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Runoff controls the development of eco-hydrological and economic conditions in an arid oasis of the downstream inland river basin

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ABSTRACT

Oasis degradation and terminal lake shrinkage are prevalent consequences of the disputed distribution of water resources in inland river basins, hindering regional sustainable development. The Ecological Water Diversion Project (EWDP) is regarded as an important measure to restore the desert-oasis ecosystem in inland river basins, and thus it is essential to comprehensively evaluate the response of eco-hydrological and socioeconomic systems to the EWDP. Based on multiple indicators, we used trend analysis, linear regression, partial least square regression, and structural equation model to disentangle the quantitative effects of the EWDP on the change of eco-hydrological and socioeconomic conditions in the Ejina Oasis (EO) in the lower reaches of the Heihe River in northwest China. Our results indicate that the ecological deterioration was prevalent before the execution of the EWDP, including the increase of groundwater depth, the disappearance of lakes, the decrease of NDVI. After the EWDP, runoff released to EO increased 69.15%, the mean groundwater depth decreased 0.48 m, 52.28% of the study area showed a significant increase in NDVI, areas of forest and grassland increased 20.17 and 25.65 km^2, respectively. The EWDP improved the hydrological regime and prompted the recovery of the oasis. Besides, socioeconomic development was facilitated under the restoration of the eco-hydrological conditions, characterized by the expansion of farmland and the thrive of the tourism industry. The hydrological variables promoted the improvement of the ecological condition with a direct strength of 0.93 and facilitated the development of the socioeconomic conditions in EO with an indirect strength of 0.84. Runoff was the most important positive contributor both to the NDVI and GDP in EO. This comprehensive evaluation framework can offer valuable insight for water resources management and sustainable development in the inland river basin of arid areas.

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Introduction

An oasis is a specific landscape where abundant vegetation and human activities are concentrated due to a stable water supply in arid and semiarid regions (Jin et al., 2010). However, oases are extremely vulnerable landscapes as well, which can be both artificially and naturally occurring. Ecological stability and sustainable development in the oases of the inland river basins are primarily dependent on water resource availability (Su et al. 2007; Zhang, Zhao et al. 2018; Xue et al. 2019; Zhang et al. 2019). Water resources play a critical role in the survival and development of oases in arid inland river basins. Whereas there is widespread competition for water resources between midstream and downstream interests in inland river basins, irrational water distribution leads to oasis degradation, land desertification, and terminal lake shrinkage downstream of the inland river basins. Such problems can be found in the Aral Sea Basin of Central Asia (Glantz 2007), the Helmand River and Urmia Lake of Iran (Stone 2015), the Murray Darling Basin of Australia (Nagler et al. 2016), and the Tarim River Basin (Bao et al. 2017) of Northwest China, to name a few examples. Climate change and human activities exacerbated ecosystem changes in the downstream reaches of inland river basins. Desertification, soil salinization, declining water tables, oasis shrinkage, and wetland/lake disappearance are the main manifestations of ecological degradation in drylands (Zhu et al. 2016). Therefore, a comprehensive quantitative analysis of groundwater, surface water body, land use/cover change (LUCC), and vegetation change resulting from water resources regulation by human interference is essential for ecosystem management and protection in arid regions.

The Heihe River (HR) is the second-largest inland river in China and had undergone severe ecological degradation since the 1980s due to human activities (e.g. urbanization and farmland expansion). Due to the steep increase in water consumption in the middle Reach (i.e. Zhangye Oasis), water flowing into the Ejina Oasis (EO) was significantly decreased. Subsequently, visible signs of ecological deterioration, like land desertification, soil salinization, water quality deterioration, and terminal lakes dry up were prevalent downstream of HR. For example, the East Juyan Lake (EJL) dried up in 1992, the groundwater depth in EO increased 1–2 m from 1980 to 2000, and the area of soil salinization in Ejina reached 2500 km^2 in the 1990s due to lack of water resource availability from the middle reach (Jin et al., 2010; Zhu et al. 2016). Importantly, the EO is usually regarded as an important ecological barrier of Northern China (Cheng et al. 2014). Therefore, to promote the ecological restoration of EO, the Chinese government launched the Ecological Water Diversion Project (EWDP) in August 2000 to restore and protect ecosystems in the inland river basin by reallocating water resources in the middle and lower reaches of the HR (Cheng et al. 2014; Zhao et al. 2016).

Several previous studies have investigated the changes in eco-hydrological conditions in the downstream HR after the EWDP (Jin et al., 2010; Hu et al. 2015; Zhao et al. 2016; Nian, Li, and Zhou 2017; Shen et al. 2017). Besides, the potential risks of the EWDP (Zhang, Wang et al. 2018), and the impacts of the EWDP on the ecology-hydrology-economy nexus in the downstream of HR (Lu et al. 2021) were investigated. These studies can offer useful information on the change of the eco-hydrological system and the socioeconomic development in EO since the execution of the EWDP. However, there are still several issues that need further study for improved management of the inland river basin. First, the relative importance of the natural factors (e.g. temperature and precipitation) and the human activities (e.g. runoff regulation and farmland reclamation) to the vegetation variation (i.e. NDVI) and the economic development (i.e. GDP) need more detailed understanding. Second, the quantified relationships among the meteorological, hydrological, ecological, and economic conditions should be elucidated.

The overall goal of this study was to quantify the variation of the eco-hydrological and socioeconomic conditions in EO before and after the EWDP and reveal the quantified relationships among meteorological, hydrological, ecological, and socioeconomic variables in EO. It was hypothesized that the EWDP improved the eco-hydrologic regimes and further facilitated socioeconomic development. The specific objectives of this study were: (1) detect variation in the eco-hydrological and socioeconomic indicators before and after the implementation of the EWDP (1990–2019), (2) disentangle the relative importance of the eco-hydrological and socioeconomic indicators for the NDVI and GDP, and (3) reveal the quantitative relationship among the meteorological, hydrological, ecological, and economic conditions in EO.

