

## Postprint: Impacts of Ecological Water Transfer on Surface Water Body Area Changes in the Lower Tarim River

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### Abstract

The surface water bodies in the Lower Tarim River, dominated by rivers and lakes, have been influenced by water conveyance projects and play an important role in regional water cycling and water balance regulation. Based on nearly 20 years of Landsat 5, Landsat 7, and Landsat 8 imagery data and ecological water conveyance data in the Lower Tarim River, this study comprehensively employed the Google Earth Engine (GEE) computing platform and multivariate statistical analysis methods to systematically analyze the changes in surface water body area and its response to ecological water conveyance. The results show that: (1) From 2000 to 2019, the areas of surface water bodies, seasonal water bodies, and permanent water bodies in the Lower Tarim River region all exhibited a fluctuating upward trend, with rates of  $15.54 \text{ km}^2 \cdot \text{a}^{-1}$ ,  $7.12 \text{ km}^2 \cdot \text{a}^{-1}$  and  $8.41 \text{ km}^2 \cdot \text{a}^{-1}$ , respectively; the areas of seasonal and permanent water bodies in the upper reach (Daxihaizi Reservoir-Yingsu, excluding Daxihaizi Reservoir), middle reach (Yingsu-Alagan), and lower reach (Alagan-Lake Taitema) of the Lower Tarim River also showed fluctuating increasing trends, with the lower reach showing the greatest increase rates of  $5.23 \text{ km}^2 \cdot \text{a}^{-1}$  and  $8.24 \text{ km}^2 \cdot \text{a}^{-1}$ , respectively. (2) The increase in surface water body area caused by ecological water conveyance was mainly manifested in the Lake Taitema area; in 2019, the areas of permanent and seasonal surface water bodies in the Lake Taitema region were approximately  $267.27 \text{ km}^2$  and  $188.00 \text{ km}^2$ , respectively, with a total water area of approximately  $455.27 \text{ km}^2$ , representing an increase of  $417.08 \text{ km}^2$  (approximately 10.92 times) compared to 2000 (approximately  $38.19 \text{ km}^2$ ). (3) Over the past 20 years, the surface water body area in the study region, especially the permanent water body area, has been closely correlated with the ecological water conveyance volume in the Lower Tarim River; the relatively low water discharge during 2007-2009 directly led to the reduction of both surface water body and seasonal water body areas to their minimum values in 2009. The research findings contribute to a comprehensive understanding of the impacts of

ecological water conveyance on surface water body changes in the Lower Tarim River and provide a scientific basis for regional water ecological protection.

## Full Text

### Effects of Ecological Water Conveyance on Changes of Surface Water Area in the Lower Reaches of Tarim River

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## Abstract

Surface water bodies, primarily composed of rivers and lakes in the lower reaches of the Tarim River, play a crucial role in regional water cycling and water balance regulation, and their area is significantly influenced by water conveyance projects. Based on ecological water conveyance data from 2000 to 2019 in the lower Tarim River, this study systematically analyzed changes in surface water area and its response to ecological water conveyance using the Google Earth Engine computing platform, Landsat 5, Landsat 7, and Landsat 8 imagery, and multiple statistical analysis methods. The results indicate: (1) From 2000 to 2019, the areas of total surface water, seasonal water, and permanent water in the lower Tarim River all exhibited fluctuating upward trends, with rates of 15.54 km<sup>2</sup>/a, 7.12 km<sup>2</sup>/a, and 8.41 km<sup>2</sup>/a, respectively. (2) The seasonal and permanent water areas in the upper segment (Daxihaizi Reservoir-Yingsu, excluding Daxihaizi Reservoir), middle segment (Yingsu-Alagan), and lower segment (Alagan-Lake Taitema) of the lower Tarim River also showed fluctuating increasing trends, with the lower segment exhibiting the highest increase rates of 5.23 km<sup>2</sup>/a and 8.24 km<sup>2</sup>/a, respectively. (3) The increase in surface water area caused by ecological water conveyance was mainly manifested in the Lake Taitema area. In 2019, the permanent water area and seasonal water area in Lake Taitema were approximately 267.27 km<sup>2</sup> and 188.00 km<sup>2</sup>, respectively, with a total water area of about 455.27 km<sup>2</sup>. (4) The surface water area in the study region, especially the permanent water area, is closely correlated with the ecological water conveyance volume in the lower Tarim River. Due to low water discharge during 2007–2009, the areas of surface water and seasonal water in the study region decreased to their minimum values in 2008. These research findings contribute to a comprehensive understanding of the impacts of ecological water conveyance on surface water changes in the lower Tarim River and

provide a scientific basis for regional water ecological protection.

