



The reallocation of water and ecosystem service values in arid ecosystems with the implementation of an ecological water diversion project

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Abstract

The rational allocation of the water resources in drylands and the scientific evaluation of their values are important for the regional sustainable development. We estimated the water consumption of each ecosystem in Ejina Oases in the arid area in northwest China based on the water balance equation, then assessed their ecosystem service values (ESVs) using the value per unit area method and the value equivalent factor per unit area method considering the cost of water consumption, respectively, and calculated their water productivities from 1990 to 2015. With the implementation of the ecological water diversion project (EWDP) in 2000, the deciduous broadleaf forest dominated by *Populus euphratica* had an increasing trend, meanwhile, lakes had a changing process from shrinking and drying up to recovery and expansion from 1990 to 2015. The total water consumption in Ejina Oases decreased from $5.26 \times 10^8 \text{ m}^3$ in 1990 to $4.79 \times 10^8 \text{ m}^3$ in 2000, and then increased continually to $5.97 \times 10^8 \text{ m}^3$ in 2015. The water consumption of forest, grassland and cultivated land hardly changed, while the water consumption of water or wetland changed obviously. The total ESVs estimated using the value per unit area method in Ejina Oases decreased from 1052.6 to 787.3 million ¥ in the period of 1990–2000, then increased to 1500.6 million ¥ in 2015, while the ESVs estimated using the value equivalent factor per unit area method decreased from 6368.7 million ¥ in 1990 to 5892.0 million ¥ in 2000, then increased to 7139.9 million ¥ in 2015, and the latter method was more reasonable. The results showed that the EWDP started in 2000 led to the reallocation of water resources and transfer of ESVs among ecosystems, which had obvious performance in the ecological environment and social economy. This study provided a comprehensive view of water use and management, ecological restoration and socio-economic development in this key ecological function zone, and will help decision-makers to formulate the scheme of rational allocation and efficient utilization of water resources in the basin.

Keywords Water consumption · Ecosystem service values · Ecological water diversion project · Value equivalent factor · Water productivity · Drylands

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Introduction

The drylands, covering 41% of earth's surface and supporting about 40% of the world's population, represent a vulnerable part of the earth's terrestrial environments and are under additional stress due to ongoing climate change (Feng et al. 2019; Fu et al. 2021; Reynolds et al. 2007). Recently, the sustainable development in drylands has attracted great attention from many international organizations, such as the 2030 Agenda and the Sustainable Development Goals championed by the United Nations Industrial Development Organization (UNIDO) and the Global Land Programme, which specially set up the Global Dryland Social-Ecological Systems (Fu et al. 2021; Lu et al. 2022). However, the

ecosystem services (ESs) in drylands are often belittled in the terrestrial ecosystem services investigation, and humans are encroachment on the limited resources used in ecosystems in drylands (Lu et al. 2015; Wei et al. 2021). Often, the economic development in the upper and middle reaches of a river, including irrigated farmland expansion and industrial water consumption, affects the ecological health of the lower reaches in arid area (Lu et al. 2015; Tan et al. 2020; Zhang et al. 2022). With the population growth, socio-economic development and the implementation of a large number of projects in the last few decades, the fate of drylands has been several twists and turns (Fu et al. 2021). Most areas still suffer from environmental degradation and poverty, while a few areas are in the state of environmental restoration under the control of ecological engineering, such as the water diversion projects and the ecological migration (Lian et al. 2021; Lu et al. 2021). Even so, there are some debates about whether it is worthwhile to use water that could otherwise be used for economic development to sustain ecosystems in drylands (Braat and de Groot 2012; Yuan et al. 2019; Zheng et al. 2019a). This is mainly because there are knowledge gap about the reasonable assessment of the value of arid ecosystems (such as the windbreak and sand-fixation, and recreation of the riparian forests and terminal lakes in inland river basins), and the trade-off between their values and the cost of maintaining them (including limited water resources and special water transmission projects).

Although, the terms ESs and ecosystem service values (ESVs) were coined and ESVs' quantitative approaches were proposed at the end of the last century (Costanza et al. 1997; Daily 1997), and a great deal of research work has been carried out on the assessment of ESVs since then and some assessment tools and models have even been developed, e.g. Invest (Integrated Valuation of Ecosystem Services and Tradeoffs) (Costanza et al. 2014; Hu et al. 2020; Zheng et al. 2019b). However, lack of data and regional uniqueness limit the use of the assessment model in drylands, and they were often neglected in ESVs' assessment because of their sparse vegetation and large areas of unused land. The desert's ecosystem, for example, was not contained in the Costanza's (1997) evaluation method, or its ESVs were given a particularly low rating in the value equivalent factor per unit area method used to estimate the regional and national ESVs (Xie et al. 2003, 2015b). In some studies, the ESVs were seriously underestimated using value per unit area method (Lu et al. 2015; Su et al. 2006), which easily lead to a misunderstanding that it was not worth using the scarce water resources to maintain the ecosystem in arid regions. It is worth noting that the value equivalent factor per unit area method is increasingly used, mainly because of its ability to take into account the regional realities, including crop yields and prices, to assess the ESVs (Xie et al. 2003, 2015b, 2021). However, many studies evaluating the drylands' ESVs did not take into account the costs (Braat and de Groot

2012; Lorilla et al. 2018; Nath et al. 2018). In fact, arid ecosystems require ecological water allocation, such as riparian forests and water body (Lu et al. 2015; Wang et al. 2019).