Materials and methods

Study area

The Heihe River originates in Qilian Mountain, flowing downstream through Yingluoxia (YLX) and Zhengyixia (ZYX) hydrological stations. At Langxinshan (LXS) hydrological station, the river divides into the east branch and west branch, which finally flow into the terminal lakes, East Juyan Lake (EJL) and West Juyan Lake (WJL), respectively (Figure 1(a)). The study area lies in the alluvial fan of the east branch of the Heihe River. The total area is ∼1,800 km^2, the oasis is surrounded by peripheral desert (Figure 1(b)). The EO is the administrative, economic, and population center of Ejina Banner, Inner Mongolia, China, as well as a famous tourist destination in Northwest China for *Populus euphratica* Oliv forests. Human activities are most extensive in this area. EO has a typical continental climate, based on the meteorological data during the period of 1980–2019 the annual precipitation and the annual mean temperature were 34.4 mm and 9.2 °C, respectively. Runoff from the middle reach of the Heihe River is the main source of water for the flora and fauna, terminal lakes, and people living in the oasis. The natural vegetation in EO is simple and sparse, including *P. euphratica*, *Tamarix ramosissima* Ledeb, and *Sophora alopecuroides* L. Extremely sparse vegetation, including *Nitraria sphaerocarpa* Maxim. and *Reaumuria soongarica* (Pall). Maxim. exists in the desert regions (Zhang et al. 2011). Soils in EO are mainly classified as fluvisols, arenosols, solonchaks, and gypsisols based on the World Reference Base for Soil Resources (IUSS Working Group WRB 2015).

Data collection and processing

Data used in this study mainly include remotely sensed images, long-term observation data, and statistical data (Table 1). Time series satellite imagery was obtained based on the Google Earth Engine cloud platform (https://code.earthengine.google.com/). Images with cloud cover <5% from June to September were collected. We conducted

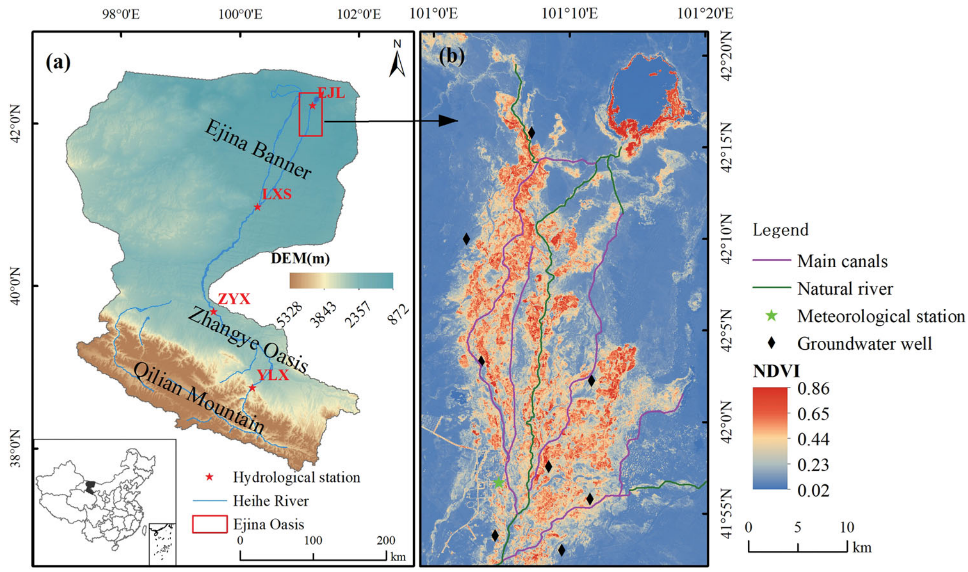

Figure 1. Location of the study area in the Heihe River Basin (a), the annual maximum NDVI of Ejina Oasis in 2019 (b). The YLX (Yingluoxia) and ZYX (Zhengyixia) hydrological stations are the division points of the upstream-middle and middle-downstream reaches of the Heihe River, respectively. LXS (Langxinshan) and EJL (East Juyan Lake) hydrological stations are located at the river inlets of the Ejina and EJL, respectively.

Table 1. Data used in this study.

Data	Time	Scale	Source
Landsat images	1990–2019	30 m	United States Geological Survey http://glovis.usgs.gov/
SPOT-5 image	2012	2.5 m	National Cryosphere Desert Data Center http://www.crensed.ac.cn/portal/
Vegetation map of HRB	2000 and 2010	1:100,000	
Surface water body data	1990–2019	30 m	Global Surface Water Dataset https://global-surface-water.appspot.com/
Runoff	1990–2019	Year	Bureau of Heihe River Water Resources Bulletin
Groundwater depth	1990–2019	Year	
Mean temperature, precipitation, and evaporation	1990–2019	Month	Weather Bureau of Ejina Banner
Population and gross domestic production	1990–2019		Statistical yearbook of Ejina Banner
Area of farmland and crop production	1990–2019		
Tourism population and tourism income	2000–2018		

unsupervised classification and manual visual interpretation following geometric and radiometric correction in ENVI software to obtain land use/land cover (LULC) type, including forest, grassland, farmland, water body, built-up area, and unused land. To subdivide forest and grassland by coverage, we calculated fractional vegetation cover (FVC) using the linear mixture model, which can be written as

Table 2. Land use/cover classification.

First class	Second class	Description
Forest	Thick forest (TF)	Natural forest/shrub or artificial forest/shrub with percent cover >60%
	Moderate coverage forest (MF)	Natural forest/shrub or artificial forest/shrub with percent cover between 30 and 60%
	Sparse forest (SF)	Natural forest/shrub or artificial forest/shrub with percent cover between 5 and 30%
Grassland	Thick grassland (TG)	Natural grassland or artificial grassland with percent cover >60%
	Moderate coverage grassland (MG)	Natural grassland or artificial grassland with percent cover between 30 and 60%
	Sparse grassland (SG)	Natural grassland or artificial grassland with percent cover between 5 and 30%
Farmland	Farmland (FL)	Land used for food crops and cash crops
Water body	Water body (WB)	Regions with detectable water distribution, including rivers, wetlands, lakes, reservoirs, inundated channels
Built-up land	Built-up land (BL)	Includes urban areas, rural settlements, and artificial impermeable surfaces
Unused land	Unused land (UL)	Land with vegetation cover below 5%, including sand, saline-sodic land, desert, and bare land

The coverage classification for forest and grassland was adopted from Wang et al. (2011).

