Remote Sensing Monitoring of Ecological Water Transfer and Analysis of Agricultural Water-Saving Benefits in Ungauged Arid Watersheds: Postprint

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Abstract

Ecological water conveyance and agricultural water conservation are important means to achieve sustainable development in inland arid basins. The lack of continuous hydrological observation data constrains the evaluation of benefits from ecological water conveyance and agricultural water conservation. To this end, taking the lower reaches of the Shule River Basin in Dunhuang, Gansu Province, China as an example, this study conducted remote sensing monitoring of ecological water conveyance at a monthly scale from 2016 to 2020 based on remote sensing hydrological stations and Google Earth Engine. On this basis, combined with multi-source remote sensing data such as evapotranspiration and land cover types, the benefits of ecological water conveyance and agricultural water conservation were evaluated, and the water resource balance relationship between the two was analyzed. The results show that: (1) Remote sensing hydrological stations and Google Earth Engine (Google Earth Engine, GEE) can provide reliable data support for remote sensing monitoring of ecological water conveyance and evaluation of agricultural water conservation benefits. (2) From 2017 to 2020, ecological water conveyance can provide an average of 2.50\$×108*m3ofecologicalwaterannuallyfordownstreamwetlandsandriverchannels,ofwhich*30.06×\$108 m3 annually from 2017 to 2020; the reduction in cultivated land evapotranspiration accounted for an average of 14.22% of the ecological water conveyance volume, effectively alleviating the problem of agricultural water use encroaching upon ecological water use in inland arid basins. This paper will provide new ideas for remote sensing monitoring of ecological water conveyance and evaluation of agricultural water conservation benefits in inland arid basins lacking observation stations, aiming to provide theoretical support for the implementation of future ecological water conveyance and agricultural water conservation projects.

Remote Sensing Monitoring of Ecological Water Conveyance and Benefit Evaluation of Agricultural Water-Saving in Arid Basins Without Observation Stations

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Abstract

Ecological water conveyance and agricultural water-saving are important means to achieve sustainable development in inland arid basins. However, the lack of continuous hydrological observation data restricts the evaluation of benefits from ecological water conveyance and agricultural water-saving. Taking the lower reaches of the Shule River Basin in Dunhuang, Gansu Province as an example, this study conducted monthly-scale remote sensing monitoring of ecological water conveyance from 2016 to 2020 based on remote sensing hydrological stations and Google Earth Engine (GEE). The benefits of ecological water conveyance and agricultural water-saving were then evaluated using multi-source remote sensing data including evapotranspiration and land cover types, and the balance between them was analyzed in terms of water resources. The results show that: (1) Remote sensing hydrological stations and GEE can provide reliable data support for remote sensing monitoring of ecological water conveyance and evaluation of agricultural water-saving benefits. (2) From 2017 to 2020, ecological water conveyance provided an average of 2.50×10^{8} m^3 of water annually to downstream wetlands and rivers, of which 30.06% reached the downstream wetland and 18.47% was utilized by vegetation around the downstream river channel, increasing the vegetation area by 112.25 km^2. (3) From 2017 to 2020, agricultural water-saving effectively reduced cultivated land evapotranspiration by an average of 0.395×10^{8} m^3 per year while maintaining an increasing trend in cultivated land area. The reduction in cultivated land evapotranspiration accounted for 14.22% of the ecological water conveyance volume, effectively alleviating the problem of agricultural water use encroaching upon ecological water in inland arid basins. This study provides a novel approach for monitoring ecological water conveyance and evaluating agricultural water-saving benefits in inland arid basins lacking observation stations, aiming to provide theoretical support for future implementation of ecological water conveyance and agricultural water-saving projects.

Keywords: ecological water conveyance; agricultural water-saving; inland arid basin; remote sensing hydrological station; Google Earth Engine (GEE)

Introduction

Water resources are crucial for the socio-economic development of human society and the sustainability of ecological environment systems in inland arid basins. In many inland arid basins, agricultural water consumption occupies the majority of water resources, severely encroaching upon ecological water use and leading to a series of ecological and environmental problems such as river drying, vegetation disappearance, and lake-wetland shrinkage. Ecological water conveyance is the most commonly used remedial measure in inland arid basins, which redistributes water resources between human socio-economic systems and natural systems by planned water delivery to downstream areas, benefiting the basin' s ecological environment. To obtain surplus water resources for ecological water conveyance while meeting socio-economic development needs, existing water use patterns must change. As agriculture is the industry with the largest water consumption and the greatest water-saving potential in inland arid basins, agricultural water-saving can provide certain ecological water for ecological water conveyance and effectively alleviate the problem of agricultural water encroaching upon ecological water. Therefore, conducting remote sensing monitoring of ecological water conveyance benefits and rationally evaluating the benefits generated by agricultural water-saving are essential for sustainable water resources planning and management in inland arid basins.