Heihe River basin (HRB), the second largest inland river basin in China, had experienced severe water shortages and environmental deterioration since the 1980s, especially the Ejina Oases in the downstream of HRB (Cheng et al. 2014). However, the Ejina Oases is a key ecological function zone and plays an important role in guaranteeing ecological safety far beyond its physical extent (Yan et al. 2018). To restore the ecosystem in the Ejina Oases, the Chinese Government initiated an ecological water diversion project (EWDP) since 2000 by which the midstream area should discharge 950 million m³ of water in normal years, as measured at the Zhengyixia Hydrological Station (ZYX) to downstream areas when the upstream Yingluoxia Hydrological Station (YLX) discharges 1580 million m³ of water, and it has made significant achievements in regional ecosystem restoration (Lu et al. 2015). With the socio-economic development, humans use more and more water, and the ecological water is likely to be compressed in the future in this region (Lian et al. 2021). How to allocate water resources rationally to balance human well-being with nature? There is an urgent need to conduct the joint research on ecosystems' water consumption and ESVs assessment, so as to provide a basis for ecological compensation or water rights trade within or between regions to maintain good ecological service function in the future.

The overarching goal of this paper is to reveal the changes in land use and land cover, water uses, ESVs, ecological environment, and socio-economy in Ejina Oases before and after the implementation of the EWDP, and their interconnectedness from 1990 to 2015. The specific objectives are: (1) To estimate the ecosystems' water use using water balance method, (2) To calculate ESVs using the value per unit area method and the value equivalent factor per unit area method considering the cost of water consumption, and (3) To compare the ecosystem services and the socio-economic development with the ecological environment improvement. This study will provide a comprehensive view of water use, ecological restoration, ESVs and socio-economic development in this key ecological function zone in arid area, which can help to further maintain water resources' rational allocation and efficient utilization in the basin, as well as promote basin's sustainable development.

Methods and data

Study area

In this study, we take the Ejina Oases in the downstream area of HRB below the Langxinshan Station (LXS) as the

study area, and its inflow is controlled by the LXS (Fig. 1). Administratively, Ejina Oasis belongs to Ejina Banner of Alxa League of Inner Mongolia Autonomous Region, China. Ejina Oases is an extremely arid region with high potential evapotranspiration (up to 3000 mm per year) and very little annual precipitation (less than 50 mm), and consists of forest, grassland, cultivated land, built-up land, water or wetland, and unused land. Agriculture depends mainly on pumping well water for irrigation, while the ecosystems in Ejina Oases depend on flood irrigation from the midstream runoff and groundwater, which mainly comes from the infiltration of the river runoff.

The decline in streamflow to the downstream area led to the severe deterioration of the ecosystems in Ejina Oases during the 1960–2000s, such as the drying up of terminal lakes and the death of *Populus euphratica* forests. The implementation of the EWDP since 2000 is the most important change in water management policy in the HRB in the past two decades, and the ecosystems in Ejina Oases have been considerably restored (Cheng et al. 2014; Li et al. 2018; Lu et al. 2021). Moreover, tourism is developing rapidly because Ejina Banner is one of China's most important tourist attractions with respect to *Populus euphratica* forests (Hu et al. 2015).

Processing of land use and land cover data

The data sources are Landsat TM and ETM+ data, and most of them were obtained from the United States Geological Survey (USGS, <https://glovis.usgs.gov/>), and a few from China Geospatial Data Cloud (<http://www.gscloud.cn/>). There were six periods of land cover data (1990, 1995, 2000, 2005, 2010 and 2015) using an integration method of remote sensing monitoring, and validation through ground

investigation and the interpretation of satellite imagery with high resolution.

The production of this data set used the object-oriented classification method based on the platform of eCognition, and the data processing was based on ArcGIS platform (Xie et al. 2019). For the time phase of remote sensing images, the period from mid-June to late September was selected in northwest China for the cloud-free images. In addition, the images in non-growth season and other time-phase that can reflect the differences of ground features, as well as DEM, vegetation coverage and other characteristic indexes were used.

In this land use/cover classification system (Feng et al. 2011; Xie et al. 2019), there are 6 types at the first scale and 40 types at the second scale. They include: forest (deciduous broadleaf forest, deciduous broadleaf shrubland, sparse forest, sparse shrubland, tree garden and shrub garden), grassland (temperate steppe, temperate meadow and sparse grassland), cultivated land, water or wetland (shrub wetland, herbaceous wetland, lake, reservoir/pond and river), built-up land (settlement, transportation land and mining field), and unused land (bare rock, gobi, bare soil, desert and salina) in Ejina Oases.

Estimation of water consumption

The estimation of ecosystems' water consumption was based on the water balance equation. There were some researches on the water balance in the downstream and the whole HRB, which provided the whole evapotranspiration or main land types'. As a terminal part of the downstream area of the HRB, the Ejina Oases can be seen as a complete catchment. Moreover, there is no stream outflow and groundwater outflow at the terminal lake or desert sink in Ejina Oases. For any length of time, the water balance can thus be expressed as

$$P + R_{in} + G_{in} = ET + \Delta S + \Delta GW + \Delta L \quad (1)$$

where P is precipitation; R_{in} is stream inflow; G_{in} is groundwater inflow; ET is evapotranspiration; ΔS is the change in soil water storage; ΔGW is the change in groundwater storage; and ΔL is the change in lake and reservoir water storage. Increases and decreases in storage result in positive and negative values, respectively.