$FVC = (NDVI - NDVI_{soil})/(NDVI_{veg} - NDVI_{soil})$, where the $NDVI_{veg}$ represents the NDVI of fully vegetation-covered pixels and $NDVI_{soil}$ represents the NDVI of the bare soil pixels. Ultimately, we assigned the LULC of EO into ten types (Table 2). Ancillary data (e.g. SPOT-5 image of EO and vegetation map of HR) were collected to assist the interpretation. We used the confusion matrix tool in ENVI for the accuracy assessment of the LULC classification results, the field checkpoints for each LULC type were between 33 and 41. The overall accuracies ranged from 87.60 to 90.40%, and kappa coefficients were between 0.85 and 0.89. The user's and producer's accuracies for the classification of each landscape were all >86%, which indicates that the classification precision is acceptable. The time-series NDVI from 1990 to 2019 were calculated by using the red and near-infrared bands of the Landsat TM and OLI images (Zheng et al. 2019). All of the spatial data were set to the WGS_1984_Albers projection and the resolution was 30×30 m.

Methods

Eco-hydrological and socioeconomic conditions

The linear regression was employed to detect the dynamic changes of hydrological variables (e.g. runoff and groundwater depth) before and after the EWDP. The intersection analysis in ArcMap was employed to reveal the LUCC before and after the EWDP. The Theil-Sen Median trend analysis (Sen's slope) was employed to investigate the interannual change of NDVI from 1990 to 2019. Sen's slope is a robust trend analysis method. It is based on non-parametric statistics and is suitable for the short series (Sen 1968). It can be written as Eq. (1):

$$slope = \text{Median}\left(\frac{NDVI_j - NDVI_i}{j - i}\right) \quad (1)$$

where *slope* represents the change slope of NDVI; $NDVI_i$ and $NDVI_j$ represent the sequential NDVI values corresponding to times i and j, where $i < j < n$, n is the length of times series. When $slope > 0$ indicates the NDVI presents an increasing trend and vice versa.

The Mann-Kendall (MK) test was employed to test the significance of the changing trend of NDVI. MK test has the merits that samples do not need to obey normalized distribution and is free of the interference of the outliers. The details of the MK test can be found in Jiang et al. (2015).

The socioeconomic indicators (i.e. GDP, population, farmland area, tourist population, and tourism income) were collected according to the conditions of EO and the availability of the database. The dynamic variations of these socioeconomic variables were analyzed by linear or non-linear regression according to the data characteristics.

Exploration of the relationships among the ecological, socioeconomic, and hydrologic variables

Partial least square regression (PLSR) is a robust multivariable regression method for analyzing high dimensional variables (Carrascal, Galván, and Gordo 2009). In this study, the GDP and NDVI were defined as dependent variables, respectively, and the meteorological variables (i.e. temperature, precipitation, and evaporation), hydrological variables (i.e. runoff, groundwater depth, and water body area), socioeconomic variables (i.e. population and farmland area) were set as independent variables to analyze the relative importance of the independent variables to the dependent variables. The variable importance (VIP) indicates the importance of the independent for the dependent variables in the projection, when this value is >0.8, it shows that this variable is significant for the independent variable (Wold, Sjostrom, and Eriksson 2001).

Structural equation model (SEM) is a multivariate statistical method that combines factor analysis and path analysis. SEM is usually used to reveal the interaction relationship (including the direct and indirect effects) and effect strength of multiple factors, especially for the multiple effects among latent variables (Hair and Sarstedt 2019). In this study, we hypothesized that the meteorological variables (e.g. temperature and precipitation) would directly, and indirectly regulate the ecological variables (e.g. NDVI), while the hydrological variables (e.g. runoff and groundwater depth) can directly affect the ecological variables, and indirectly impact the socioeconomic variables (e.g. GDP and farmland area) through the ecological variables. The ratio of chi-square and degree of freedom (CMIN/DF), goodness-of-fit index (GFI), and root mean square error of approximation (RMSEA) were explored for model estimation. When the CMIN/DF < 3, GFI > 0.9, RMSEA < 0.1, these indicate that the model fitted well.

Results

Changes in hydrological regime

From 1990 to 2000, the annual runoff at LXS exhibited a reduction trend with an average runoff of $3.76 \times 10^8\ m^3\ yr^{-1}$. Since 2000, attributed to the execution of the EWDP, runoff at LXS significantly increased ($p < 0.05$). From 2001 to 2019, the annual mean

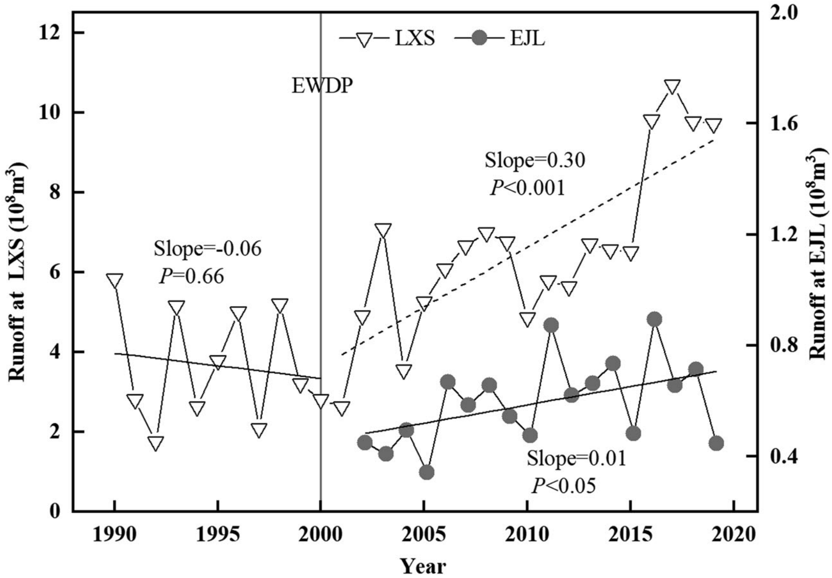

Figure 2. Changes in inter-annual runoff at Langxinshan (LXS) and East Juyan Lake (EJL) hydrological stations.

runoff at LXS was $6.36 \times 10^8\,m^3$, a $2.6 \times 10^8\,m^3$ overall increase compared with that of the 1990s. The annual runoff flowing into EJL also increased significantly ($p < 0.05$) since the execution of the EWDP, and remained $\sim 0.60 \times 10^8\,m^3\ yr^{-1}$ in recent years (Figure 2). Generally, the EWDP significantly improved the runoff delivered to EO.