Numerous studies have been conducted on ecological water conveyance monitoring and agricultural water-saving benefits evaluation separately. Regarding ecological water conveyance benefits, researchers have evaluated ecological effects based on monitoring data from the lower reaches of the Tarim River, analyzing groundwater depth and vegetation cover at large spatiotemporal scales. Others have used the Soil-Adjusted Vegetation Index threshold method to analyze spatiotemporal changes in vegetation cover and its response to ecological water conveyance in the lower Tarim River. Some studies have monitored changes in Populus euphratica forests using Landsat imagery and explored the impact of ecological water conveyance through dual-temporal change detection and time trajectory analysis. Researchers have also quantitatively described runoff changes in the main stream and tributaries of the lower Tarim River using equations and evaluated the effectiveness of ecological water conveyance. Similar studies have been conducted in the Heihe River Basin and Shiyang River Basin in northwest China. Regarding agricultural water-saving benefits, research has gradually shifted from traditional irrigation benefit evaluation to comprehensive evaluation of social, economic, and ecological benefits. Various methods have been applied including improved Delphi methods, matter-element extension models, AHP and entropy weight methods, and multi-objective evaluation combined with TOPSIS methods. Although many achievements have been made in studying either ecological water conveyance benefits or agricultural water-saving benefits, there is an urgent need to simultaneously evaluate both benefits and analyze their balance relationship in water resources.

To deeply and comprehensively evaluate the benefits generated by ecological water conveyance and agricultural water-saving projects in inland arid basins lacking observation stations and analyze their internal balance relationship, this study leverages the advantages of remote sensing hydrological stations in river discharge estimation and Google Earth Engine (GEE) in spatial data processing. Taking the lower reaches of the Shule River Basin in Dunhuang, Gansu Province as a case study, we: (1) estimate long-term monthly-scale river discharge based on remote sensing hydrological stations to achieve remote sensing monitoring of ecological water conveyance in the lower Shule River, and obtain and process underlying surface and evapotranspiration data in the lower Shule River Basin based on GEE; (2) quantitatively evaluate ecological water conveyance benefits from three aspects: changes in ecological water conveyance volume and efficiency, vegetation area change, and vegetation evapotranspiration change; (3) quantitatively evaluate agricultural water-saving benefits from two aspects: cultivated land area change and cultivated land evapotranspiration reduction; and (4) analyze the balance relationship between ecological water conveyance and agricultural water-saving in terms of water resources. This study provides new ideas for ecological water conveyance monitoring and benefit evaluation of ecological water conveyance and agricultural water-saving in inland arid basins lacking observation stations, aiming to provide theoretical support for future implementation of ecological water conveyance and agricultural water-saving projects.

1 Study Area, Data, and Methods

1.1 Study Area Overview

River discharge is one of the most critical factors in evaluating ecological water conveyance benefits. Due to climate and harsh geographical environments, many inland arid basins lack hydrological stations, making it difficult to grasp changes in river discharge before and after ecological water conveyance. The International Association of Hydrological Sciences explicitly launched the Prediction in Ungauged Basins (PUB) program in 2003, and many studies have since introduced satellite remote sensing data into large river discharge calculation, achieving series of results with GRACE and Landsat data. However, low spatial resolution of satellite remote sensing data and difficulties in underwater topography measurement have limited the application of satellite remote sensing data in medium and small river discharge calculation. To address these difficulties, "remote sensing hydrological stations" estimate long-term river discharge by combining low-altitude UAV remote sensing imagery with satellite remote sensing imagery, enabling remote sensing monitoring of ecological water conveyance. Remote sensing hydrological stations use UAV remote sensing imagery combined with field measurements to generate centimeter-level digital channel models, calculate hydraulic parameters such as cross-sectional area, slope, and hydraulic radius from water surface width, and then calculate river discharge using the Manning formula. Remote sensing hydrological stations have been established in ungauged basins such as the Ebinur Lake Basin and the Tibetan Plateau to estimate long-term river discharge, with validation showing good performance in relative accuracy and Nash-Sutcliffe efficiency coefficient between estimated and measured discharge, indicating that remote sensing hydrological stations are suitable for discharge estimation in medium and small rivers in ungauged basins.