In this study, P was from the Ejina Station; R_{in} was controlled by the LXS; ET can be estimated by multiplying the area of each land cover and their per evapotranspiration simulated by the model (Guo et al. 2011; Li et al. 2018; Peng et al. 2010; Zhang et al. 2006); ΔS was neglected in this study due to the soil water storage is few in extreme arid region; G_{in} was also neglected because the groundwater inflow from Badain Jaran Desert occurred in Gurinai region

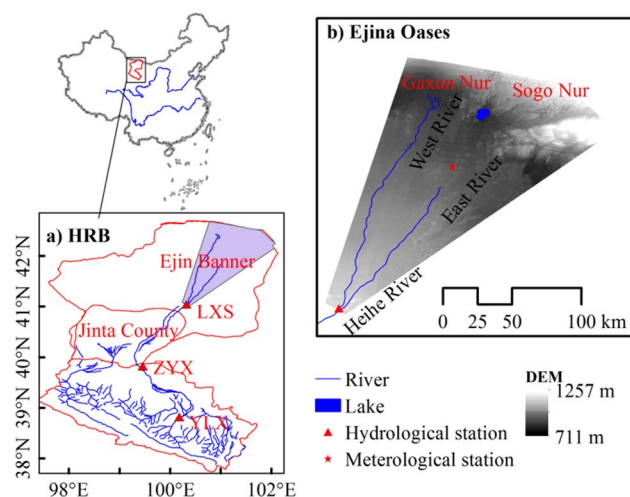


Fig. 1 Study area of Ejina Oases in downstream of Heihe River basin in northwest China

outside the study area (Li et al. 2018); ΔGW was estimated by multiplying the area, the change in the groundwater depth and water storage coefficient of layers (Peng et al. 2011; Tian et al. 2015; Xi et al. 2011); and ΔL was estimated using area of water and shape of the lake shore (Ye et al. 2017; Zhang et al. 2014).

$$ET = \sum_{i=1}^n ET_i \times A_i \quad (2)$$

ET_i is the water consumption per area of each land cover and referenced to the existing research results (Table 1); n is the number of the land cover types; and A_i is the area of each land cover.

$$\Delta GW = \mu \times \Delta H \times A \quad (3)$$

μ is the water storage coefficient of layers, ΔH is the average change in the groundwater depth, and A is the total area. Groundwater depth change data were obtained from groundwater monitoring wells and field surveys, while the water storage coefficient of layers was referred to the relevant literature (Peng et al. 2011; Tian et al. 2015; Xi et al. 2011).

Ecosystem services values estimation

We used two methods to estimate ESVs. The ESVs in this region was firstly estimated using the modified value per unit area method proposed by Costanza (1997). Due to the differences of vegetation coverage of the ecosystems, the scholars introduced modification coefficients to distinguish the impact of vegetation coverage on ecosystem services based on the Costanza's method (Lu et al. 2015; Su et al. 2006). For example, the modification coefficients for dense grassland and sparse grassland were 1.5 and 0.5, respectively. The determination of these modification coefficients was guided by the experts in this field. This modified method had been used in Shiyang River Basin and HRB, and the ESVs per

unit area for ecosystems were listed in Table 2 according to the previous studies (Lu et al. 2015; Su et al. 2006).

Meanwhile, we used the value equivalent factor per unit area method to estimate the ESVs as a comparison. In this method, we firstly evaluated the value of the equivalent coefficient for a standard unit ESV. The equivalent coefficient for a standard unit ESV (hereinafter referred to as the standard equivalent coefficient) refers to the economic value of natural food production in 1 hm² farmland with the level of the national average yield every year (Xie et al. 2015a, 2015b), which can be used to determine the equivalent coefficient of other ESs combining the expert knowledge. In this study, referring to the treatment method in the national scale provided by Xie et al (2015b), we

Table 2 The ESVs per unit area for each land type

First types	Second types	ESVs per unit area (\$ ^a)
Forest lands	Deciduous broadleaf forest	453
	Deciduous broadleaf shrubland	332.2
	Sparse forest	211.4
	Sparse shrubland	211.4
	Tree garden	453
	Shrub garden	332.2
Grasslands	Temperate steppe	232
	Temperate meadow	348
	Sparse grassland	116
Cultivated land	Dry farmland	92
Wetlands	Shrub wetland	8498
	Herbaceous wetland	8498
	Lake	8498
	Reservoir/Pond	8498
	River	8498

^aIn the following calculation of ecological service value, the unit is Yuan (¥), and the exchange rate between \$ and ¥ is 6.55

Table 1 The reference values of the evapotranspiration of different landscapes in Ejina Oases

Main landscape types	Annual evapotranspiration (mm)
Forest	288–371.3 (Guo et al. 2011; Li et al. 2018; Zhang et al. 2006)
Tamarix	163–401.6 (Guo et al. 2011; Li et al. 2018; Peng et al. 2010; Si et al. 2006)
Other desert shrubs	165.6 (Li et al. 2018; Si et al. 2013)
Temperate steppe	78–150.7 (Guo et al. 2011; Li et al. 2018; Si et al. 2013)
Wetland	373.8 (Guo et al. 2011; Li et al. 2018)
Cropland	502.9 (Li et al. 2018)
Urban and other built up	180.9 (Li et al. 2018)
Lake	998.9 (Li et al. 2018)
Reservoir	912.7 (Li et al. 2018)
River	623.1 (Li et al. 2018)
Desert	58.2 (Li et al. 2018)

took the net profit of food production per unit area of local farmland ecosystem as the ESVs of a standard equivalent coefficient. Because the statistical data in Ejina Banner were limited, the grain yield value of farmland ecosystem was calculated based on the statistical data of the Inner Mongolia Autonomous Region and China from 2001 to 2015. The standard equivalent coefficient was calculated as follows:

$$D = \sum_{i=1}^{15} \frac{(P_{w,i} * Y_{w,i} - C_{w,i} * A_{w,i}) + (P_{c,i} * Y_{c,i} - C_{c,i} * A_{c,i})}{15 * (A_{w,i} + A_{c,i})} \quad (4)$$

where D is the average of the standard equivalent coefficient from 2001 to 2015 (¥/hm²), $P_{w,i}$ and $P_{c,i}$ are the prices of the wheat and corn in year i in China (¥/kg), $Y_{w,i}$ and $Y_{c,i}$ are the yield of wheat and corn in year i in Inner Mongolia Autonomous Region (kg), $C_{w,i}$ and $C_{c,i}$ are the cost of wheat and corn in year i in China (¥/hm²), and $A_{w,i}$ and $A_{c,i}$ are the area of wheat and corn in year i in Inner Mongolia Autonomous Region (hm²), respectively. The data were obtained from the yearbooks and statistical yearbooks of Alxa League, Inner Mongolia Autonomous Region and China, and literature (Wang 2017). According to the formula, the average of the standard equivalent coefficient in Alxa League from 2001 to 2015 was 2857 ¥/hm².

