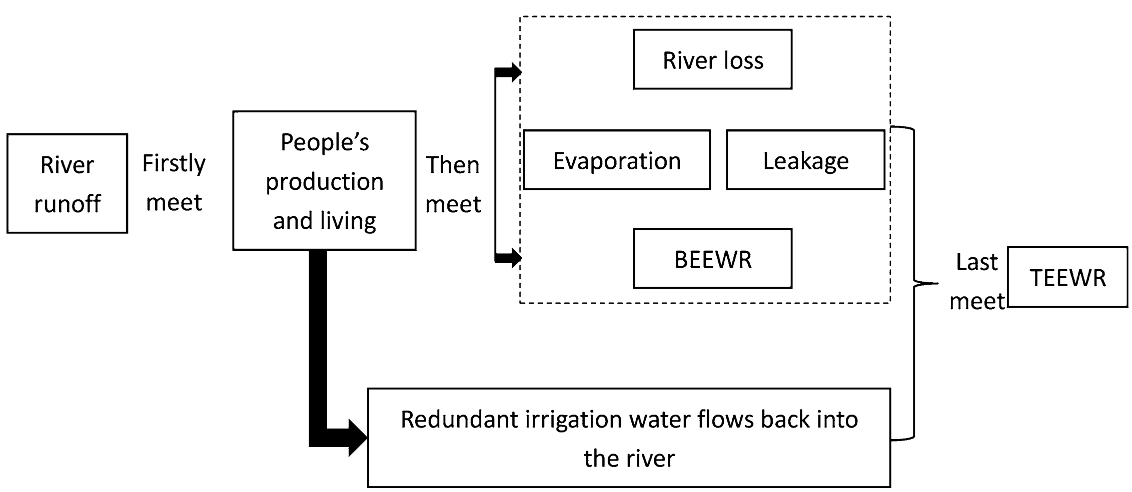

Fig. 2 Water resources utilization and water balance map of the arid Yarkand River Basin

