Land Use/Cover Change Processes and Trends in the Lake Balkhash Basin Postprint

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Abstract

Balkhash Lake basin is an important watershed spanning Xinjiang, China (within the border) and Kazakhstan (outside the border). Using three periods of Land Use and Land Cover (LULC) data from the 1970s, 2005, and 2015, along with methods such as the Markov model, this study analyzes the LULC change processes and trends in the basin since the construction of the Kapchagay Reservoir (the largest hydraulic engineering project in the basin) in 1972 and the dissolution of the former Soviet Union, and compares the differences between within and outside the border, providing a basis for land resource management and ecological environmental protection in the region. The results show that LULC changes in the Balkhash Lake basin exhibit the following trends: cropland and forest areas first decreased and then increased (with an overall increase), water bodies and unused land first increased and then decreased (with an overall decrease), while grassland and urban and rural construction land areas continued to increase. This indicates that LULC changes in the later period had a greater impact on the LULC changes during the entire study period. The above changes were dominated by bidirectional conversion; therefore, the change process of the entire basin remained in equilibrium throughout the study period. The LULC type structure and change processes differed between within and outside the border, with more uniform distribution within the border than outside. Both single-type and regional LULC change trend and state indices indicate that LULC type change processes within the border were more stable than those outside the border. However, since the area outside the border accounts for 86% of the total basin, it dominated the LULC type structure and change processes of the entire basin. The entire basin remained in equilibrium during the study period.

Full Text

Preamble

Change Processes and Trends of Land Use/Cover in the Balkhash Lake Basin

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Abstract: The Balkhash Lake basin is a critical transboundary watershed spanning Xinjiang, China (domestic portion) and Kazakhstan (overseas portion). Utilizing Land Use and Land Cover (LULC) data from the 1970s, 2005, and 2015, along with Markov model analysis, this study examines the processes and trends of LULC change since the construction of the Kapchagay Reservoir—the largest water conservancy project in the basin—and the dissolution of the Soviet Union. The results demonstrate that LULC changes in the Balkhash Lake basin exhibit distinct patterns: cultivated land and forest area initially decreased then increased (showing overall growth), water bodies and unused land initially increased then decreased (showing overall reduction), while grassland and urban-rural construction land showed continuous expansion. These patterns indicate that later-stage changes had greater impact on the overall LULC dynamics throughout the study period. The changes were dominated by bidirectional conversions, maintaining the entire basin in a state of equilibrium during the study period. Significant differences exist between the domestic and overseas portions in terms of LULC structure and change processes. The domestic portion exhibited more uniform type distribution than the overseas portion, and both single-type and regional trend-state indices confirmed that LULC changes were more stable domestically. However, because the overseas area accounts for 86% of the total basin area, it dominated the overall LULC structure and change processes. These findings provide a scientific basis for land resource management and ecological environmental protection in the region.

Keywords: Balkhash Lake basin; land use/cover change; land transfer matrix; spatio-temporal variation

1. Introduction

Land Use and Land Cover (LULC) change represents a crucial component and primary driver of global change, significantly impacting atmospheric, soil, vegetation, and water resources. These changes affect biogeochemical cycles, energy exchange, water cycles, and ecological processes, connecting to various aspects of global environmental change. As environmental degradation increasingly threatens sustainable development, researchers worldwide have recognized the importance of LULC change in global environmental processes. The Balkhash Lake basin, a renowned transboundary watershed in Central Asia, has experienced substantial LULC alterations due to intensive water conservancy projects, extensive irrigation expansion, and institutional transformations. The Kapchagay Reservoir, constructed in 1970, and the dissolution of the Soviet Union in 1991, which led to Kazakhstan' s independence and systemic reforms, have profoundly influenced LULC patterns. Concurrently, China' s reform and opening-up policies since 1978 triggered large-scale land and water development in the domestic portion of the basin. These human activities, combined with natural factors, have caused significant water level fluctuations in Balkhash Lake, affecting water quality, fisheries, and the ecological health of the Ili River delta. While previous studies have examined water level changes and their climatic drivers, comprehensive analysis of LULC change processes and trends across the entire transboundary basin remains limited. This study addresses this gap by analyzing LULC changes from the 1970s to 2015, comparing domestic and overseas portions to provide insights for land management and ecological protection.