Then, we estimated the basic equivalent of the value of ecosystem services per unit area. The basic equivalent of the value of ESs per unit area refers to the average annual value equivalent of each ecosystem service per unit area of different types of ecosystems (hereinafter referred to as the basic equivalent). The basic equivalent reflects the average annual value of different ecosystems and their various ESs across the country, and is also the premise and basis for the reasonable construction of dynamic equivalents representing the spatial difference and temporal variances of ESVs. We determined the basic equivalent in Ejina Oases by integrating the national average provided by Xie et al (2015b) and local conditions (Xie et al. 2021), and referring to an adjacent case of Wu'an city in Hebei Province (Yao 2016).

In Ejina Oases, there is riparian forest along the river, including deciduous broadleaf forest, deciduous broadleaf shrubland, sparse forest and sparse shrubland, which depend mainly on groundwater. Similarly, the irrigated land needs irrigation using river runoff or groundwater. Thus, their water supply service should be negative values as similar as the value of the paddy fields proposed by Xie et al (2015b) and Yao (2016). We set the values of the water supply service of the riparian forest and the irrigated land negative according to their evapotranspiration, equal to their cost of water consumption (Li et al. 2018), because these land use types require large amounts of groundwater or irrigation but are difficult to provide

water resources. In addition, the bare land in Ejina Oases had the ability of water supply (Li et al. 2018), and should be set the same value as desert (Xie et al. 2003, 2015b; Yao 2016) (Table 3).

Water productivities of ecosystems and other ecological and socio-economic indicators

In this study, in order to compare the benefits of ecosystems, we calculated the water productivity of various ecosystems through dividing their ESVs by water consumption. It was helpful to the optimal allocation of water resources in changing environments.

Moreover, we collected the climatic and socio-economic indicators to validate the changes in the ES and ESVs, including the sand and dust weather, tourist population and the industrial value-added. The climatic data at the Ejina Meteorological Station from 1990 to 2015 were collected from the China Administration of Meteorology, and the socio-economic data were obtained from the regional statistical yearbook and annual reports.

Results

Land use and land cover changes

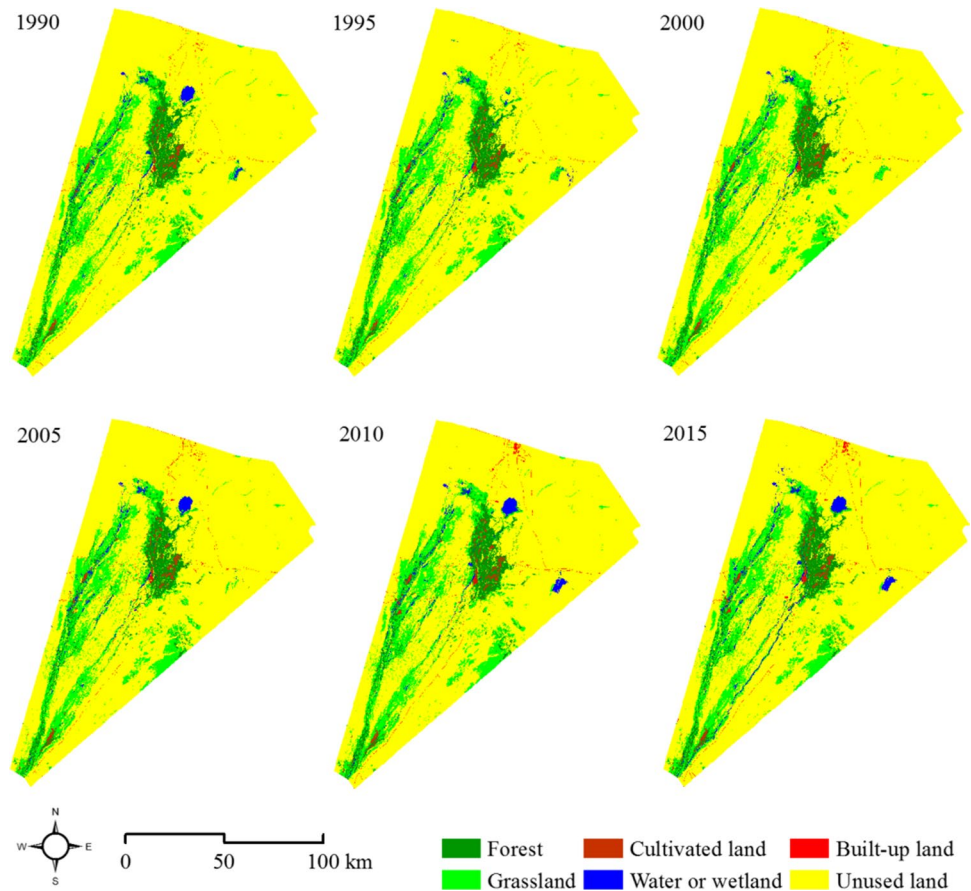
The Ejina Oases was dominated by unused land, accounting for about 78%. At the first level, there was little change for the forest, grassland and cultivated land, except for the water or wetland, which first decreased in the period of 1990–2000 and then continued to increase in the period of 2000–2015, and the built-up land continued to increase from 1990 to 2015 (Fig. 2). However, the land use/cover changes were more complex at the second level. For the forest, the sparse forest accounted for about 64%, and the deciduous broadleaf forest dominated by *Populus euphratica*, deciduous broadleaf shrubland, tree garden, and shrub garden were in increasing trend, while the sparse forest and sparse shrubland were in decreasing trend. For grassland, the sparse grassland accounted for nearly 98%, and increased in the period of 1990–1995 and decreased in the period of 1995–2015, while the temperate steppe was in the decreasing trend. For the water or wetland, the subtypes changed obviously, and the herbaceous wetland was the main type and in the increasing trend in the period of 1990–2015, but its proportion increased from 60.4 to 89.6% in the period of 1990–2000 and then decreased to 44.7% in 2015; the lake first decreased in the period of 1990–2000 and then increased in the period of 2000–2015; while the proportions of the reservoir/pond, river and shrub wetland were small and changed dramatically due to the influence of water discharge in the middle reach. For the built-up land, all the settlement, transportation