**Keywords:** Tarim River; surface water body; ecological water conveyance; temporal and spatial changes; impact analysis; Google Earth Engine

## Introduction

In recent years, under the dual influence of global climate change and human activities, the Tarim River has experienced river channel dry-up, river-lake system fragmentation, lake shrinkage, and water environment deterioration since the 1970s, endangering the basin's already fragile ecological environment and triggering a series of ecological problems that severely constrain sustainable regional socioeconomic development. In response, the State Council approved and implemented the "Tarim River Recent Comprehensive Management Plan" in 2001, officially launching the Tarim River Basin comprehensive management project. By the end of 2019, the ecological water conveyance project in the lower Tarim River had been implemented for 20 years, resulting in restored surface water area, significantly raised groundwater levels, and improved ecological conditions. Surface water bodies, primarily rivers and lakes, are significantly affected by the water conveyance project and play an important role in the water cycle and water balance regulation of the lower Tarim River, representing the most accessible water resources for regional populations.

Reviewing research progress on the impacts of water conveyance projects in the lower Tarim River, relatively few systematic studies have examined surface water area changes and their response to ecological water conveyance in the past 20 years. The Google Earth Engine platform, launched by Google in 2010, integrates multi-source data and combines powerful cloud computing capabilities, enabling rapid acquisition and processing of massive remote sensing imagery. It has been widely applied in large-scale geospatial data analysis, providing strong technical support for dynamic monitoring and spatiotemporal change analysis of resources and environments at global and large watershed scales, solving problems of computational complexity and high costs associated with traditional massive remote sensing image processing and analysis. This provides technical support for studying spatiotemporal changes of surface water in the lower Tarim River region.

Therefore, this study selected the lower Tarim River region as the research area, focusing on river- and lake-dominated surface water bodies. Using the Google Earth Engine platform and comprehensive statistical analysis methods, we systematically analyzed the changing characteristics of surface water area in the lower Tarim River region over the past 20 years and explored the impacts of ecological water conveyance on surface water area, providing a scientific basis for rational water resource utilization and ecological environmental protection after ecological water conveyance.

## 1.1 Study Area Overview

The initial ecological water conveyance project in the lower Tarim River involved releasing water from the Daxihaizi Reservoir to the downstream river channel, with the conveyance volume being the discharge from Daxihaizi Reservoir. Therefore, this study's research area covers the buffer zone around the river from the terminus of Daxihaizi Reservoir (excluding the reservoir itself) to Lake Taitema [Figure 1: see original paper]. To accurately analyze the impacts of ecological water conveyance on the spatiotemporal changes of surface water area, the study area was divided into three segments: the upper segment (Daxihaizi Reservoir-Yingsu, excluding Daxihaizi Reservoir), the middle segment (Yingsu-Alagan), and the lower segment (Alagan-Lake Taitema) [Figure 1: see original paper].

### 1.2.1 Image Data

This study primarily utilized the Google Earth Engine cloud computing platform to obtain Landsat 5, Landsat 7, and Landsat 8 imagery covering the research area from 2000 to 2019. A total of [MATH\_0] images were obtained. The study calculated the Modified Normalized Difference Vegetation Index (mNDVI), Normalized Difference Water Index (mNDWI), and Enhanced Vegetation Index (EVI) for the research area using the following formulas:

$$\text{mNDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

$$\text{mNDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}$$

$$\text{EVI} = 2.5 \times \frac{\text{NIR} - \text{Red}}{\text{NIR} + 6.0 \times \text{Red} - 7.5 \times \text{Blue} + 1}$$

where Blue, Green, Red, NIR, and SWIR represent the blue band (0.45–0.52  $\mu\text{m}$ ), green band (0.52–0.60  $\mu\text{m}$ ), red band (0.63–0.69  $\mu\text{m}$ ), near-infrared band (0.77–0.90  $\mu\text{m}$ ), and short-wave infrared band (1.55–1.75  $\mu\text{m}$ ), respectively.

When  $\text{mNDWI} > \text{EVI}$  and  $\text{mNDWI} > \text{NDVI}$ , it indicates that the vegetation signal in the image pixel is weaker than the water signal, meaning the pixel can be classified as water. Additionally, the criterion  $\text{EVI} < 0.1$  was used to minimize interference from wetland vegetation signals on water body extraction. Afterward, seasonal and permanent water bodies were determined by calculating the frequency of water occurrence in each remote sensing image. For each Landsat pixel in the lower Tarim River, the water frequency over the 20-year period was calculated using the following formula:

$$F(y) = \frac{1}{N_y} \sum_{i=1}^{N_y} \omega_{y,i} \times 100\%$$

where  $F(y)$  is the water frequency calculation index for the pixel;  $y$  is the year of Landsat imagery;  $N_y$  is the total number of observations for that pixel in year  $y$ ; and  $\omega_{y,i}$  indicates whether the pixel observation is water (1) or non-water (0).