1.1 Study Area Overview

The Balkhash Lake basin (42°11 15 -49°48 N, 72°24 -87°24 E) is a prominent transboundary watershed in Central Asia' s arid region, covering a total area of 4.16×10^{4} km^2. The overseas portion comprises 3.59×10^{4} km^2 (86% of the basin), primarily in Kazakhstan, while the domestic portion covers 0.57×10^{4} km^2 in northwestern Xinjiang' s Ili Kazakh Autonomous Prefecture. The basin features a basin landscape with higher elevations in the southeast and lower elevations in the northwest, centered on Balkhash Lake. The highest point is Khan Tengri Peak, while the lowest is Balkhash Lake itself, which serves as the terminal point for numerous rivers. The region experiences an extreme continental arid climate with abundant solar radiation, large temperature variations, and strong evaporation. Annual precipitation ranges from 110–1000 mm, while evaporation exceeds precipitation by several times, reaching 24–25 times the precipitation amount in some areas. Vertical zonation is pronounced, with distinct landscape belts including alpine glaciers, subalpine steppes, forest-steppe, semi-desert and desert steppe, oases, saline lands, deserts, lakes, and marshes.

1.2 Data Sources and Processing

This study utilized the Central Asian Five Countries Land Use/Cover raster dataset (1970s, 2005, 2015) provided by the Land Change and Ecological Simulation Team of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Based on the ESA global land cover data and Landsat

MSS/TM/ETM/OLI imagery, the dataset achieved classification accuracies of 85% for the 1970s-2005 period and 80% for 2015. The 1970s data, with limited availability, was synthesized primarily from 1975 data supplemented by adjacent years. The dataset employed a 300 m spatial resolution and the Chinese Academy of Sciences Land Use Classification System, comprising six primary classes: cultivated land, forest, grassland, water body, urban-rural construction land, and unused land. The study area was extracted using basin boundary data from the Data Basin platform, digital elevation data from USGS Earth Explorer, and administrative boundaries exported from BIGEMAP. All raster data were resampled to a uniform 300 m$×$300 m resolution to facilitate area statistics and transfer analysis.

1.3 Research Methods

LULC change processes were characterized through area variations, providing intuitive reflection of change magnitude during the study period. Several quantitative indices were selected based on the land use transfer matrix and related literature:

1.3.1 Land Use Transfer Matrix

This method reflects the structural characteristics and mutual conversion patterns among LULC types during the study period, revealing the loss directions and sources of specific types. The mathematical expression is:

$$S_{ij} = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{pmatrix}$$

where S_{ij} represents the area converted from type i to type j (when $i = j$, it indicates unchanged area), and n is the number of LULC types ($n = 6$).

1.3.2 Single-Type Change Magnitude

This index quantifies the area change of a specific LULC type over time:

$$\Delta U = \frac{U_b - U_a}{U_a} \times 100\%$$

where ΔU is the change magnitude (%), U_a is the initial area (km^2), and U_b is the final area (km^2).

1.3.3 Single-Type Spatial Dynamics

This measures the spatial extent of area change for a specific type:

$$S = \frac{\Delta U_{in} + \Delta U_{out}}{U_a} \times 100\%$$

where S is the spatial dynamics index, ΔU_{in} is the total area converted to the type from others, and ΔU_{out} is the total area converted from the type to others.

1.3.4 Single-Type Trend and State Index
This reflects the expansion or contraction intensity and stability of a specific type:

$$P_s = \frac{U_{in} - \Delta U_{out}}{U_{in} + \Delta U_{out}}, \quad -1 \leq P_s \leq 1$$

where $P_s > 0$ indicates expansion, $P_s < 0$ indicates contraction, and values approaching 0 suggest frequent bidirectional conversion and equilibrium. Values approaching $±$1 indicate unidirectional conversion and disequilibrium.