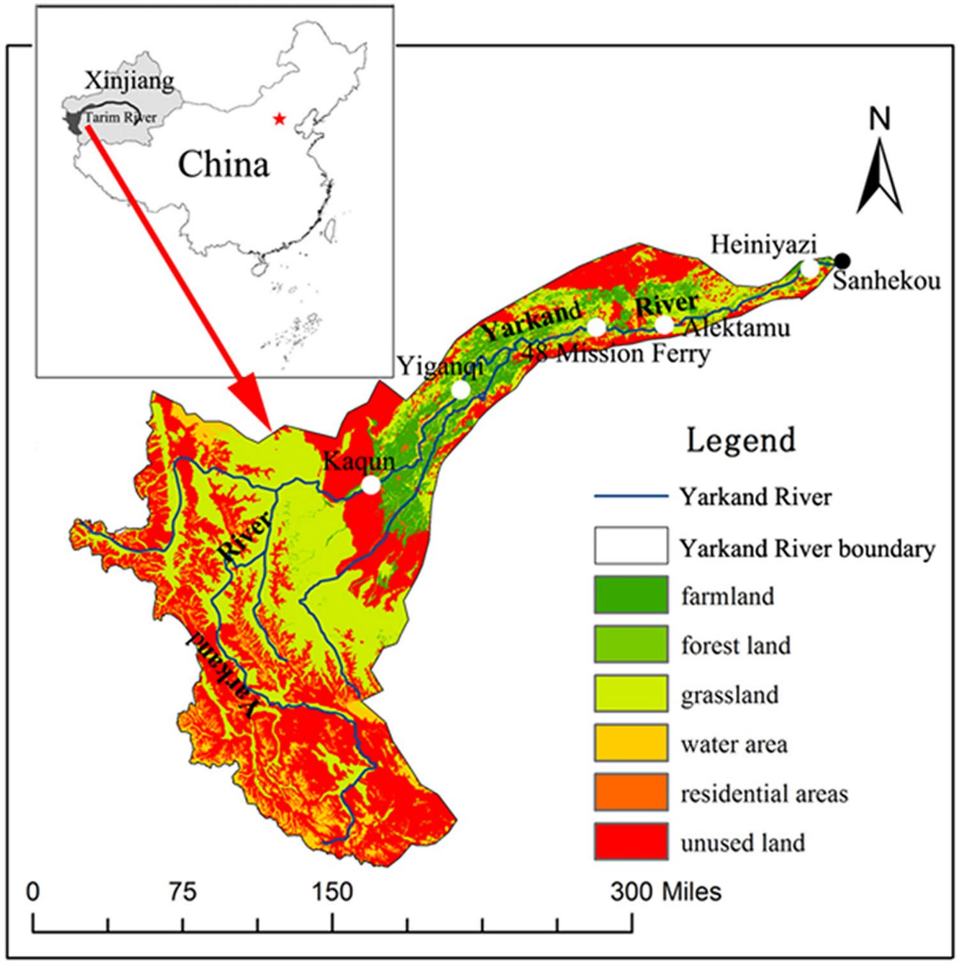

Fig. 3 Illustrative map of the Yarkand River Basin and main sections in Xinjiang, China. Drawing number: GS(2016)1600

4.1 Different ecological protection areas of riparian forests

Using the methods outlined above, different ranges or zones of ecological protection of riparian forest vegetation in the Yarkand River Basin were delineated. The total area of vegetation in the Yarkand River Basin is 7427 km^2, whereas the total length of the river is 1078 km. The distribution of vegetation is similar on both sides of the river. The width of vegetation on both sides of the river is 6.890 km, and the average width of vegetation on one side of the riverbank is 3.445 km. Vegetation is more uniformly distributed, and there is no minimum width of vegetation. The minimum width of vegetation is greater than 1.000 km, and thus the classification is at 1.000-km intervals on one side. Moreover, vegetation was divided into four parts at 1-km intervals to allow for different ecological protection areas on both sides of the riverbank to be obtained. The four specific areas included: (1) 1.000 km away from the river, with an area of 2156 km^2; (2) 2.000 km away from the river, with an area of 4312 km^2; (3) 3.000 km away from the river, with an area of 6468 km^2; and (4) 3.445 km away from the river, with an area of 7427 km^2.

4.2 Calculation of Y_{ec} for different ecological protection zones

Y_{ec} for the four ecological protection zones was calculated using estimates of phreatic evaporation. A commonly used equation for the calculation of phreatic evaporation was used here and is expressed as [24]:

$$\text{Averyanov formula}: E = a(1 - H/H_{\max})^b E_{\Phi 20}$$

In formula, E is phreatic evaporation intensity (mm); H is the groundwater depth (m), $E_{\emptyset 20}$ is the water surface evaporation of 20 m^2 evaporation pool, the average value measured by Aksu water balance station for many years is 1292.2 mm, H_{max} is the groundwater limit depth (m), calculated by 5 m, a and b are the empirical coefficients, $a = 0.62$, $b = 2.8$ respectively.

A detailed description of the calculation process is shown in Table 1.

Table 1 The calculation process of Y_{ec} and TEEWR under the four protection targets

	Calculation process	Results ($10^8 m^3$)
Yec		
The 1st protection range	$0.62\times(1–2.5/5)^{2.8}\times1.76\times2156\times10^6$	3.38
The 2nd protection range	$0.62\times(1–2.5/5)^{2.8}\times1.76\times4312\times10^6$	6.76
The 3rd protection range	$0.62\times(1–2.5/5)^{2.8}\times1.76\times6468\times10^6$	10.13
The 4th protection range	$0.62\times(1–2.5/5)^{2.8}\times1.76\times7427\times10^6$	11.64
TEEWR		
The 1st protection range	3.38 + (3.38 × 15.07)/(68.16–51.43–15.07)	34.06
The 2nd protection range	6.76 + (6.76 × 15.07)/(68.16–51.43–15.07)	68.13
The 3rd protection range	10.13 + (10.13 × 15.07)/(68.16–51.43–15.07	102.09
The 4th protection range	11.64 + (11.64 × 15.07)/(68.16–51.43–15.07)	117.31