Table 3 The basic equivalent of ecosystem service value per unit area

LULC types (Feng et al. 2011)		Ecosystem types for ESVs estimation (Xie et al. 2015b)	Supply services			Regulating services				Support services			Cultural service		Total
			F	R	W	G	C	E	H	S	M	B	A		
Cultivated land	Paddy field		1.36	0.09	-2.63	1.11	0.57	0.17	2.72	0.01	0.19	0.21	0.09		3.89
	Irrigated land		1.36	0.09	-1.324	1.11	0.57	0.17	2.72	0.01	0.19	0.21	0.09		5.196
	Deciduous broadleaf forest		0.29	0.66	0.34	2.17	6.5	1.93	4.74	2.65	0.2	2.41	1.06		22.95
	Evergreen needleleaf forest		0.22	0.52	0.27	1.7	5.07	1.49	3.34	2.06	0.16	1.88	0.82		17.53
	Deciduous broadleaf shrubland		0.19	0.43	0.22	1.41	4.23	1.28	3.35	1.72	0.13	1.57	0.69		15.22
Forest	Sparse forest		0.155	0.355	0.135	1.175	3.515	0.995	1.755	1.43	0.11	1.3	0.57		11.495
	Sparse shrubland		0.095	0.215	0.11	0.705	2.115	0.64	1.675	0.86	0.065	0.785	0.345		7.61
	Orchard		1.25	0.58	-1.14	1.98	3.72	1.1	3.87	1.85	0.26	1.38	0.61		15.46
	Deciduous broadleaf forest		0.29	0.66	-0.978	2.17	6.5	1.93	4.74	2.65	0.2	2.41	1.06		21.63
	Deciduous broadleaf shrubland		0.19	0.43	-1.057	1.41	4.23	1.28	3.35	1.72	0.13	1.57	0.69		13.943
Riparian forest	Sparse forest		0.155	0.355	-0.489	1.175	3.515	0.995	1.755	1.43	0.11	1.3	0.57		10.87
	Sparse shrubland		0.095	0.215	-0.529	0.705	2.115	0.64	1.675	0.86	0.065	0.785	0.345		6.9713
	Temperate steppe, lawn		0.1	0.14	0.08	0.51	1.34	0.44	0.98	0.62	0.05	0.56	0.25		5.07
	Temperate meadow		0.22	0.33	0.18	1.14	3.02	1	2.21	1.39	0.11	1.27	0.56		11.43
	Sparse grassland		0.05	0.07	0.04	0.255	0.67	0.22	0.49	0.31	0.025	0.28	0.125		2.535
Water or wetland	Shrub wetland, herbaceous wetland		0.51	0.5	2.59	1.9	3.6	3.6	24.23	2.31	0.18	7.87	4.73		52.02
	Lake, reservoir/pond, river and canal/channel		0.2	0.06	2.07	0.21	0.57	1.46	25.58	0.25	0.02	0.65	0.48		31.55
	Desert		0.01	0.03	0.02	0.11	0.1	0.31	0.21	0.13	0.01	0.12	0.05		1.1
Unused land	Bare rock, Gobi, bare soil and salina		0	0	0.02	0.02	0	0.1	0.03	0.02	0	0.02	0.01		0.22

F Food production, *R* Raw material production, *W* Water supply, *G* Gas regulation, *C* Climate regulation, *E* Environmental purification, *H* Hydrology regulation, *S* Soil retention, *M* Maintenance of nutrient cycling, *B* Biodiversity, *A* Aesthetic landscape

Fig. 2 The land use/cover changes from 1990 to 2015 in the Ejina Oases



land and mining field increased in the period of 1990–2015. The cultivated land firstly decreased from 106.9 km² to 100.0 km² in period of 1990–1995, and then increased to 114.1 km² in 2015.