The Shule River is located in Gansu Province, China, originating from the Qilian Mountains, with a main stream length of 670 km from east to west. The basin has scarce precipitation, arid climate, with multi-year average temperature of 6.9-8.8°C, annual average precipitation of 40.2-57.5 mm, and annual average evaporation of 2577.4-2653.3 mm. The West Lake Wetland is located at the end of the Shule River with a total area of 6600 km^2, which helps maintain ecological stability in Dunhuang City and the western section of the Hexi Corridor. The Shuangta Reservoir is located on the main stream of the Shule River with a designed total storage capacity of 2.4$×10^{8}$ m^3. The section downstream of the reservoir to the West Lake Wetland is the lower reaches of the Shule River (Fig. 1 [Figure 1: see original paper]). Due to water shortage in the Shule River Basin, environmental problems such as river drying and vegetation disappearance have occurred in the downstream river channel and West Lake Wetland. With the proposal of the "Dunhuang Water Resources Rational Utilization and Ecological Protection Comprehensive Plan" in 2011, agricultural water-saving transformation was carried out on 309.53 km^2 of cultivated land in the Shuangta Irrigation District, and 82.94 km of ancient river channels in the lower Shule River were regulated. From July 2017, the Shuangta Reservoir began to deliver large amounts of ecological water to the downstream West Lake Wetland. Since the water level station at Section 2 was built after July 2017 and located at Section 2 formed after the completion of river channel regulation and confinement works, existing hydrological stations cannot monitor changes in river discharge before and after ecological water conveyance.

1.2 Data Sources and Processing

1.2.1 Low-Altitude Remote Sensing and Field Measurement Data

The DJI Mavic Air 2 UAV served as the low-altitude remote sensing data acquisition platform, with Pix4D software used to plan flight missions. In July 2021, scans were conducted at three remote sensing hydrological station sections in the lower Shule River Basin (Fig. 1 [Figure 1: see original paper]), with radar current meters and sonar used to measure flow velocity and water depth at each section (Table 1). Section 1 is located at the Liudun Highway Bridge in Xihu Township, Dunhuang City, where the ancient Shule River channel downstream of the section completed regulation and confinement works in July 2017, so discharge changes at this section will reflect changes in ecological water conveyance volume. Section 2 is located at the Nanliang section near the confluence of the Shule River and Dang River, where a water level station was established after the completion of river channel regulation and confinement works, with its measured discharge data used to validate the accuracy of remote sensing hydrological stations. Section 3 is located at the Shule River Bridge within the West Lake Wetland, and its discharge reflects the water volume reaching the West Lake Wetland before and after ecological water conveyance. Since the Dang River Reservoir does not undertake ecological water conveyance tasks, the study boundary was selected as the area mainly affected by ecological water conveyance and agricultural water-saving (including the Shuangta Irrigation District, areas around the main Shule River channel, and the West Lake Wetland) to evaluate the benefits of ecological water conveyance and agricultural water-saving (Fig. 1 [Figure 1: see original paper]).

1.2.2 GEE Satellite Remote Sensing Data Normalized Difference Water Index (NDWI), land cover type, and evapotranspiration data were all obtained and processed using GEE (Table 2). When acquiring and processing satellite remote sensing data based on GEE, the area mainly affected by ecological water conveyance and agricultural water-saving was selected as the study boundary. The specific data selection, processing methods, and study boundary selection are as follows:

1) **Normalized Difference Water Index (NDWI)**: Since Sentinel-2 surface reflectance data has a 10 m spatial resolution and can meet the needs of water body identification, monthly-scale data were fused using the mean algorithm, and NDWI was calculated according to Equation (1) to extract water body area in the river channel.

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

where GREEN and NIR are the reflectance values of the green and near-infrared bands in the remote sensing imagery, respectively.