The four protection targets were obtained by using the methods described in Sect. 3.1 'Delimitation of different ecological protection ranges of riparian forests'

In the Yarkand River Basin, the mean groundwater level (H) is 2.5 m, the maximum groundwater level (H_{max}) is 5 m, and the plate observations of conventional meteorological evaporation ($E_{\Phi20}$) were 1.76 m. Moreover, H and H_{max} were determined from field monitoring, and $E_{\Phi20}$ was obtained from the China Meteorological Science Data Sharing Service Website (http://cdc.cma.gov.cn/satellite).

4.3 Calculation of TEEWR

The Kashi Administration of the Tarim River Basin suggested that X in the Kaqun Hydrological Station of the Yarkand River was $68.16\times10^8 m^3$. TEEWR can be calculated as:

$$\mathrm{TEEWR} = Y_{ec} + (Y_{ec} \times \overline{X}_{loss})/(X - X_{live} - \overline{X}_{loss})$$

Calculated TEEWR values are shown in Table 1.

5 Discussion

5.1 Feasibility of the method

The different ecological protection zones of riparian forests were based on distance from the river channel and width of the riparian forests. The delineated ecological protection zones were subjectively defined; thus, the feasibility of the method applied in this study needs to be evaluated. Seasonal changes and the natural characteristics of the vegetation were used to determine the ecological protection goals in the Yarkand River Basin study area (in order of ascending size). The goals were based on relevant literature and reports (e.g., [25]) from the basin. Within the first protection zone (target), there are some key *Populus euphratica* forest areas that are distributed on both sides of the 320-km-long river channel from Alektamu to Sanhekou (Fig. 3). Young forests, middle-aged forests, mature forests, aging forests, and dead forests exist. The area of *Populus euphratica* forest encompasses 900 km^2. The second protection zone (target) includes natural vegetation along the river in the lower reaches of the Yarkand River. It is an ecologically sensitive vegetation area covering a total area of 2227 km^2. The third protection zone (target) was defined on the 'Ecological Protection Red Line' policy implemented by the Chinese government [26]. The ecological protection red line of natural vegetation in the Yarkand River Basin encompasses 7429 km^2. The ecological protection red line for the plains in the basin includes 94 km^2 of forest land, 507 km^2 of sparse forest land, 157 km^2 of shrub forest land, and 6671 km^2 of natural grassland. Based on calculated phreatic evaporation, the ecological water requirements under the three protection targets were calculated to be 1.41×10^8 m^3, 3.49×10^8 m^3, and 11.64×10^8 m^3, respectively. Employing the method described above to calculate TEEWRs, the TEEWR values for the three protection targets were 14.21×10^8 m^3, 35.17×10^8 m^3, and 117.31×10^8 m^3, respectively (Table 2). Among them, the TEEWR value of the second protection target is only 1.11×10^8 m^3 different from that of the first protection target in the method used herein. In contrast, the TEEWR value of the third protection target (117.31×10^8 m^3, Table 2) is equal to that of the fourth protection target (117.31×10^8 m^3, Table 1).

Table 2 Ecological water requirements and TEEWR under the three protection targets

Ecological protection targets	Area (km^2)	Ecological water requirements ($10^8 m^3$)	TEEWR($10^8 m^3$)
The 1st	900	1.41	14.21
The 2nd	2227	3.49	35.17
The 3rd	7429	11.64	117.31

The three protection targets were obtained by consulting relevant literature and reports

The difference between the calculated TEEWR by the two methods is not significant, which indicates that the calculation methods of different ecological protection zones and the river's TEEWR are indeed feasible.