Water consumption composition

The total water consumption in the Ejina Oases decreased from 5.26×10^8 m³ to 4.79×10^8 m³ in the period of 1990–2000, and then increased continually to 5.97×10^8 m³ in 2015 (Fig. 3). The water consumption of forest, grassland and cultivated land hardly changed, while the water consumption of water or wetland and built-up land changed obviously. The water consumption of forest was the largest, except that water consumption of water or wetland exceeded forest's in 2015, and its proportion had been increasing from 36.4 to 39.1% with the decreases in water or wetland in the period of 1990–2000; then decreased from 39.1 to 31.5% with the recovery of water or wetland in the period of 2000–2015. The water consumption of grassland was the second until 2005 and the third after 2005 with the increase in the water or wetland's water consumption, and its proportion increased from 26.9 to 30.1% in the period 1990–1995 and then decreased continually

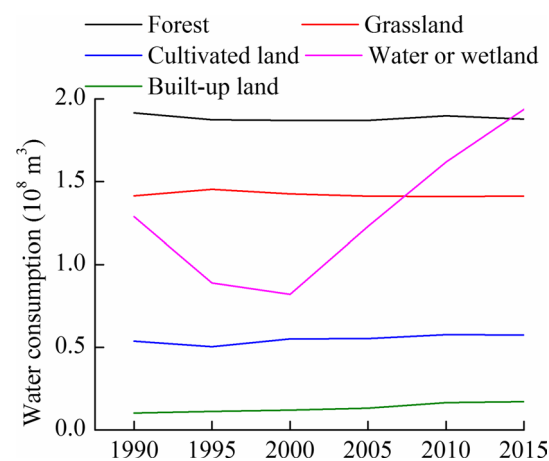


Fig. 3 The water consumption composition in the Ejina Oases from 1990 to 2015

to 23.6%. The water or wetland's water consumption decreased from 1.29×10^8 m³ to 0.82×10^8 m³ in the period of 1990–2000, and then increased continually to 1.94×10^8 m³ in 2015. Its proportion decreased from 24.5 to 17.1% in the period 1990–2000 and then increased continually to 32.4%. The cultivated land's water consumption was

stable at about 0.50×10^8 – 0.58×10^8 m³, and its proportion was about 9.6–11.5%.

The stream inflow at LXS changed dramatically in the range of 1.83×10^8 – 10.8×10^8 m³, and gradually became stable at about 6×10^8 m³ with the implementation of the EWDP since 2000. The precipitation in Ejina fluctuated wildly from 9.2 to 77.3 mm, but it was difficult to generate runoff and recharge groundwater because there were almost daily precipitation events of less than 5 mm in this region (Fig. 4a). Compared with runoff change, groundwater change lagged behind about one year, and groundwater depth increased in most of years before 2001 and then entered reduced mode (Fig. 4b).

The changes in ecosystem services values

The total ESVs estimated using the modified value per unit area method in Ejina Oases decreased from 1052.6 to 787.3 million ¥ in the period of 1990–2000. From 2000 to 2015, the total value increased to 1500.6 million ¥, which was more than it in 1990 (Fig. 5a). The ESVs of water or wetland changed significantly and was the largest, which amounted to 63.9% at least in 2000 and up to 81.1% in 2015. The ESVs of

the grassland and forest were about the same and more stable compared to the water or wetland's. The grassland's ESVs were the second, and its proportion increased from 13.5 to 18.3% in the period of 1990–2000 and then decreased to 9.5% in 2015. The proportion of forest increased from 13.1 to 17.0% in the period of 1990–2000 and then decreased to 8.9% in 2015.

The ESVs estimated using the value equivalent factor per unit area method was shown in Fig. 5b. The total ESVs decreased from 6368.7 to 5892.0 million ¥ in the period of 1990–2000. From 2000 to 2015, the total value increased to 7139.9 million ¥, which was more than it was in 1990. The ESVs of forest was the largest, except that ESVs of water or wetland exceeded forest's in 2015, and its proportion had been increasing from 36.2 to 38.1% with the decreases in water or wetland's area and its ESVs in the period of 1990–2000; then decreased from 38.1 to 31.6% with the recovery of water or wetland and its ESVs in the period of 2000–2015. The ESVs of water or wetland decreased from 27.1 to 21.9% in the period of 1990–2000 and then increased continually to 35.6%, and it was the second in 1990, 2005 and 2010 and the third in 1995 and 2000. The ESVs of grassland increased from 21.3 to 23.3%

Fig. 4 The changes in runoff, climate and groundwater from 1990 to 2015 in the Ejina Oases (**a** the changes in runoff at LXS and climate; **b** the changes of groundwater)

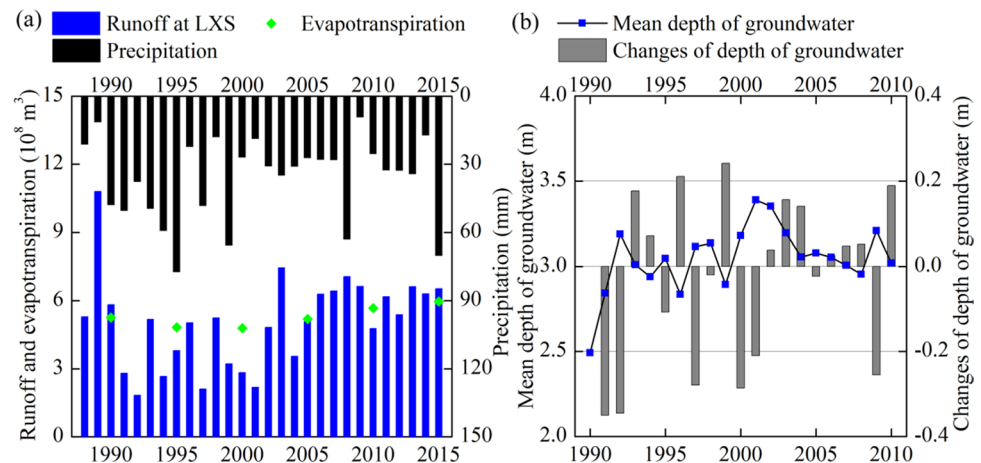
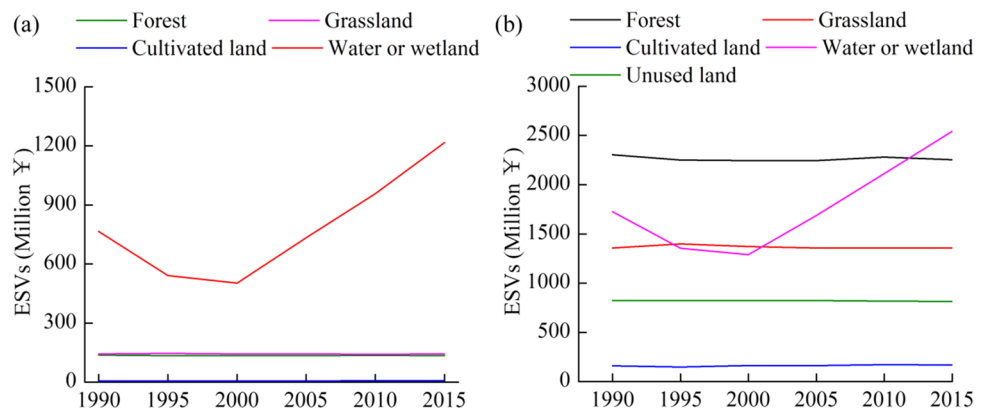