2) **Land Cover Type**: Since ecological water conveyance and agricultural water-saving were not implemented in 2016, MODIS land cover type products can meet research needs. The missing land cover type data for 2016 were assumed to be the same as those for 2017.
3) **Evapotranspiration**: Annual-scale evapotranspiration data were obtained by fusing MODIS net surface evapotranspiration products using the mean algorithm. However, MODIS evapotranspiration values in arid region cultivated land are typically underestimated. For example, measured evapotranspiration in the Changma Irrigation District in the upper Shule River in 2019 was about 750 mm, while the MODIS product showed only 207.5 mm. Therefore, MODIS evapotranspiration products were uniformly multiplied by 3.61 to correct for systematic errors. The

corrected evapotranspiration data were applied to evaluate the benefits of ecological water conveyance and agricultural water-saving.

1.3 Research Methods

The research steps are as follows: (1) Obtain UAV low-altitude remote sensing data and field measurement data, and acquire NDWI, land cover type, and evapotranspiration data based on GEE. (2) Use remote sensing hydrological stations to estimate long-term monthly-scale river discharge. (3) Based on land cover type and evapotranspiration data, quantitatively evaluate ecological water conveyance benefits from three aspects: ecological water conveyance volume and efficiency change, vegetation area change, and vegetation evapotranspiration change. (4) Based on land cover type and evapotranspiration data, quantitatively evaluate agricultural water-saving benefits from two aspects: cultivated land area change and cultivated land evapotranspiration reduction. (5) Analyze the balance relationship between ecological water conveyance and agricultural water-saving in terms of water resources (Fig. 2 [Figure 2: see original paper]).

1.3.1 Remote Sensing Hydrological Station Establishing a remote sensing hydrological station mainly includes four steps: digital channel model construction, river discharge estimation, long-term discharge estimation, and discharge accuracy evaluation. The main data required are shown in Table 3 .

1) Digital Channel Model Construction: Digitizing natural river channels can accurately extract topographic information. Low-altitude remote sensing data of river channel topography were obtained using UAVs, and Pix4D software was used to generate digital surface models and digital orthophoto images. Combined with field-measured flow velocity and water depth data, a digital channel model was generated (Fig. 3 [Figure 3: see original paper]). UAV imagery combined with field measurements was then used to determine slope and roughness, and measure the daily water surface width.

2) Long-term Water Surface Width Calculation: Leveraging the advantages of satellite remote sensing historical data revisit capability and GEE in water body identification, long-term water surface width data can be calculated using satellite remote sensing historical data and sub-pixel decomposition. Specifically, monthly water surface area within a certain river reach was extracted from Sentinel-2 data, and the monthly average water surface width was obtained by dividing water surface area by river reach length. The calculation formula is:

$$W_{water} = \frac{A_{water}}{L_{water}}$$

where W_{water} is the average water surface width (m), A_{water} is the water surface area of the river reach (m^2), and L_{water} is the river reach length (m).

3) Long-term River Discharge Estimation: Since river channel topography at selected sections generally changes little, there is a one-to-one relationship between river discharge and water width. Based on the obtained long-term water surface width, the digital channel model was used to calculate corresponding water depth, water level, cross-sectional area, wetted perimeter, and hydraulic radius, and then flow velocity and discharge were calculated using the Manning formula. The calculation formulas are:

$$V = \frac{k}{n} R^{2/3} J^{1/2}$$

$$Q = V \times A$$

where V is flow velocity (m/s), n is roughness (obtainable from tables), R is hydraulic radius (m), J is slope, A is cross-sectional area (m^2), k is a conversion constant ($k = 1$), and Q is discharge (m^3/s).

4) Discharge Accuracy Evaluation: The Nash-Sutcliffe efficiency coefficient (NSE) and root mean square error (RMSE) were selected to evaluate the accuracy of remote sensing hydrological station discharge estimation. NSE evaluates the quality of discharge estimation, with values closer to 1 indicating better results. RMSE reflects the deviation between estimated and measured discharge. The calculation formulas are:

$$NSE = 1 - \frac{\sum_{t=1}^{T} (Q_t - Q_t^{obs})^2}{\sum_{t=1}^{T} (Q_t^{obs} - \bar{Q}^{obs})^2}$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T} (Q_t - Q_t^{obs})^2}{T}}$$

where T is the total time period, Q_t is the estimated discharge at time t (m^3/s), Q_t^{obs} is the measured discharge at time t (m^3/s), and $\bar{Q}^{obs}$ is the average measured discharge over period T (m^3/s).