During the 1990s, the groundwater depth fluctuation increased, a 0.41 m overall increase from 1990 to 2000. Since 2000, the groundwater depth significantly decreased ($p < 0.05$), the mean groundwater depth was $\sim$2.60 m in recent years, a 0.48 m overall decrease compared with the initial period of EWDP. Additionally, compared with 2001, the groundwater depth of the region around the EJL decreased by 2.14–3.10 m in 2019 (Figure 3(a)). Overall, the groundwater depth in EO showed an obvious decreasing trend after the execution of the EWDP.

We observed an obvious reduction of surface water bodies from 1990 to 2000, among which the disappearance of the EJL and the Xiala Nur Reservoir was most obvious (Figure 4). Since the implementation of the EWDP, broader regions were inundated. In 2010, the water area of EJL and Xiala Nur Reservoir reached 39.97 and 2.60 km^2, respectively. Besides, since 2010, the eastern oasis-desert ecotone was inundated due to the increase of runoff (Figure 4). During the 1990s, the water body area was $\sim$3 km^2 (except 1990 and 1998, attributed to the relatively high runoff at LXS in both years). Since 2000, the area of the surface water body significantly increased ($p < 0.05$), and in recent years, the average total area of the surface water body was $\sim$80 km^2 (Figure 3(b)). The EJL was first inundated in 2002, since then it presented a significant expansion trend, and its area was stable at $\sim$44 km^2 in recent years (Figure 3(b)). In general, the EWDP promoted the restoration and improvement of the surface water body in EO.

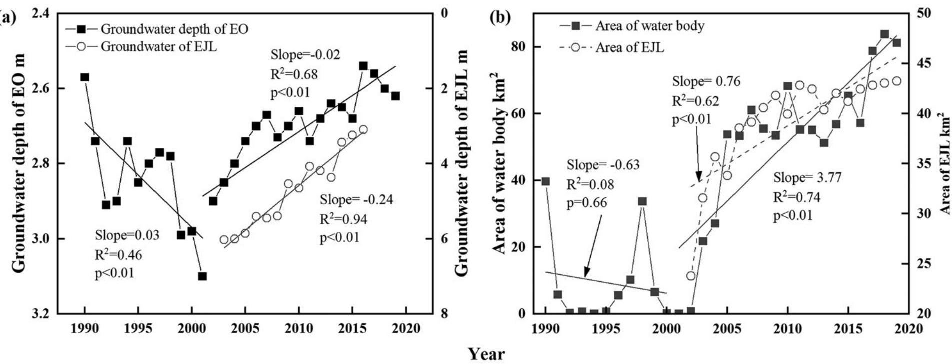

Figure 3. Changes in groundwater depth in Ejina Oasis (EO) and East Juyan Lake (EJL) (a), area of water body in Ejina Oasis and area of EJL (b).

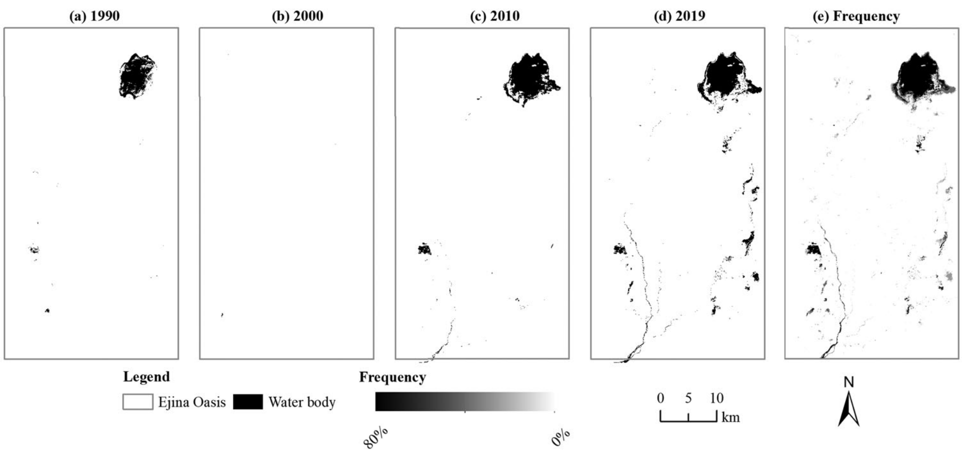

Figure 4. Changes in the spatial distribution of surface water (a–d) and water body frequency (e) in Ejina Oasis. Water body frequency refers to the times a raster filled with water for a specific period divided by the length of the period.

Changes in ecological conditions

Land use/cover change

Forests are mainly distributed along the river, while grasslands (mainly for the sparse grassland) primarily lie in the transitional areas between oasis and desert, and farmland is scattered throughout the oasis (Figure 5(a)). Before 2000, the oasis clearly shrank, especially the downstream, the recession of high coverage vegetation (e.g. thick forest) was obvious. While after 2000, the thick forest was gradually restored and further expanded, and sparse grassland in the oasis-desert ecotone extended toward the desert. Farmland increased from 2000 to 2010 and then remained stable, while the built-up land unceasingly enlarged during the whole study period (Figure 5(b)). Sparse grassland was the main vegetation type, accounting for ∼15% of the study area, followed by sparse forest and thick forest, which both occupied ∼6% of the study area. In 1990, 2000, 2010, and 2019, the total area of the forest (including thick forest, moderate cover forest, and sparse forest), grassland (including thick grassland, moderate cover

