Optimization of Ecological Water Conveyance Scheduling in the Aksu River Basin for Ecological Restoration (Postprint)

Authors: Nie Yan, Guo Yongrui

Date: 2022-04-12T19:08:37+00:00

Abstract

Ecological water conveyance scheduling is one of the most effective measures for ecological protection and restoration. Implementing ecological water conveyance holds significant importance for restoring natural ecosystems in arid and semi-arid regions and maintaining the health of oasis ecosystems. Based on the current status of ecological water conveyance in the Aksu River Basin, an optimization framework for watershed ecological water conveyance scheduling based on ecological restoration objectives was established through identifying key natural vegetation areas and estimating ecological water demand. First, high-resolution satellite imagery (Gaofen series) was employed to identify natural vegetation information, establishing a natural vegetation dataset for the Aksu River Basin from 2015 to 2020. By statistically analyzing the occurrence frequency of natural vegetation on a pixel-by-pixel basis, three key natural vegetation areas were identified: the Aiximan Lake wetland area, the First Division marginal Populus euphratica forest area, and the Fifth Regiment marginal Populus euphratica forest area, covering a total area of 1257.69 km^2. Using the area quota method and water balance method, the ecological water conveyance volumes for the three key natural vegetation areas were estimated to be 1.53×10^{8} m^3, 2.73×10^{8} m^3, and 1.14×10^{8} m^3, respectively. The optimal timing for watershed ecological water conveyance was determined to be from May to September, with water conveyance conducted once or twice annually. It is recommended that a single water conveyance event should exceed 0.2×10^{8} m^3 and last more than 10 days. Canal network analysis revealed that the eight water delivery outlets established in the three key natural vegetation areas can serve as references for future ecological water conveyance pathways. The research results hold important guiding value for ecological water conveyance scheduling and fine management of ecological water use in the Aksu River Basin.

Full Text

Introduction

Ecological water conveyance scheduling represents one of the most effective measures for ecological protection and restoration. Implementing ecological water transfer projects holds significant importance for rehabilitating natural ecosystems and maintaining the health of oasis ecosystems in arid and semi-arid regions. In light of the current ecological water conveyance practices in the Aksu River Basin, this study establishes an optimization framework for watershed-scale ecological water conveyance scheduling based on ecological restoration objectives. This framework integrates the identification of priority natural vegetation areas with scientific estimation of ecological water demand.

High-resolution GF series satellite imagery was employed to identify natural vegetation information, enabling the construction of a natural vegetation dataset for the Aksu River Basin spanning 2015–2020. Through pixel-by-pixel frequency analysis of natural vegetation occurrence, three priority natural vegetation regions were identified: the Eichmann Lake wetland area, the Populus euphratica forest region on the edge of the First Division, and the Populus euphratica forest region on the edge of Wutuan, covering a total area of 1257.69 km^2. The ecological water demand for these three priority regions was estimated using the area quota method and water balance method, yielding requirements of 1.53$\times10^{8}$ m^3, 2.73$\times10^{8}$ m^3, and 1.14$\times10^{8}$ m^3, respectively.

Based on the monthly distribution of ecological water stock in the basin and seasonal vegetation water demand patterns, the optimal timing for ecological water conveyance was determined to be from May to September. The analysis recommends either single or twice-yearly water conveyance operations, with single-event volumes exceeding 0.2$\times10^{8}$ m^3 and durations longer than ten days to ensure effectiveness. Network analysis of the basin' s canal system identified eight optimal ecological water gates across the three priority regions, providing valuable guidance for future water conveyance scheduling and fine-scale ecological water management in the Aksu River Basin.

1 Study Area Overview

The Aksu River Basin is located in western Xinjiang Uygur Autonomous Region, geographically positioned between 40°08 -41°35 N and 78°47 -82°43 E, with a total watershed area of approximately 5.3$\times10^{4}$ km^2. The basin is formed by the confluence of the Kumalak and Toshgan rivers upstream, historically known as the Aksu River. As the largest tributary of the Tarim River, the Aksu River carries an average annual runoff of 78.2$\times10^{8}$ m^3. The region exhibits a pronounced continental monsoon climate characterized by dryness and low precipitation. Typical desert vegetation includes Populus euphratica, Tamarix chinensis, Haloxylon ammodendron, and Phragmites australis.