By calculating water frequency, the study area was classified according to the rules:  $>75\%$  as permanent water,  $25\text{-}75\%$  as seasonal water, and  $<25\%$  as non-water. The research area was thus categorized into non-water (pixel value set to 0), seasonal water (value set to 1), and permanent water (value set to 2), with total surface water area being the sum of seasonal and permanent water areas.

### 1.2.2 Ecological Water Conveyance Data

By the end of 2019, a total of  $81.64 \times 10^8 \text{ m}^3$  of water had been conveyed to the lower Tarim River, with the Tarim River contributing  $67.78 \times 10^8 \text{ m}^3$  (83.03%) and the Kongque River contributing  $13.86 \times 10^8 \text{ m}^3$  (16.97%). The year with maximum water conveyance was 2017, with  $12.15 \times 10^8 \text{ m}^3$  delivered solely from the Tarim River main stream. The year with minimum water conveyance was 2007, with only  $1.75 \times 10^8 \text{ m}^3$ .

### 1.3.2 Mann-Kendall Trend Test

This study employed the non-parametric Mann-Kendall trend test to analyze temporal trends in surface water area. For the time series of surface water area  $T_1, T_2, \dots, T_n$ , the method constructs a statistical variable  $S$ :

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(T_j - T_i)$$

where the sign function is defined as:

$$\text{sign}(T_j - T_i) = \begin{cases} 1 & \text{if } T_j - T_i > 0 \\ 0 & \text{if } T_j - T_i = 0 \\ -1 & \text{if } T_j - T_i < 0 \end{cases}$$

Based on the null hypothesis of no trend in surface water area, the statistic  $S$  approximately follows a standard normal distribution when  $n \geq 10$ , with variance calculated as:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^g t_p(t_p-1)(2t_p+5)}{18}$$

where  $n$  is the number of data points,  $g$  is the number of tied groups, and  $t_p$  is the number of data points in the  $p$ -th tied group.

The  $Z$  statistic is then designed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

When  $Z > 0$ , it indicates an increasing trend in surface water area; when  $Z < 0$ , it indicates a decreasing trend. When  $|Z| \geq 1.96$ , it indicates significance at the  $\alpha = 0.05$  level; when  $|Z| \geq 2.58$ , it indicates significance at the  $\alpha = 0.01$  level.

### 1.3.3 Correlation Coefficient Analysis

This study used the Pearson correlation coefficient method to analyze the relationship between surface water area and ecological water conveyance volume. The calculation formula is:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}}$$

where  $r$  is the correlation coefficient between water area and conveyance volume;  $X_i$  and  $Y_i$  are the annual sequences of the two variables;  $\bar{X}$  and  $\bar{Y}$  are the annual mean values; and  $n$  is the number of years.

The correlation coefficient  $r$  ranges from -1 to 1, with positive values indicating positive correlation, negative values indicating negative correlation, and larger absolute values indicating stronger correlation. Generally,  $|r| < 0.2$  indicates extremely weak or no correlation;  $0.2 \leq |r| < 0.4$  indicates weak correlation;  $0.4 \leq |r| < 0.6$  indicates moderate correlation;  $0.6 \leq |r| < 0.8$  indicates strong correlation; and  $0.8 \leq |r| \leq 1$  indicates extremely strong correlation.

## 2.1 Temporal Variation Analysis of Surface Water Area

The analysis results of surface water area changes from 2000 to 2019 in the lower Tarim River show that the total surface water area, seasonal water area, and permanent water area all exhibited fluctuating upward trends (with the total surface water area showing a statistically significant increasing trend), with  $Z$  values of [MATH\_1], [MATH\_2], and [MATH\_3], respectively, and increasing rates of 15.54 km<sup>2</sup>/a, 7.12 km<sup>2</sup>/a, and 8.41 km<sup>2</sup>/a, respectively. The average areas of total surface water, seasonal water, and permanent water during this period were 312.21 km<sup>2</sup>, 249.05 km<sup>2</sup>, and 63.17 km<sup>2</sup>, respectively, with minimum areas of 49.00 km<sup>2</sup>, 48.93 km<sup>2</sup>, and 0.06 km<sup>2</sup> (in 2000) and maximum areas of 523.93 km<sup>2</sup>, 475.30 km<sup>2</sup>, and 216.44 km<sup>2</sup> (in 2019). The areas of total surface

water, seasonal water, and permanent water in the lower Tarim River region (below Daxihaizi) increased from 49.00 km<sup>2</sup>, 48.93 km<sup>2</sup>, and 0.06 km<sup>2</sup> in 2000 to 498.54 km<sup>2</sup>, 300.76 km<sup>2</sup>, and 197.78 km<sup>2</sup> in 2019, respectively.