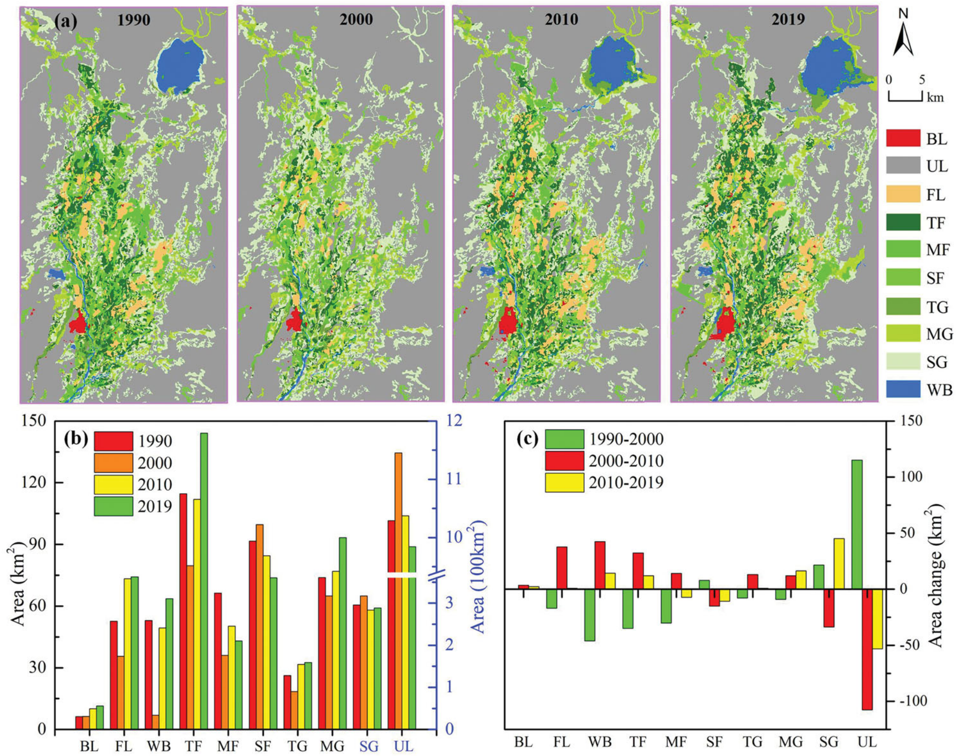

Figure 5. Spatial distribution of land use/cover types in 1990, 2000, 2010, and 2019 (a), land use/cover structure (b), and land use/cover change (c) in Ejina Oasis. BL: Built-up land; FL: Farmland; WB: Water body; TF: Thick forest; MF: Moderate coverage forest; SF: Sparse forest; TG: Thick grassland; MG: Moderate coverage grassland; SG: Sparse grassland; UL: Unused land.

grassland, and sparse grassland), and water body were 778.19, 653.94, 770.14, and 824.49 km^2, respectively.

Land use/cover change (LUCC) differed greatly before and after the EWDP (Figures 5c, 6a). From 1990 to 2000, the transformation from a water body (43.35 km^2), sparse grassland (33.13 km^2), and sparse forest (12.82 km^2) to unused land was the major process of LUCC. Besides, moderate coverage grassland (28.21 km^2) conversion to sparse grassland and thick forest (22.35 km^2) conversion to sparse forest occurred as well. While from 2000 to 2019, the unused land converted to the water body and water body and sparse grassland gained 50.61 and 42.25 km^2, respectively. Besides, sparse grassland (16.21 km^2) and unused land (10.07 km^2) converted to farmland were also significant (Figure 6(b)). Overall, before the EWDP, the conversion of oasis vegetation and water body to unused land was the primary trend. After the EWDP, the expansion of natural oases and farmland from unused land was the primary trend.

Vegetation cover change

From 1990 to 2000, the region that gained and lost NDVI accounted for 3.85 and 12.72% of the study area, and the slopes were 1.33×10^{-2} and $-2.54 \times 10^{-2}\,\text{yr}^{-1}$,

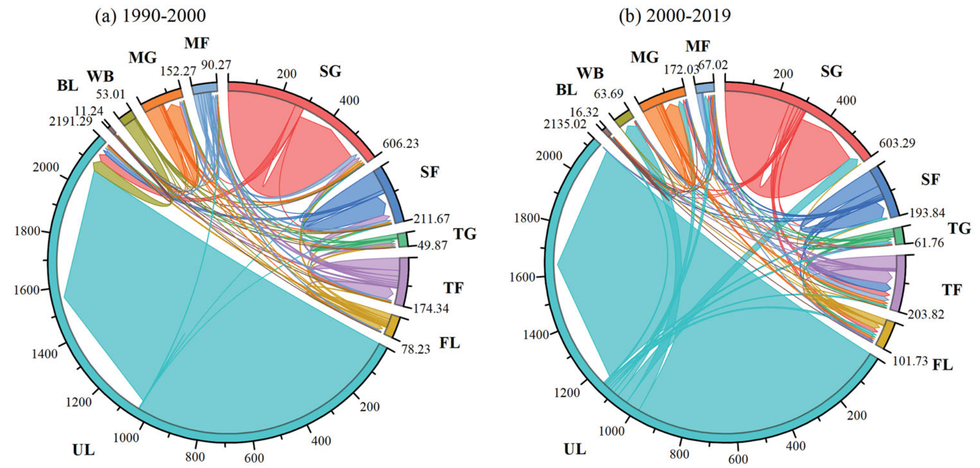

Figure 6. Land use/cover shifts from 1990 to 2000 (a) and from 2000 to 2019 (b). Numbers around the circle indicate the area (km^2). The abbreviation of land use/cover refer to Figure 5.

respectively. The NDVI reduction was prevalent (Figure 7(a)). From 2000 to 2010, 25.12 and 6.27% of the area exhibited a significant increase and decrease in NDVI, and the slopes were 3.41×10^{-2} and $-1.14 \times 10^{-2}\,yr^{-1}$, respectively. Regions with increasing NDVI were mainly distributed alongside the river and in the lakeside wetlands of the EJL (Figure 7(b)). From 2010 to 2019, 12.01 and 2.81% of the study area exhibited significant increases and decrease in NDVI with slopes of 1.30×10^{-2} and $-0.83 \times 10^{-2}\,yr^{-1}$. Regions with increases in NDVI were primarily distributed in the ecotone of the oasis and desert, while regions with decreasing NDVI were scattered throughout the whole study area (Figure 7(c)). Overall, before 2000, oasis vegetation experienced a dominant browning trend, 37.24% of the study area went through the loss of NDVI, 12.72% with a significant decreasing trend. Whereas, since 2000, more than 52% of the study area showed significant greening (Figure 7(d)).