Current ecological water conveyance in the Aksu River Basin relies on four main channels. For the Eichmann Lake wetland, three conveyance routes exist: (1) water allocation from the West Bridge diversion hub via the Victory Canal and Ayinke trunk canal to Sayilik Lake; (2) water delivery through the Victory Canal' s No. 1 sluice to Yituan Haizi wetland; and (3) water transfer from the West Bridge diversion hub via the Laoda River to the No. 1 sluice, then through the Yangwalike canal to the No. 4 sluice for Eichmann Lake replenishment. For the First Division edge Populus euphratica forest region, conveyance channels are distributed in the Tanan irrigation district, primarily utilizing the Tanan Second Trunk Canal.

2.1 Data Sources

High-resolution GF-1 satellite imagery with infrequent cloud cover, high visibility, and complete watershed coverage was obtained from the China Centre for Resources Satellite Data and Application (http://www.cresda.com/). GF-6 imagery partially covering concentrated Populus euphratica distribution areas and Landsat 8 imagery were also acquired. ENVI 5.3 software was used for radiometric calibration, atmospheric correction, geometric correction, mosaicking, clipping, and image fusion preprocessing. Natural vegetation information was extracted using Classification and Regression Tree (CART) decision tree supervised classification. Validation sample areas were selected for accuracy assessment, achieving a Kappa coefficient above 0.85, indicating high identification accuracy.

2.2.1 Area Quota Method

The ecological water demand of natural vegetation was calculated using the area quota method with the following formula:

$$W = \sum_{i=1}^{n} w_i = \sum_{i=1}^{n} r_i A_i$$

where W represents the total ecological water demand of natural vegetation (m^3), w_i is the water demand for vegetation type i (m^3), r_i is the ecological water quota for vegetation type i ($\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$), and A_i is the area of vegetation type i (hm^2).

Referencing the *Aksu River Basin Management Gazette*, irrigation quotas were set at 6150 $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$ for forest land and 4750 $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$ for shrub-grassland in the Eichmann Lake wetland and First Division edge regions. For the Wutuan edge Populus euphratica forest region and downstream areas, forest land irrigation quotas were 4750 $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$ and shrub-grassland quotas were 3750 $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$.

2.2.2 Water Balance Method

As an inland lake in an arid region, Eichmann Lake' s ecological water demand primarily consists of inflow water, calculated as the difference between water surface evaporation, lake seepage, and precipitation recharge. The water balance method was applied with the following formula:

$$W_j = (E_j - P_j) \times S + Q_j$$

where W_j is the monthly lake ecological water demand (m^3), E_j is monthly water surface evaporation from evaporation pans (mm), P_j is monthly average precipitation (mm), S is lake area (hm^2), and Q_j is monthly lake seepage, estimated at 0.01 $mm \cdot d^{-1}$.

3.1 Identification of Priority Natural Vegetation Regions

To identify concentrated and contiguous priority natural vegetation distribution areas, pixel-by-pixel frequency statistics of natural vegetation (primarily Populus euphratica and shrubs) were conducted using the established Aksu River Basin natural vegetation dataset from 2015-2020. Frequency values ranged from 1 to 6, with higher values indicating more stable vegetation occurrence. The analysis identified three priority regions: the Eichmann Lake wetland area, the First Division edge Populus euphratica forest region, and the Wutuan edge Populus euphratica forest region, with natural vegetation serving as the primary restoration target and natural lakes as secondary targets.

Spatial distribution patterns show vegetation frequency decreasing from center to periphery, with central areas reaching 5-6 occurrences where Populus euphratica growth is relatively stable. Edge areas with 1-2 occurrences are more vulnerable to anthropogenic disturbance. The First Division edge region exhibits the most stable Populus euphratica growth, with the largest proportion of area showing 5-6 occurrence frequencies. Natural vegetation is also widely distributed along both sides of the Aksu River with relatively high frequency.

3.2.1 Natural Vegetation Ecological Water Demand

Aiming to restore and maintain stable ecological structure and function of natural vegetation communities, the distribution frequency range from the 2015-2020 dataset was used as the restoration target area. Calculations using the area quota method yielded annual ecological water demands of 1.53×10^{8} m^3, 2.73×10^{8} m^3, and 1.14×10^{8} m^3 for the Eichmann Lake wetland, First Division edge region, and Wutuan edge region, respectively, totaling 5.4×10^{8} m^3 when combined with the watershed irrigation water utilization coefficient (0.65).

3.2.2 Natural Lake Ecological Water Demand

Although Eichmann Lake' s natural water surface has expanded annually, it remains severely reduced compared to historical levels, particularly in western and southern areas. Using the 2018 water surface area (61.57 km^2) as the restoration target, meteorological data from the Eichmann Lake wetland were analyzed. Based on previous research, the unit area ecological water demand for natural lakes was calculated as 10,809 $m^3 \cdot hm^{-2}$, yielding an annual ecological water demand of 0.67×10^{8} m^3 to achieve restoration targets.