1.3.2 Ecological Water Conveyance Benefit Evaluation Ecological water conveyance benefits were evaluated from three aspects: ecological water conveyance volume and efficiency change, vegetation area change, and vegetation evapotranspiration change. Ecological water conveyance volume refers to the total water volume entering the downstream river channel each year. Water conveyance efficiency refers to the ratio of total water volume reaching the West Lake Wetland to ecological water conveyance volume. Vegetation area change reflects underlying surface changes caused by ecological water conveyance, analyzed mainly through land cover type products. Vegetation evapotranspiration change reflects vegetation growth and development. The vegetation area change was obtained by subtracting the baseline year (first year in the sequence) vegetation area from each year’ s vegetation area, then multiplied by that year’ s unit area vegetation evapotranspiration to obtain annual vegetation evapotranspiration change. The calculation formulas are:

$$EW1 = \sum_{t=1}^{12} Q_t \times 3600 \times 24 \times 30$$

$$EW3 = \sum_{t=1}^{12} Q_t \times 3600 \times 24 \times 30$$

$$\sigma = \frac{EW3}{EW1} \times 100\%$$

$$\Delta ET_{veg,y} = (A_{veg,y} - A_{veg,base}) \times ET_{veg,y} \times 1000$$

where $EW1$ is the ecological water conveyance volume (total water volume reaching Section 1 in a year) (m^3), $EW3$ is the total water volume reaching the West Lake Wetland (total water volume at Section 3 in a year) (m^3), Q_t is the monthly average discharge at Section 1 (m^3/s), σ is water conveyance efficiency (%), $\Delta ET_{veg,y}$ is the vegetation evapotranspiration change in year y (m^3), $ET_{veg,y}$ is the unit area vegetation annual evapotranspiration in year y (mm), and $A_{veg,y}$ and $A_{veg,base}$ are vegetation areas in year y and the baseline year, respectively (km^2).

1.3.3 Agricultural Water-Saving Benefit Evaluation Agricultural water-saving benefits were evaluated from two aspects: cultivated land area change and cultivated land evapotranspiration reduction. Cultivated land area change reflects whether ecological water conveyance hinders agricultural development, evaluated through land cover type data. Cultivated land evapotranspiration reduction quantifies agricultural water-saving benefits. Using MODIS evapotranspiration from cultivated land without water-saving outside the Shuangta Irrigation District as a baseline, the same-ratio amplification method in hydrology was referenced to estimate evapotranspiration of cultivated land in the Shuangta Irrigation District under a no water-saving scenario, then subtracting MODIS evapotranspiration of cultivated land in the Shuangta Irrigation District to obtain the evapotranspiration reduction caused by agricultural water-saving. The calculation formulas are:

$$\Delta ET_{cul,y} = ET^{est}_{cul,y} - ET^{modis}_{cul,y}$$

$$ET^{est}_{cul,y} = ET^{modis}_{cul,base} \times \frac{ET_{nowater,y}}{ET_{nowater,base}}$$

where $\Delta ET_{cul,y}$ is the evapotranspiration reduction of cultivated land in the Shuangta Irrigation District in year y (m^3), $ET_{cul,y}^{est}$ is the estimated evapotranspiration of cultivated land in the Shuangta Irrigation District under no water-saving scenario in year y (m^3), $ET_{cul,y}^{modis}$ and $ET_{cul,base}^{modis}$ are MODIS evapotranspiration of cultivated land in the Shuangta Irrigation District in year y and the baseline year, respectively (m^3), and $ET_{nowater,y}$ and $ET_{nowater,base}$ are MODIS evapotranspiration of cultivated land without water-saving in year y and the baseline year, respectively (m^3).

2 Results

2.1 Accuracy Assessment of Remote Sensing Hydrological Stations

Remote sensing hydrological stations and digital channel models were established at Section 2, and Sentinel-2 data were used to calculate monthly water surface width and estimate river discharge from July 2017 to December 2020. Compared with measured discharge from the water level station at Section 2, the estimation accuracy was evaluated using Equations (8) and (9) (Table 4). Since December to March is the freezing period, discharge was set to 0 without calculation. The results show that the estimated discharge at Section 2 has small errors in most months, with NSE of 0.75 and RMSE of 1.49 m^3/s. The most obvious error comes from July 2018, when the remote sensing hydrological station estimated a peak discharge. This is because with the completion of river channel regulation and confinement works in July 2017, ecological water could be delivered to the West Lake Wetland along the channel, so large discharge increases occur every July due to river thawing. Therefore, excluding the July error, the remote sensing hydrological station' s discharge estimation results are reliable and suitable for river discharge monitoring in ungauged basins.