Socioeconomic development

The socioeconomic conditions of EO underwent dramatic change during the study period, especially after the implementation of the EWDP (Figure 8). Specifically, from 1990 to 1999, GDP increased from 0.31×10^8 to 1.64×10^8 CNY, while from 2000 to 2018, GDP sharply increased, and exceed 50×10^8 CNY in 2017. The population steadily increased with a slope of $115.22\,yr^{-1}$ (0.68%) during the study period (Figure 8(a)). Before EWDP, the area of farmland exhibited a slightly declining trend, while after the EWDP, it showed a sharply rising trend ($1.62\,km^2\ yr^{-1}$), $30.14\,km^2$ overall increase from 2000 to 2019. Along with the expansion of the farmland, the crop production significantly increased ($8000\,tons\ yr^{-1}$) since 2000, and reached 130,000 tons in recent years (Figure 8(b)). For tertiary industry, the tourist population and tourism income in 2001 was merely 62,300 visitors and 0.13×10^8 CNY, respectively. However, in 2018, these figures rose to over 2×10^6 tourists and 30×10^8 CNY, respectively (Figure 8(c)). At present, tourism income accounts for over 50% of the total GDP, and tourism has

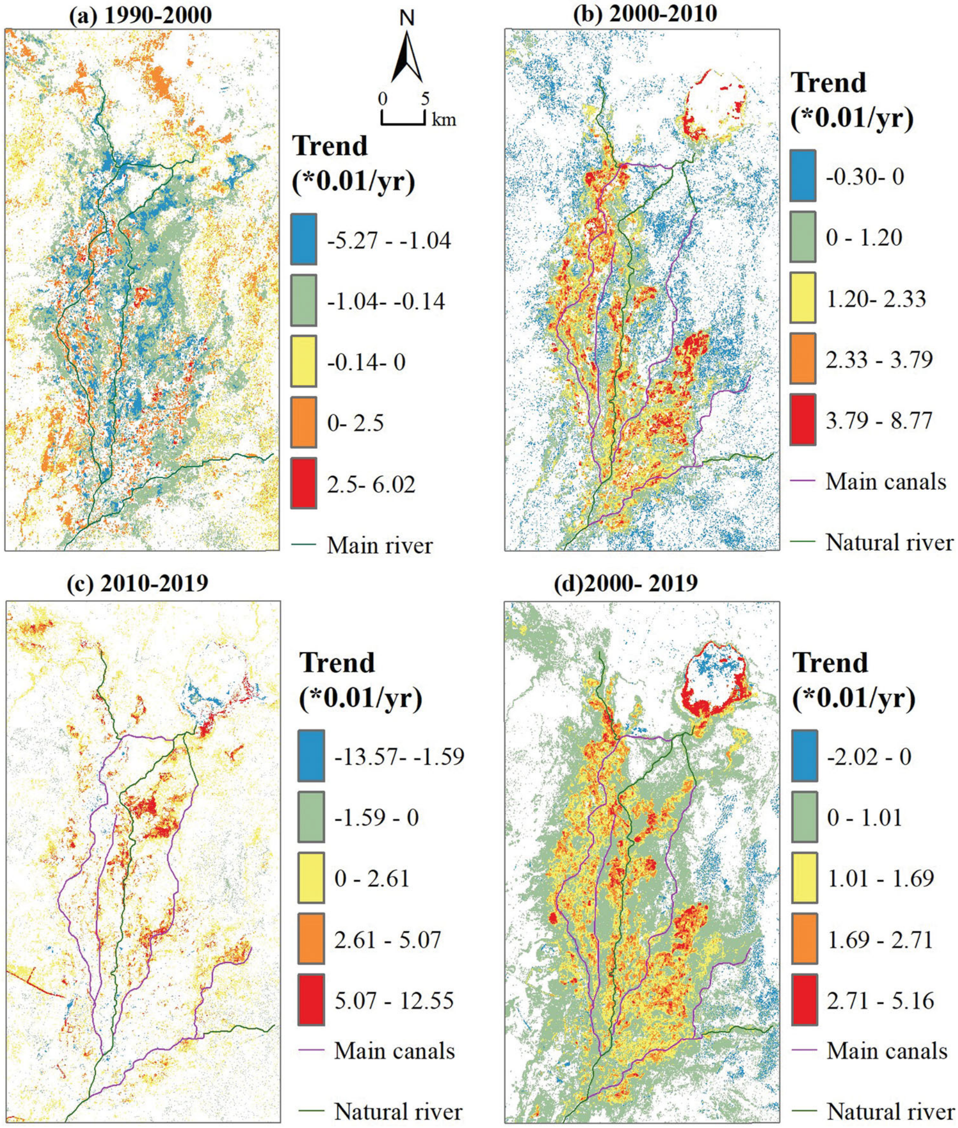

Figure 7. Significant changes in annual maximum NDVI of Ejina Oasis from 1990 to 2000 (a), 2000 to 2010 (b), 2010 to 2019 (c), and 2000 to 2019 (d). Blank areas represent insignificant changes ($p > 0.05$).

become the pillar industry of Ejina. In short, after the EWDP the economy in EO rapidly developed dominated by the prosperity of agriculture and tourism.

Interactions among hydrological, ecological, and socioeconomic variables

The runoff (VIP = 1.01, $b = 1.02$) and the water body area (VIP = 0.90, $b = 0.92$) were the primary positive contributors to the NDVI change in EO, while the groundwater depth (VIP = 0.89, $b = -0.47$), the area of farmland (VIP = 0.88, $b = -0.48$) and the population (VIP = 0.67, $b = -0.27$) were the primary negative contributors to the NDVI change. The

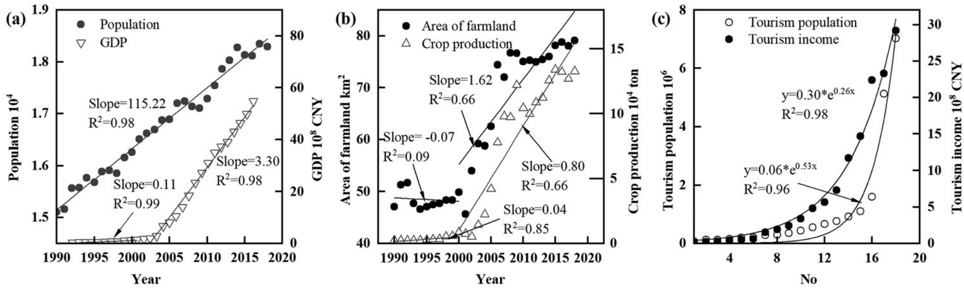

Figure 8. Changes in population and GDP (a), area of farmland and crop production (b), and tourist population and tourism income (c) in Ejina Oasis. In (c), the numbers of the X-axis represent the time series from 2000 to 2018 (e.g., No. 1 means year 2000, No. 2 means year 2001, and so on).

meteorological factors (i.e. precipitation, temperature, and evaporation) had a slight effect on the NDVI. As for the GDP, the population (VIP = 1.10, $b = 0.87$), area of farmland (VIP = 0.97, $b = 0.57$), area of water body (VIP = 0.89, $b = 0.28$), and runoff (VIP = 0.85, $b = 0.20$) were the relative important positive factors, while evaporation (VIP = 0.70, $b = -0.16$) exerted a negative effect on the GDP (Figure 9). Generally, the rising of runoff promoted the increase of the NDVI and the economic development in EO, while the sharp expansion of farmland and population growth exerted a slightly negative effect on NDVI. The meteorological factors had limited effects on the NDVI and GDP.