3.3 Determination of Ecological Water Conveyance Timing

Optimal timing must consider both vegetation water demand and actual water resource availability. Seasonal variations in total water resources and oasis agricultural water use directly affect ecological water availability. Analysis of monthly runoff from upstream hydrological stations and planned water use in irrigation districts reveals that ecological water stock is insufficient from October to April, but abundant from May to September, with the highest surplus occurring in July and August.

Temporal analysis of natural vegetation growth shows rapid growth begins in May and continues until leaf fall in October. Comparison with NDVI responses to historical water conveyance events indicates that May conveyance produces the most pronounced vegetation growth response, while events at other times show delayed or weaker effects. Therefore, May to September is recommended as the optimal conveyance period. Current annual operations conduct either single events in July-August (when water efficiency is highest and vegetation demand is greatest) or twice-yearly events with an additional May conveyance before the rapid growth period. Single-event volumes should exceed 0.2×10^{8} m^3 with durations longer than ten days to ensure effectiveness.

3.4 Optimization of Ecological Water Conveyance Paths

Current conveyance practices do not cover the Wutuan edge region, and gates in the First Division edge region are located too far from primary vegetation distribution areas, reducing effectiveness due to infiltration, lateral diffusion, and evapotranspiration losses. To scientifically determine optimal conveyance routes, this study constructed a watershed-scale water conveyance network dataset for the three priority regions, integrating the existing canal system and topographic slopes.

A 30-meter resolution global digital elevation model (ASTER GDEM) was used to extract elevation characteristics. The basin shows higher elevations in the northwest and lower in the southeast. Specifically, the Eichmann Lake wetland is higher in the north and east, the First Division edge region slopes from west to east, and the Wutuan edge region slopes from north to south. Based on these characteristics, three high-elevation sluice gates were selected as target stops in each region to facilitate efficient areal conveyance.

Water diversion hubs and barrages served as network analysis starting points, including the Joint Canal Head, West Bridge Diversion Hub, Xiehla Diversion Hub, Keya River Intake, Tailan River Intake, Wutuan Intake, and Tarim Barrage. Using ArcMap 10.2 Network Analyst, the shortest paths from these diversion points to target sluices were calculated, generating optimal reference routes for ecological water conveyance.

The analysis reveals that water from the West Bridge Diversion Hub and Tarim Barrage can serve the Eichmann Lake wetland, First Division edge region, and downstream Populus euphratica forests. The Wutuan Intake on the Kalayurgun River (with average annual runoff of 2.2$\times10^{8}$ m^3) can supply the Wutuan edge region. These simulated optimal paths provide valuable references for future watershed-scale ecological water conveyance engineering.

4 Conclusions

1) Three priority natural vegetation regions were identified based on spatial frequency analysis: the Eichmann Lake wetland, First Division edge Populus euphratica forest region, and Wutuan edge Populus euphratica forest region. Ecological water demands were estimated at 1.53$\times10^{8}$ m^3, 2.73$\times10^{8}$ m^3, and 1.14$\times10^{8}$ m^3, respectively, totaling 5.4$\times10^{8}$ m^3.

2) Considering seasonal water stock distribution and vegetation growth requirements, May through September is recommended as the optimal conveyance period. Annual operations may consist of single or twice-yearly events, with single-event volumes exceeding 0.2$\times10^{8}$ m^3 and durations longer than ten days to ensure effectiveness.

3) A watershed-scale water conveyance network dataset was established based on diversion hubs and canal systems. Eight target sluice gates were identified as optimal conveyance points, with network analysis revealing the shortest paths to each priority region. The First Division edge region requires the longest conveyance distance, exceeding 70 km.

References

[1] Deng Mingjiang, Huang Qiang, Chang Jianxia, et al. Large scale ecological operation research and practice[J]. Journal of Hydraulic Engineering, 2020, 51(7): 757-773.

[2] Chen Si, Zhang Daiqing, Yu Guorong, et al. Review of research on ecological operation of reservoir[J]. China Population, Resources and Environment, 2017, 27(11): 99-102.

[3] Deng Mingjiang, Huang Qiang, Zhang Yan, et al. Study on ecological scheduling of multi scale coupling of reservoir group[J]. Journal of Hydraulic Engineer-

ing, 2017, 48(12): 1387-1398.