2.2 Ecological Water Conveyance Benefit Evaluation

2.2.1 Changes in Ecological Water Conveyance Volume and Efficiency

Based on Sentinel-2 data, remote sensing hydrological stations were used to calculate monthly-scale river discharge from 2017 to 2020 (Fig. 4 [Figure 4: see original paper]), and ecological water conveyance volume and efficiency were calculated (Fig. 5 [Figure 5: see original paper]). Discharge at Section 1 showed a significant increasing trend from 2017 to 2020 ($P < 0.05$), with average growth rates of 0.099 m^3/s and 0.049 m^3/s, respectively. Since river channel regulation and confinement works were not completed before July 2017, the ancient Shule River channel downstream of Section 1 was wide and shallow, so the Shuangta Reservoir did not release large amounts of ecological water. The water volume reaching Section 1 was 1.37$\times10^{8}$ m^3, which was lost through evaporation and seepage in the ancient river channel, resulting in zero discharge at Section 3 and water conveyance efficiency of 0. After the completion of river channel regulation and confinement works in July 2017, the Shuangta Reservoir significantly increased ecological water release. The water volume reaching Section 1 increased to 2.50$\times10^{8}$ m^3, with an average of 0.75$\times10^{8}$ m^3 of ecological water reaching Section 3, and average water conveyance efficiency increased to 30.06%. This indicates that ecological water conveyance implementation significantly increased total water volume entering the downstream river channel, and river channel regulation and confinement works substantially reduced losses along the conveyance route, enabling ecological water to successfully reach the West Lake Wetland.

2.2.2 Vegetation Evapotranspiration Change Based on land cover type products and evapotranspiration products, annual vegetation area was 统计 ed and vegetation evapotranspiration change was calculated (Fig. 6 [Figure 6: see original paper]). Vegetation area showed a significant increasing trend from 2017 to 2020 ($P < 0.05$), with an average annual growth rate of 10.21 km^2, reaching 112.25 km^2 in 2020. The largest increase occurred in 2020, up to 39.75 km^2. Unit area vegetation evapotranspiration showed a fluctuating trend, but its average annual growth rate was only 0.007 mm$\cdot$a^{-1}, which can be considered essentially unchanged. Therefore, with vegetation area growth and little change in unit area evapotranspiration, vegetation evapotranspiration change showed a significant increasing trend at an average rate of 0.052$\times10^{8}$ m$^3\cdot$a^{-1} ($P < 0.05$). The substantial increase in vegetation evapotranspiration change in 2020 was mainly related to increased ecological water conveyance after July 2017 and the lag effect of vegetation growth response to ecological water conveyance.

2.3 Agricultural Water-Saving Benefit Evaluation

Using cultivated land without water-saving far from the Shuangta Irrigation District as a baseline (no water-saving cultivated land), land cover type and evapotranspiration data were used to estimate cultivated land evapotranspiration in the Shuangta Irrigation District under a no water-saving scenario and calculate annual cultivated land evapotranspiration reduction (Fig. 7 [Figure 7: see original paper]). From 2017 to 2020, cultivated land area showed a fluctuating increasing trend with an average annual growth rate of 2.89 km^2, reaching 333.75 km^2 and 340.50 km^2 in 2019 and 2020, respectively. The increasing trend of estimated annual cumulative evapotranspiration under no water-saving scenario was more obvious than that of measured evapotranspiration, with average annual growth rates of 0.01$\times10^{8}$ m$^3\cdot$a^{-1} and 0.06$\times10^{8}$ m$^3\cdot$a^{-1}, respectively. Estimated and measured evapotranspiration were similar in 2017, and basically the same in 2018. However, from 2019 onward, measured evapotranspiration remained consistently lower than estimated evapotranspiration. Cultivated land evapotranspiration reduction was relatively high in 2019 and 2020, reaching 0.635$\times10^{8}$ m^3 and 0.712$\times10^{8}$ m^3, respectively. From 2017 to 2020, cultivated land evapotranspiration reduction averaged 0.395$\times10^{8}$ m^3 per year, accounting for 13.16% of estimated evapotranspiration. This demonstrates that agricultural water-saving can effectively reduce cultivated land evapotranspiration and improve irrigation efficiency while maintaining an increasing trend in cultivated land area.