The SEM model fitting parameters suggest that the model fitted the data well. SEM results showed that there are different patterns of direct and indirect effects among the meteorological, hydrological, ecological, and socioeconomic variables (Figure 10). Specifically, the hydrological variables had significant positive effects on the ecological variables, with a path coefficient of 0.93 ($p < 0.001$). The ecological variables had significant positive effects on the socioeconomic variables, with a path coefficient of 0.90 ($p < 0.01$). The hydrological variables indirectly affected the socioeconomic variables through the ecological variables, and the indirect effect coefficient can be expressed as $0.93 \times 0.90 = 0.84$ ($p < 0.01$). The meteorological variables had relatively small effects on the hydrological and ecological variables, with path coefficients of 0.36 and −0.06 ($p > 0.05$). These SEM results show that the improvement in hydrological conditions induced by the EWDP promoted the ecological recovery, and further accelerated the socioeconomic development in EO.

Discussion

Driving factors of the changing eco-hydrological regime and socioeconomic conditions

Runoff regulation is regarded as an important management option affecting the ecosystem in an inland river basin. The EWDP maintained a suitable water table in EO and facilitated the rehabilitation of the degraded oasis. Attributed to the efficient flood irrigation and river seepage, the groundwater depth obviously decreased. The shallower groundwater depth feeds soil moisture better through capillarity for maintaining the root system, which promoted the increase of the area of forest and grassland. With the

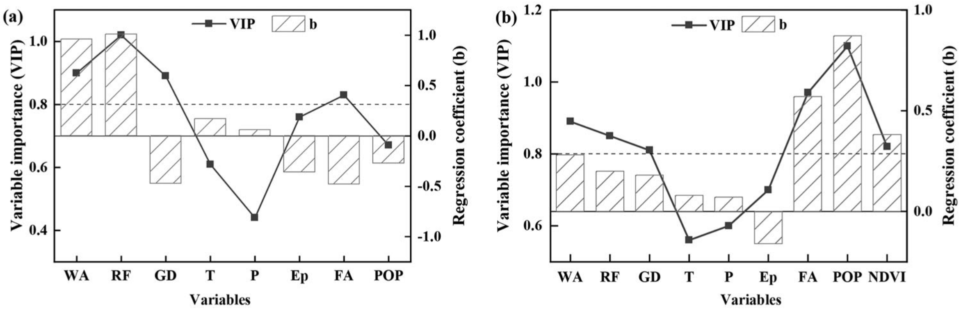

Figure 9. Variable importance and regression coefficient of the PLSR model for the change of NDVI (a), and GDP (b) in Ejina Oasis. Abbreviation: Ep (evaporation), T (temperature), P (precipitation), GD (groundwater depth), RF (runoff), NDVI (normalized difference vegetation index), WA (water body area), OA (oasis area), FA (area of farmland), POP (population).

recovery of oasis vegetation, 51.79% of the study area exhibited a significant rise in NDVI from 2000 to 2019. Field investigations have also confirmed significant increases in vegetation species diversity and vegetation coverage after the EWDP (Peng et al. 2017). The area of the terminal lake (EJL) clearly increased since 2003, a previous study found that there is a significant positive correlation between the released runoff at LXS and the lake area of EJL (Lu et al. 2021). Attributed to the efficient inundation and recharge of groundwater, the wetland vegetation around the EJL was markedly restored (Hu et al. 2015), and the NDVI significantly increased from 0.08 to 0.14 during 2000–2019 (Figure 7). Besides, the seasonal water body in the oasis-desert ecotone expanded to ~9 km^2 due to the flood irrigation, which promoted the sprawl of the oasis vegetation into the desert (Figure 5(a)). Generally, increasing runoff caused by the EWDP improved the hydrological regime in EO and further promoted the recovery of the oasis vegetation.

Additionally, the EWDP also promoted economic development in EO, especially for the agriculture and tourism industry (Figure 8). Farmland area increased 1.89 times, and crop production raised ~8000 tons per year from 2000 to 2019. To increase income, the local people reclaim farmland from grassland and desert to cultivate crash crops (e.g. melon and cotton), and intensive cultivation was adopted for higher production (Hu et al. 2015). Zhang, Wang et al. (2018) indicated that the sown area in EO exhibited a significant positive correlation with the runoff at LXS. Besides, the population in EO increased stably thanks to the enhancement of the eco-hydrological conditions (Figure 8(a)). Furthermore, the increased runoff stimulated the development of ecotourism as well. The desert riparian forests (i.e. *P. euphratica* forests) and the desert lakes (e.g. EJL) provide beautiful landscapes, which attracted plenty of tourists. Thus, the tourist population and tourism income notably increased since 2000 (Figure 8(c)). It is noted that the policy factor (e.g. China Western Development and Belt and Road Economic Construction) and the prosperity of the whole country's economy are also important factors driving the rapid development of the economy (e.g. tourism) in EO, which needs further investigation.

Moreover, a series of countermeasures of ecological protection (e.g. grazing constraints, the establishment of *P. euphratica* forest nature reserves, and artificial forest planting) were also implemented in EO to assist ecological restoration (Hu et al. 2015),