1.3.5 Regional Trend and State Index
This index reflects the overall LULC change state across the entire region:

$$P_t = \frac{\sum_{i=1}^{n} U_{in} - \sum_{i=1}^{n} \Delta U_{out}}{\sum_{i=1}^{n} U_{in} + \sum_{i=1}^{n} \Delta U_{out}}, \quad 0 \leq P_t \leq 1$$

where P_t approaching 1 indicates balanced bidirectional conversion across all types, while values approaching 0 suggest unidirectional, unbalanced conversion. The index is classified as: extreme unbalanced (0-0.25), unbalanced (0.25-0.50), quasi-balanced (0.50-0.75), and balanced (0.75-1.00).

2. Results

2.1 LULC Distribution in the Balkhash Lake Basin

Grassland and unused land consistently dominated the basin' s LULC, collectively accounting for over 85% of the total area. Water bodies, cultivated land, and forest followed, while urban-rural construction land remained the smallest type. Throughout the study period (1970s-2015), grassland comprised 60.03-63.04%, primarily distributed in the northern and southeastern basin; unused land accounted for 23-28%, mainly south of Balkhash Lake. Water bodies represented approximately 11.15-15.37%, predominantly in the overseas portion as the third-largest type. Cultivated land occupied about 2.71-4.99%, concentrated along the Ili River in the southeast. Forest covered 1.07-1.43%, located in mountainous areas, while urban-rural construction land was minimal at 0.35-0.57%, centered in cultivated land areas [FIGURE:2, FIGURE:3].

The domestic portion exhibited more uniform LULC distribution than the overseas portion, though the overseas area was six times larger, dominating the overall basin pattern. For instance, the domestic distribution was grassland (67.01%), unused land (15.37%), cultivated land (12.57%), water (2.29%), forest (1.43%), and construction land (0.35%), while the overseas distribution was grassland (59.24%), unused land (29.15%), water (12.35%), cultivated land

(2.71%), forest (1.07%), and construction land (0.35%). Both portions shared grassland as the dominant type and construction land as the smallest, but differed in the relative proportions of other types. Change magnitudes were greater in the later period (2005–2015) than the early period (1970s–2005). During the early period, all types except cultivated land and forest increased, with construction land showing the most significant growth (17.31%). In the later period, all types except water bodies and unused land increased, with water and unused land decreasing by 5.54% and 13.43%, respectively. Cultivated land and forest, after initial reductions, increased by 16.05% and 32.58% in the later period .

2.2 LULC Structural Changes

Over the entire study period (1970s–2015), the basin' s LULC structure changed significantly. Grassland and urban-rural construction land continuously increased, with proportions rising from 60.03% to 63.04% and 0.35% to 0.57%, respectively. Cultivated land and forest experienced initial decline followed by increase, showing overall growth. Conversely, water bodies and unused land initially increased then decreased, showing overall reduction. The overseas portion dominated the basin-wide change process, with only cultivated land showing different trends from the basin average. The domestic portion matched the basin-wide trend only for forest and construction land, while cultivated land, water bodies, and unused land showed continuous increases [TABLE:1, TABLE:2].

The spatial dynamics index (S) for the entire study period was higher than both sub-periods, indicating that LULC conversions accumulated over time. The complex conversion patterns, primarily bidirectional exchanges between grassland and cultivated land/forest/water bodies/unused land, with notable unidirectional conversion from cultivated land to unused land, maintained the basin in equilibrium throughout the study period.

2.3 LULC Conversion Patterns

During the early period, bidirectional conversions between grassland and cultivated land, forest, and unused land exceeded 15$×10^{2}$ km^2 each. Grassland-to-forest and grassland-to-unused land conversions were roughly balanced, while cultivated land-to-grassland conversion (48$×10^{2}$ km^2) far exceeded the reverse (15$×10^{2}$ km^2), causing substantial cultivated land loss in the northern and central basin. In the later period, bidirectional conversions between grassland and other types remained dominant, all exceeding 21$×10^{2}$ km^2. The increased grassland area primarily originated from unused land (140$×10^{2}$ km^2), while grassland losses mainly converted to cultivated land (150$×10^{2}$ km^2) and water bodies (12$×10^{2}$ km^2), concentrated in the middle-lower Ili River and around Balkhash Lake [Figure 4: see original paper].