3 Discussion

3.1 Balance Relationship Between Ecological Water Conveyance and Agricultural Water-Saving

Based on the results of ecological water conveyance volume and efficiency change, vegetation evapotranspiration change, and cultivated land evapotranspiration reduction, the balance relationship between ecological water conveyance and agricultural water-saving in terms of water resources was analyzed (Table 5). Agricultural water-saving began in 2017, and cultivated land evapotranspiration reduction was relatively large. However, since river channel regulation and confinement works were not completed at that time, the Shuangta Reservoir had not begun to release large amounts of ecological water, so the proportion of agricultural water-saving in ecological water was relatively small. From 2017 to 2020, the Shuangta Reservoir delivered water through regulated and confined river channels, with ecological water conveyance volume reaching an average of 2.50$×10^{8}$ m^3 per year, and cultivated land evapotranspiration reduction averaging 0.395$×10^{8}$ m^3 per year, accounting for 14.22% of ecological water conveyance volume. This indicates that agricultural water-saving in the Shuangta Irrigation District can alleviate agricultural water encroachment on ecological water to some extent, but due to limitations in irrigation district area and water-saving technology, the ecological water provided by agricultural water-saving is ultimately limited, and the remaining ecological water conveyance volume still needs to be provided by reservoir ecological water transfer. Vegetation evapotranspiration change averaged 0.46$×10^{8}$ m^3 from 2017 to 2020, accounting for 18.47% of the water volume at Section 1. Since vegetation growth has a certain lag in response to ecological water conveyance, vegetation evapotranspiration change was relatively small in 2017-2018, accounting for only 14.26% of ecological water conveyance volume. From 2019, large amounts of new vegetation appeared around the Shuangta Irrigation District and low-lying areas along the river channel, causing this percentage to increase to an average of 23.57%. This shows that with continuous ecological water conveyance, the downstream ecological environment gradually recovers, and more water resources are utilized by vegetation, improving the basin' s water conservation capacity.

3.2 Reliability Analysis of Ecological Water Conveyance Volume and Agricultural Water-Saving Volume

Wang Hechuang et al. pointed out that the Shuangta Reservoir released an average of 2.35$×10^{8}$ m^3 of ecological water, with 0.88$×10^{8}$ m^3 reaching the area near Section 3. Our results show that the water volume reaching Section 3 is as high as 2.52$×10^{8}$ m^3. This difference occurs because rainfall, irrigation return flow, and groundwater seepage in the basin all increase river discharge, and the specific relationships among hydrological elements need to be accurately simulated using hydrological models in future studies. Additionally, rainfall is not the main water resource source for crop and vegetation growth.

Based on monthly average grid rainfall data, the basin’ s rainfall showed an overall increasing trend from 2017 to 2020, but the average rainfall was still far less than the annual average potential evaporation. The average annual evapotranspiration of cultivated land and vegetation in the study area was 492.41 mm and 771.71 mm, respectively, both far greater than annual rainfall. This indicates that agricultural development in the irrigation district still relies on artificial water diversion for irrigation, and vegetation is mainly distributed along river channels and low-lying groundwater seepage areas.

Our study on the balance relationship between ecological water conveyance and agricultural water-saving mainly focuses on water resources, emphasizing how much ecological water conveyance volume and agricultural water-saving volume exist, but the correlation between them is insufficiently studied. Future research should comprehensively consider the balance between ecological and socio-economic benefits, study the internal drivers of ecological water conveyance and agricultural water-saving development from a socio-hydrology perspective, and provide guidance for basin ecological water conveyance and agricultural water-saving management. The threshold for the balance between ecological water conveyance and agricultural water-saving should be studied to better provide theoretical support for future project implementation.

3.3 Uncertainty Analysis

The time span of this study on ecological water conveyance volume and efficiency change is relatively short (2017-2020) compared with other similar studies, mainly because the Shule River Basin only began ecological water conveyance to the West Lake Wetland in July 2017, so the downstream river channel had no discharge before this time. However, comparing discharge from July-December 2017 (representing the situation before channel-based ecological water conveyance) with discharge from 2018-2020 (representing the situation after channel-based ecological water conveyance) can reflect the impact of ecological water conveyance.