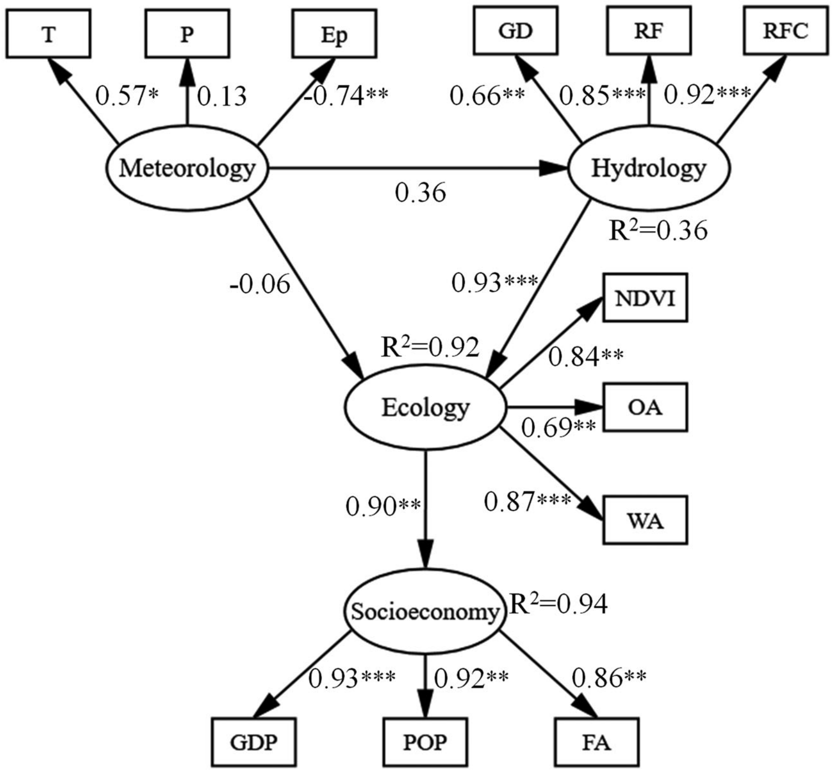

Figure 10. Structural equation model accounting for the hypothesized direct and indirect relationships among the meteorology, hydrology, ecology, and socioeconomy variables in Ejina Oasis. The arrows indicate the paths, and the numbers adjacent to the arrows are standardized path coefficients. Asterisks indicate the significance level of the coefficient (*** indicates $p < 0.001$, ** indicates $p < 0.01$, and * indicates $p < 0.05$). R^2 is the proportion of variance explained, the initial variable (Meteorology) is without R^2. The boxes represent the observed variables, while the ellipses represent the latent variables, which can be represented by the directly linked observed variables. The check parameters of SEM were CMIN/DF = 2.831, GFI = 0.944, and RMSEA = 0.074. Abbreviations: Ep (evaporation), T (temperature), P (precipitation), GD (groundwater depth), RF (runoff), RFC (cumulative runoff), NDVI (normalized difference vegetation index), WA (water body area), OA (oasis area), GDP (gross domestic product), area of FA (farmland), POP (population).

which promoted the restoration of the oasis ecosystem (Lu et al. 2021). Overall, the improvement of the eco-hydrological conditions facilitated economic development, in turn, socioeconomic development promoted the implementation of the environmental protection measures, and thus a positive feedback loop formed initially between ecological protection and economic development.

Implications for oasis ecosystem management in arid inland basins

Although the EWDP had overall positive effects on the eco-hydrological regimes and socioeconomic development, some ecological risks (e.g. vegetation degradation) still emerged ascribed to the increasing anthropogenic interference (e.g. farmland expansion and population growth) (Figures 7, 9). Oasis expansion dominated by the increase of artificial oasis (e.g. farmland) is widespread (He et al. 2018), whereas, substantial increases in farmland will overuse groundwater in arid regions (Hu et al. 2015). Once the groundwater level is lower than the suitable ecological groundwater level (2–5 m), the degradation of natural vegetation will occur (Jin et al., 2010; Zhao et al. 2016). Moreover, due to the strong evaporation, intensive farmland irrigation will lead to secondary salinization, which damages the adjacent natural vegetation (Zhang et al. 2016). Besides, the construction of the canals for water delivery reduced the recharge of groundwater alongside the canals, further leading to the local degradation of vegetation (Figure 7). In addition, socioeconomic development (especially population increase and the rapid development of tourism) will inevitably limit water availability for natural vegetation. Although tourism can bring considerable economic profits, the negative effects of tourism (e.g. littering pollution, destruction of desert soil biocrust by trampling, and plant removal) should not be neglected. Since the ecosystem in the dryland is extremely vulnerable, once the surface microbiotic soil crusts and vegetation are destroyed by tourists, recovery will become very difficult due to the harsh environment (Zhu et al. 2016).

Several water allocation and ecosystem management suggestions are provided based on our results. First, water resources should be preferentially allocated to the natural ecosystem, agricultural water consumption should be controlled by constraining the farmland area, and improving the water utilization efficiency by water-saving irrigation. As for reducing secondary salinization caused by farmland irrigation, irrigation in winter and spring may be helpful. Besides, conservation tillage is a good choice to reduce the negative effect of farming on the ecosystem (Zhu et al. 2016). Second, the appropriate oasis scale and terminal lake area should be determined based on the water resources carrying capacity. Third, groundwater replenishment should be guaranteed, and groundwater extraction for socioeconomic development should be constrained in case of runoff scarcity in dry years. Finally, the integration of administrative measures, market mechanisms, and stakeholder participation should be implemented for more holistic water resource management.

Long-term and high-resolution remote sensing data is an important tool to detect small and abrupt changes in vegetation, which is critical for the evaluation of ecological environment variation (e.g. vegetation cover and land use/cover change) in drylands. However, uncertainties also exist in the processing and analysis of remote sensing images to obtain related indicators. Such as the interpretation of the land use/cover, although the higher resolution images (e.g. SPOT 5) and vegetation type map were used to improve the interpretation precision, the error was still inevitable, which lead to some uncertainties for the study.

Conclusions

The EWDP had effectively redistributed water resources between the middle and lower reach of Heihe River, the annual streamflow released to the EO was increased ∼65% after the execution of the EWDP. The mean groundwater table raised 0.48 m. Due to these increases in runoff and rising of groundwater table, over 52% of the study area showed a significant increase in vegetation cover, and the mean NDVI increased by

0.05 from 2000 to 2019. The total area of the forest and grassland increased by 170.55 km^2. Additionally, the EWDP had accelerated socioeconomic development in EO. Farmland almost doubled during 2000–2019, and crop production increased to over 130,000 tons. Furthermore, the tourism industry rapidly developed with the restoration of the riparian *P. euphratica* forests and terminal lakes. SEM revealed that hydrological variables promoted the improvement of the ecological conditions with a direct strength of 0.93, and facilitated the development of the socioeconomic systems in EO with an indirect strength of 0.84. Whereas, the PLSR indicated that the anthropogenic interference (e.g. farmland reclamation, population growth) had negative effects on the oasis vegetation. Generally, the EWDP posed obvious positive effects on the hydro-ecological and socioeconomic systems of EO. A positive feedback loop initially formed between EO's ecological protection and economic development. Thus, the rational distribution of water resources and the harmonized development of the economy and ecological protection is possible in the inland river basin. The framework and method of this study can be applied in other inland river basins worldwide.

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