5.2 Limitations of the method

During the process of determining different ecological protection zones of desert riparian forest vegetation in inland river basins of arid regions, the first protection zones were set artificially as vegetation distribution ranges measuring 1 km from rivers or the smallest distance from the river. The other ecological protection zones were determined at intervals of 1 km or a multiple of the smallest distribution ranges. It must be noted that the determination of the ranges is subjective. However, compared with other artificial methods, this criterion can refine the scope of ecological protection and cover all ecosystem types with higher accuracy. There are two limitations of this method: first, it is assumed that the distribution characteristics of vegetation in the whole basin are the same, i.e., vegetation types, vegetation coverage, distribution density, and structure composition are generally identical. In fact, however, vegetation types, coverage, density, and composition vary spatially along the river and with distance from the river. More specifically, in many arid regions the farther from the river, the fewer types of vegetation, the less coverage, the thinner the density, and the simpler the composition. Furthermore, in the process of calculating the ecological water demand of vegetation by the phreatic evaporation method, only the factors of groundwater depth and potential evapotranspiration intensity are considered, while vegetation types, coverage, density, and composition are not. Therefore, the calculation results of the ecological water demand of vegetation may be overestimated. Furthermore, in the process of transforming the ecological water demand of natural vegetation in different ecological protection areas into a river TEEWR, it is assumed that the ratio of residual water (the annual average runoff minus X_{live}) to $\overline{X}_{loss}$ and the ratio of TEEWR to corresponding X_{loss} are the same, i.e., TEEWR $= Y_{ec} + X_{loss}$. The method of determining X_{loss} corresponding to the ecological water demand of vegetation in different areas is simple and idealized. In future work, more accurate X_{loss} could be obtained through field survey and measurement.

5.3 Implication of the method

There are many inland rivers in the world, such as Amu Darya River, Syr Darya River, Heihe River, and Shiyang River, among others [27–30]. These river basins have similar ecological, environmental and social characteristics [2, 31, 32]. Agricultural, domestic and ecological water mainly rely on the inland rivers for water; therefore, it is necessary to calculate and analyze TEEWR of each inland river to understand the hydrological characteristics and water resources availability in the basin. In this paper, the proposed calculation and assessment methods of TEEWR have excellent clarity, maneuverability and reliability, and can therefore be applied to other inland rivers for effective water resources management.

6 Conclusions

In this paper, the Yarkand River Basin, a typical inland river basin in an arid region of China, was selected to analyze and assess the TEEWR along a river course. The following conclusions were reached:

1. Areas of ecological protection based on riparian forests in the Yarkand River Basin were defined as: (a) 1.000 km away from the river, with an area of 2156 km^2; (b) 2.000 km away from the river, with an area of 4312 km^2; (c) 3.000 km away from the river, with an area of 6468 km^2; and (d) 3.445 km away from the river, with an area of 7427 km^2. The Y_{ec} in the four ecological protection zones were 3.38×10^8 m^3, 6.76×10^8 m^3, 10.13×10^8 m^3, and 11.64×10^8 m^3, respectively. The TEEWR for the four ecological protection targets were 34.06×10^8 m^3, 68.13×10^8 m^3, 102.09×10^8 m^3 and 117.31×10^8 m^3, respectively.
2. The calculation of TEEWRs provided in this paper appears feasible, but there are limitations: (a) the determination of the protection zones or ranges is subjective; (b) it is assumed that the characteristics of vegetation in the whole basin are the same, which may lead to the over-estimation of the ecological water demand of vegetation; (c) it is assumed that the ratio of residual water (the annual average runoff minus X_{live}) to $\overline{X}_{loss}$ and the ratio of TEEWR to the corresponding X_{loss} are the same. In future work, more accurate parameters for determining X_{loss} could be obtained through field measurement and in-depth study.

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Author contributions AF conceived and designed the experiments, analyzed the data and wrote the manuscript. WL performed the experiments. YW prepared the figures and revised the paper.

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Declarations

Conflict of interest There is no conflict of interest.

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