Fig. 5 The ESVs estimated using the modified value per unit area method (**a**) and the value equivalent factor per unit area method (**b**)



in the period of 1990–2000 and then decreased continually to 19.0% in 2015. It should be noted that the ESVs of unused land calculated by this method ranged from 815.4 to 824.3 million ¥, and its proportion was between 11.4% and 14.0%.

Water productivities of ecosystems

The water productivities were obviously different due to the different methods of calculating the ESVs (Table 4). The water productivities of each ecosystem based on the value equivalent factor per unit area method (3.0–14.0 ¥/m³) were generally greater than the value calculated by the modified value per unit area method (0.1–6.1 ¥/m³), and the difference between the water productivities of each ecosystem was small in the former. Among them, the water productivities of the cultivated land were 3.0 and 0.1 ¥/m³, respectively.

Table 4 The water productivities of ecosystems (¥/m³)

Ecosystems	Basic equivalent of the value method	Value per unit area method
Water or wetland	14.05	6.06
Forest	12.01	0.72
Grassland	9.61	1.01
Cultivated land	2.95	0.12
Total	10.83	2.06

Ecological effect and tourism development

The annual precipitation showed drastic changes in the period of 1990–2015, and the mean annual precipitation showed a decreasing trend on the whole, while the annual temperature was in an obvious increasing trend (Fig. 6a). The climate in Ejina Oases exhibited a tendency of warming and drying. The average annual relative humidity and wind speed were in decreasing trend, in which the wind speed decreased significantly (Fig. 6b).

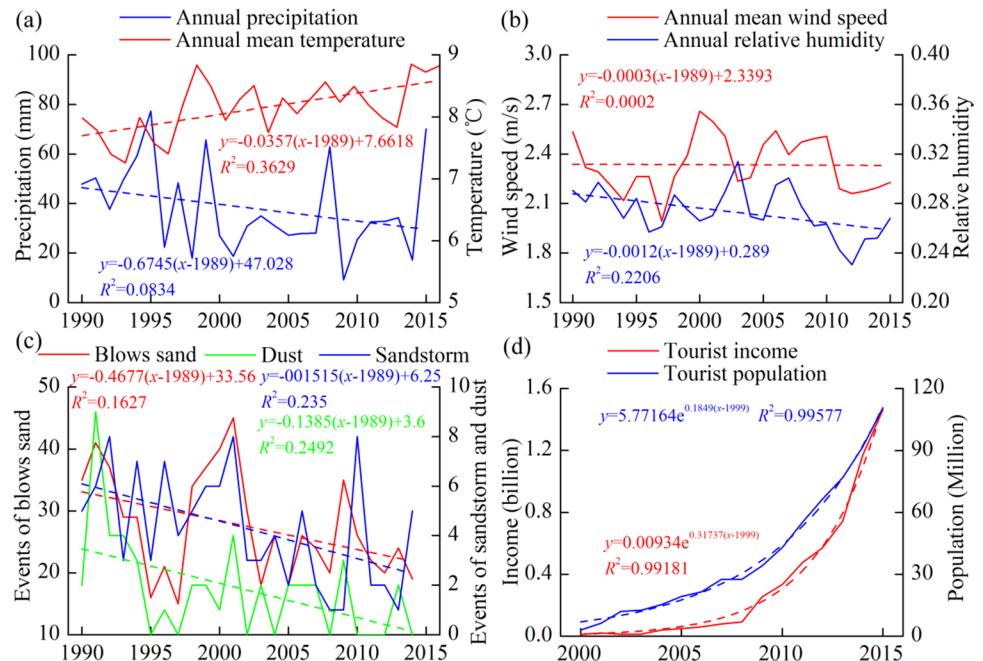
Meanwhile, the events of sandstorm, blow sand and dust changed obviously and their numbers were 5.4, 29.4 and 2.7 per year before EWDP, while they changed into 3.5, 26.2 and 1.2 after EWDP, respectively (Fig. 6c). With the improvement of the environment, the tertiary industry had a spectacular development and increased from 12.0 to 1462.0 million ¥ in Ejina Banner from 2000 to 2015, and the tourist population had exploded and increased from 0.03 million in 2000 to 1.1 million in 2015 (Fig. 6d).