This study’ s evaluation of ecological water conveyance and agricultural water-saving benefits and their balance relationship in ungauged inland arid basins is conducted at annual scale, which is more conducive to grasping overall trends in ecological water conveyance volume and agricultural water-saving volume. The main reasons are: the irrigation period in the Shuangta Irrigation District is 170 days, basically covering all time except the freezing period (December-March). This study did not consider the impact of inter-annual rainfall variation on benefit evaluation and balance relationship analysis. To better explain this, based on monthly average grid rainfall data, the basin’s rainfall from 2017 to 2020 showed an overall increasing trend, but average rainfall was still less than 100 mm, far less than annual average potential evaporation. Meanwhile, Sun Dongyuan et al. showed that the runoff of the Shule River main stream in 2017-2018 was 9.91\$×10^{8}\$ m^{3} and 2.79\$×10^{8}\$ m^{3}, respectively, with annual average runoff increasing at rates of 1.075\$×10^{8}\$ m$^{3}\cdot(10a)^{-1}$ and 0.126\$×10^{8}\$

$m^3 \cdot (10a)^{-1}$, both in exceptionally wet years after 2015. Although increased rainfall increases water availability, it is not the main factor causing runoff in the lower Shule River; the amount of ecological water conveyance significantly affects downstream discharge.

Additionally, fallow land and sparse grassland areas affect the calculation of cultivated land and vegetation evapotranspiration in this study. Since data on whether cultivated land is fallow is difficult to obtain directly, and higher-resolution satellite remote sensing products are unavailable for identifying sparse grasslands, this issue cannot currently be addressed. However, future studies could combine higher-resolution remote sensing imagery to identify fallow land based on differences in evapotranspiration distribution within the year for different cultivated lands, and use resampling methods to extract sparse grasslands not identified by land cover products.

4 Conclusions

This study took the lower reaches of the Shule River Basin in Dunhuang, Gansu Province as an example, conducted monthly-scale remote sensing monitoring of ecological water conveyance from 2016-2020 based on remote sensing hydrological stations and Google Earth Engine, and evaluated ecological water conveyance and agricultural water-saving benefits using multi-source remote sensing data including evapotranspiration and land cover types, analyzing their balance relationship in water resources. The main conclusions are:

1) Remote sensing hydrological stations and GEE can provide data support for ecological water conveyance monitoring and agricultural water-saving benefit evaluation in ungauged inland arid basins. Remote sensing hydrological stations fully leverage the advantages of high-precision UAV low-altitude remote sensing and satellite remote sensing historical data revisit capability to estimate long-term river discharge in ungauged basins, achieving long-term ecological water conveyance remote sensing monitoring. Validation results show good performance of remote sensing hydrological station discharge estimation.

2) With river channel regulation and confinement works substantially reducing conveyance losses, ecological water conveyance can provide sufficient water resources for downstream wetlands and river channels, with significant vegetation recovery. From 2017-2020, ecological water conveyance increased water volume entering the lower river channel to an average of 2.50\$×10^{8}\$ m^3 per year, with 30.06% reaching the West Lake Wetland and 18.47% utilized by vegetation around the downstream river channel, increasing vegetation area by 112.25 km^2.

3) Agricultural water-saving can effectively reduce cultivated land evapotranspiration while maintaining an increasing trend in cultivated land area. With cultivated land area maintaining a growth rate of 2.89 $km^2 \cdot a^{-1}$, agricultural water-saving reduced cultivated land evapotranspiration by an

average of 0.395$×10^{8}$ m^3 per year from 2017-2020, accounting for 13.16% of estimated evapotranspiration under no water-saving scenario, effectively improving irrigation efficiency.

4) Agricultural water-saving alleviates the problem of agricultural water encroaching on ecological water in inland arid basins. From 2017-2020, average annual ecological water conveyance volume in the lower Shule River Basin was 2.50$×10^{8}$ m^3, and average annual cultivated land evapotranspiration reduction was 0.395$×10^{8}$ m^3, with agricultural water-saving accounting for 14.22% of ecological water conveyance volume on average.

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Note: Figure translations are in progress. See original paper for figures.