The overseas portion exhibited more complex changes, with dramatic cultivated land reduction in the early period (144$×10^{2}$ km^2) converting primarily to grassland (99$×10^{2}$ km^2) and unused land (34$×10^{2}$ km^2). Later, forest and grassland increases (45×10^{2} km^2 and 150×10^{2} km^2, respectively) derived from grassland conversion, while water body changes concentrated around Balkhash Lake and the Ili River delta. The domestic portion showed continuous cultivated land expansion from grassland (24×10^{2} km^2), with balanced conversions between forest-grassland and grassland-unused land. The domestic LULC change process was more stable than the overseas portion, as confirmed by both single-type (Ps) and regional (Pt) trend-state indices. However, the overseas portion' s larger area meant its quasi-balanced changes dominated the basin-wide balanced state (Pt values: early period 0.78, later period 0.77, entire period 0.78) [TABLE:3, TABLE:4].

3. Discussion

Although analyzing the large Balkhash Lake basin required substantial time and effort, the existing LULC dataset enabled quantitative interpretation of change processes and trends. Since the 1970s, the overseas portion experienced massive land and water development, Soviet dissolution, and Kazakhstan' s institutional reforms, while the domestic portion underwent China' s reform and opening-up policies, significantly altering LULC patterns.

The Kapchagay Reservoir' s construction promoted irrigation expansion, while post-Soviet land privatization policies encouraged agricultural investment and land reclamation. Kazakhstan' s 2003 land privatization resolutions stimulated conversion of 45×10^{2} km^2 of grassland to cultivated land, increasing overseas cultivated land from 182×10^{2} km^2 to 211×10^{2} km^2, consistent with previous research. Meanwhile, domestic cultivated land continuously increased by 24×10^{2} km^2, primarily from grassland conversion.

In this arid region with precipitation of 110–1000 mm and evaporation several times higher, cultivated land depends heavily on irrigation. Water body changes correlated inversely with cultivated land expansion and Balkhash Lake area reduction. Approximately 250×10^{2} km^2 of water bodies converted to unused land around the lake and Ili River delta, indicating lake shrinkage consistent with previous studies. The water body trend-state index suggests continued reduction, highlighting the urgency of water resource protection.

Population growth from 3.1×10^{6} to 6.58×10^{6} drove construction land expansion from 14.4×10^{2} km^2 to 23.8×10^{2} km^2. Despite being the smallest LULC type, construction land showed the most dramatic change (Ps = 0.29), followed by unused land (0.25) and forest (0.24). Grassland, the largest type, remained relatively stable (Ps = 0.05). Both single-type and regional indices confirmed domestic LULC changes were more stable than overseas changes. The basin maintained overall equilibrium, with stable grassland changes balancing more dramatic changes in smaller LULC types.

4. Conclusions

This study analyzed LULC change processes and trends in the Balkhash Lake basin from the 1970s to 2015, comparing domestic and overseas portions. Key findings include:

1) Grassland and unused land consistently dominated the basin, collectively exceeding 85% of the area. The overseas portion accounted for over 86% of these two types. Urban-rural construction land was the smallest type at 0.35–0.57%, lower domestically than overseas. Water bodies, the third-largest type, were concentrated overseas, while forest was primarily domestic.

2) Different development stages and socioeconomic systems produced varying LULC changes. Cultivated land and forest initially decreased then increased, showing overall growth. Grassland and construction land continuously increased, rising from 60.03% to 63.04% and 0.35% to 0.57%, respectively. Water bodies and unused land showed the opposite trend, decreasing overall. Only cultivated land in the overseas portion deviated from the basin-wide trend, while only forest and construction land in the domestic portion matched the basin-wide pattern.

3) LULC changes were dominated by bidirectional conversions, with more spatial conversion in the later period than the early period. Spatial dynamics for the entire study period exceeded both sub-periods, indicating temporal accumulation effects. Both single-type (Ps) and regional (Pt) trend-state indices showed domestic changes were more stable than overseas changes. While overseas changes remained quasi-balanced, the relatively stable domestic changes maintained the entire basin in a balanced state throughout the study period.

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