[4] Wang Daoxi, Zhang Jie, Du Deyan. Practice of ecology oriented water dispatching in the Heihe River Basin[J]. Yellow River, 2016, 38(10): 96-99.

[5] Deng Mingjiang, Shi Quan. Management and regulation pattern of water resource in inland arid regions[J]. Advances in Earth Science, 2014, 29(9): 1046-1054.

[6] Fu Aihong, Chen Yaning, Li Weihong. Assessment on ecosystem health in the Tarim River Basin[J]. Acta Ecologica Sinica, 2009, 29(5): 2418-2426.

[7] Cui Wangcheng, Li Weihong, Xu Hailiang, et al. Research on the ecological operation in the lower reaches of Tarim River based on water conveyance[J]. Scientia Sinica Techologica, 2016, 46(8): 864-876.

[8] Richard M V, Sieber J, Archfield S A, et al. Relations among storage, yield and instream flow[J]. Water Resources Research, 2007, 43(5): 909-918.

[9] Sun Tianyao, Li Xuemei, Xu Min, et al. Spatial temporal variations of vegetation coverage in the Tarim River Basin from 2000 to 2018[J]. Arid Land Geography, 2020, 43(2): 415-424.

[10] Gao Qing, Kuerban Aili, Zhou Xiaofeng, et al. Soil moisture retrieval and monitoring in the Aksu River Basin[J]. Acta Ecologica Sinica, 2019, 39(14): 5138-5148.

[11] Wang Rui. Estimation and characteristic analysis of vegetation and lake ecological water demand in Aksu River irrigation district[D]. Wuhan: Central China Normal University, 2020.

[12] Liu Qianqian, Hanati Gulimire, Su Litan, et al. Response process of groundwater table to ecological water conveyance in the lower reaches of Tarim River riparian zone[J]. Arid Land Geography, 2017, 40(5): 979-986.

[13] Li Lijun, Zhang Xiaoqing, Chen Changqing, et al. Ecological effects of water conveyance on the lower reaches of Tarim River in recent twenty years[J]. Arid Land Geography, 2018, 41(2): 238-247.

[14] Han Lu, Wang Haizhen, Niu Jianlong, et al. Response of Populus euphratica communities in a desert riparian forest to the groundwater level gradient in the Tarim Basin[J]. Acta Ecologica Sinica, 2017, 37(20): 6836-6846.

[15] Chen Minjian, Wang Hao, Wang Jianhua, et al. Ecological water demand analysis in arid region[J]. Acta Ecologica Sinica, 2004, 24(10): 2136-2142.

[16] Bai Yuan, Xu Hailiang, Zhang Qingqing, et al. Evaluation on ecological water requirement in the lower reaches of Tarim River based on groundwater restoration[J]. Acta Ecologica Sinica, 2015, 35(3): 630-640.

[17] Wang Zhicheng, Jiang Junxin, Fang Gonghuan, et al. Analysis on the suitable scale of the Aksu Oasis under the limit of water resources[J]. Journal of Glaciology and Geocryology, 2019, 41(4): 986-992.

[18] Li Hongbin, Liu Yating, Wang Weiguang, et al. Assessing the impact of meteorological factors on streamflow in Aksu River[J]. Journal of Irrigation and Drainage, 2021, 40(1): 115-122.

[19] Li Lei, Lu Lin, Sun Xiaolong, et al. Study on the network structure and interactive relationship of tourism flow along high speed railway: An example of Hefei-Fuzhou high speed railway[J]. Human Geography, 2020, 35(1): 132-140.

[20] Sang X, Guo Q Z, Wu X X. Intensity and stationarity analysis of land use change based on CART algorithm[J]. Scientific Reports, 2019, 9(2): 570-574.

[21] Liu Zhaobin. High resolution remote sensing image building extraction based on CART decision tree[D]. Wuhan: Central China Normal University, 2018.

[22] Liu Xin. Using CART algorithm extract residential from LandSat 8 images: Zhangye, Linze case study[D]. Lanzhou: Lanzhou University, 2015.

[23] Yong Zheng, Zhao Chengyi, Shi Fengzhi, et al. Variation characteristics of groundwater depth and its ecological effects in the main stream of the Tarim River in the past 20 years[J]. Journal of Soil and Water Conservation, 2020, 34(3): 182-189.

[24] Pang A, Sun T, Yang Z. Economic compensation standard for irrigation processes to safeguard environmental flows in the Yellow River estuary, China[J]. Journal of Hydrology, 2013, 482: 129-138.

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