Discussion

The differences of ESVs in drylands estimated using two methods

We assessed the ESVs in Ejina Oases using value per unit area method and the value equivalent factor per unit area method considering the cost of water consumption, and there were great differences between the ESVs results. The ESVs in Ejina Oases were in the range of 787.3–1500.6

Fig. 6 The climatic and ecological changes and tourism development (**a** the precipitation and temperature; **b** wind speed and relative humidity; **c** blows sand, sandstorm and dust; **d** tourism development)



million ¥ using the modified Costanza's (1997) evaluation method (Lu et al. 2015; Su et al. 2006), while it changed into 5892.0–7139.9 million ¥ using the value equivalent factor per unit area method, including 815.4–824.3 million ¥ of the unused land, which was ignored in the former method (Costanza et al. 1997). Similarly, the ESVs for each ecosystem vary greatly in these two methods. As given in Xie et al. (2003), there were still some problems in the Costanza's (1997) evaluation method, such as the low estimation of cultivated land and high estimation of wetlands (Xie et al. 2003). For the value equivalent factor per unit area method, Xie et al. (2008) based on Costanza's (1997) evaluation method and improved it by conducting a professional questionnaire survey of 700 ecologists and other relevant scholars in China that evaluated the status of China's ecosystem and socio-economic development, and it was closer to the regional reality. Take the value of aesthetic landscape for example, the tertiary industry had a spectacular development (12.0 to 1462.0 million ¥) in Ejina Banner in the period of 2000–2015, which was related to the *Populus euphratica* forest and its yellow leaf period was the local tourist peak season. Of course, the spectacular tertiary development was related to the background of the rapid development of national society and economy. As given in the ESVs of *Populus euphratica* forest estimated using the value equivalent factor per unit area method, its value of aesthetic landscape in the cultural service was 21.83–22.27 million ¥, which was comparable to tourism revenues at the beginning of this century and far less than recent tourism revenues in Ejina Banner. This also meant that the ESVs should be a dynamic quantity (Costanza et al. 2014).

Moreover, compared the huge differences in unit price between water or wetland and other land types (such as forest and grassland) in the modified Costanza's (1997) evaluation method, the differences were much smaller among ecosystems in the value equivalent factor per unit area method. In addition, we considered the cost of water consumption in ESVs assessment using the value equivalent factor per unit area method in this region, including the riparian forest depending on groundwater and the cultivated land needing irrigation. This meant that some ecological functions of such ecosystems were at the cost of water consumption, which provided references for the trade-off between the value of arid ecosystems and the cost of maintaining them (Wei et al. 2021). In addition, the value of bare land and desert in the water supply was also taken account of in this study, even it was very small (Li et al. 2018), and with the rise of ecotourism and desert tourism, the cultural value of drylands will become more and more important. The above two aspects are the difference between estimation of ecosystem service value in drylands and previous studies (Xie et al. 2003, 2015a, 2015b). Of course, the public's willingness to pay for ecosystem services was not matched with the value of

ESs in many regions (Wei et al. 2021; Wu et al. 2021), which was also the challenge of ESVs research.

Water productivities of ecosystems and its water management implications

In general, we can calculate the value of cultivated land based on the grain yields and its prices, and thus estimate the water productivity. However, it was hard to get convincing results on the productivity of the ecosystem. In this study, we calculated water productivity of various ecosystems by calculating their water consumption and ESVs. Because of the different methods of calculating the ESVs, the water productivities were also different. Among them, the water productivities of the cultivated land were 3.0 and 0.1 ¥/m³, respectively, and the former was more reasonable compared with the actual situation.

Although these results had great differences and uncertainties, they provided an attempt for quantitative evaluation of water productivities of various ecosystems in drylands. Meanwhile, they can help to answer the question about how to allocate water resources rationally to balance human well-being with nature. In dry years with less streamflow from the upstream, for example, shrinking arable land was a priority because the water benefits were relatively low, and then limiting water or wetland's area because of its high water consumption. In addition, it also provided a reference for the ecological compensation or water rights trade within or between regions. For instance, Ejina Banner can purchase/sell certain water resources from/to the middle reaches according to its own needs and benefits, and vice versa, so as to promote the water resources benefits of the whole basin, promote the cooperation and coordination among regions in the basin, and thus move towards basin sustainable development.

The mechanism of EWDP affects land use and then influences ecosystem service value

The EWDP, the most important water management policy in the HRB in the past decades, ensures the available water in the downstream (Fig. 4a), elevates the groundwater level (Fig. 4b), and promotes the restoration of riparian forest ecosystem, especially the *Populus euphratica* forests. Meanwhile, the EWDP provides the ecological water in the terminal lake and maintains a stable water area through special water transmission channels (Lu et al. 2021; Xie et al. 2021). Thus, the EWDP determines the land use pattern and its changes in Ejina Oases. Of course, with social development, regional build-up land continues to expand. Accordingly, the value of regional ecosystem services also changes, especially the Water or wetland's ESVs changes obviously.

Conclusions

This study successfully discovered the land use and land cover changes with the implementation of EWDP, and estimated the water balance in the Ejina Oases and the water consumption of each ecosystem in the period of 1990–2015. The water or wetland dominated the changes in the downstream ecological environment, as well as the change and allocation of water consumption and ESVs. The EWDP caused the reallocation of water resources in the region and among ecosystems, as well as the transfer of ESVs between ecosystems, which had obvious performance in ecological environment and social economy. The ESVs in this area were estimated and compared using two methods, including the modified value per unit area method and the value equivalent factor per unit area method, and there were significant differences in the total ESVs and each ecosystem's. Thus, there were also significant differences in the total water productivities and each ecosystem's, and both of them were less than the actual revenue from the ecosystems. However, it quantitatively evaluated the water productivities of various ecosystems in the drylands at the first time, and provided a reference for the ecological compensation and water trading between regions in the river basin.

Authors contributions Conceptualization ZL, QF; Methodology ZL, QF and JX; Formal Analysis and Investigation ZL, JX; Writing-Original Draft Preparation ZL, JX; Writing-Review and Editing ZL, QF, JX, ZY, MZ and MX.

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Data availability The authors are ready to respond to any request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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