In the first year after water conveyance began (2000), the total surface water area and seasonal water area increased sharply from 48.58 km<sup>2</sup> and 48.02 km<sup>2</sup> to 491.26 km<sup>2</sup> and 475.30 km<sup>2</sup>, respectively. From 2000 to 2019, the total surface water area showed fluctuating changes, decreasing sharply in 2008 and reaching its minimum values for both total surface water and seasonal water areas in that year, followed by a sharp increase in 2010 and a slow upward trend thereafter [Figure 2: see original paper].

The surface water area, seasonal water area, and permanent water area in the upper segment of the lower Tarim River also showed fluctuating upward trends ( $Z$  values of [MATH\_4], [MATH\_5], and [MATH\_6]), with increasing rates of 0.31 km<sup>2</sup>/a, 0.31 km<sup>2</sup>/a, and 0.01 km<sup>2</sup>/a, respectively. The average areas of total surface water, seasonal water, and permanent water in this segment were 11.44 km<sup>2</sup>, 11.21 km<sup>2</sup>, and 0.23 km<sup>2</sup>, respectively, with minimum areas of 1.08 km<sup>2</sup>, 1.47 km<sup>2</sup>, and 0.03 km<sup>2</sup> (in 2000) and maximum areas of 17.65 km<sup>2</sup>, 17.18 km<sup>2</sup>, and 1.54 km<sup>2</sup> (in 2019). Similar to the entire study area, the total surface water area and seasonal water area decreased sharply in 2008, reaching their minimum values in that year .

The surface water area, seasonal water area, and permanent water area in the middle and lower segments of the lower Tarim River also exhibited fluctuating upward trends, with all water types except seasonal water in the lower segment showing statistically significant increases. The middle segment' s total surface water, seasonal water, and permanent water areas increased at rates of 1.75 km<sup>2</sup>/a, 1.58 km<sup>2</sup>/a, and 0.16 km<sup>2</sup>/a, respectively, while the lower segment' s corresponding areas increased at rates of 13.48 km<sup>2</sup>/a, 5.23 km<sup>2</sup>/a, and 8.24 km<sup>2</sup>/a, respectively .

## 2.2 Spatial Variation Analysis of Water Area

The surface water in the lower Tarim River region shows obvious spatially heterogeneous distribution, changing over time and presenting different states. Overall, water bodies are mainly distributed in the lower segment of the study area. The proportion of seasonal water in the lower Tarim River region is relatively high, with an average proportion of 83.60% during the study period, a maximum of 99.87% (in 2000), and a minimum of 42.69% (in 2019). The year with the largest proportion of permanent water in the total water surface area was 2019 (57.31%), followed by 2017 (39.67%) and 2018 (37.02%).

[Figure 3: see original paper] shows the spatial distribution of surface water area in the lower Tarim River from 2000 to 2019. The increase in surface water area caused by ecological water conveyance was mainly manifested in the Lake Taitema area (defined in this study as the area below 39°39'54" N). In 2000, Lake Taitema had only a small amount of seasonal surface water, with an area

of approximately 38.19 km<sup>2</sup>. By 2019, both permanent and seasonal water areas in Lake Taitema had increased significantly to approximately 267.27 km<sup>2</sup> and 188.00 km<sup>2</sup>, respectively, with a total water area of about 455.27 km<sup>2</sup>—an increase of 417.08 km<sup>2</sup> compared to 2000 [Figure 4: see original paper].

From 2000 to 2019, the average proportions of permanent water area in the upper, middle, and lower segments were 0.36%, 1.30%, and 98.34%, respectively, while the average proportions of seasonal water area were 4.50%, 7.67%, and 87.83%, respectively [Figure 5: see original paper]. This indicates that the lower segment has the largest surface water area, consistent with the spatial distribution shown in [Figure 3: see original paper]. The proportions of permanent and seasonal water in the upper segment both showed decreasing trends, with permanent water proportion decreasing from 1.54% to 0.03%. Conversely, the proportions of permanent and seasonal water in the lower segment both showed increasing trends, with permanent water proportion increasing from 42.69% to 98.34%, mainly distributed in the Lake Taitema area (accounting for approximately 98.34% to 99.98%). The middle segment showed relatively low growth rates for both permanent and seasonal water areas.

### 2.3 Correlation Between Surface Water Area and Water Conveyance Volume

Since 2000, the total surface water area, seasonal water area, and permanent water area in the lower Tarim River have all shown positive correlations with ecological water conveyance volume, with correlation coefficients ( $r$  values) of 0.54 (moderate positive correlation), 0.07 (extremely weak positive correlation), and 0.71 (strong positive correlation), respectively. These results demonstrate that the surface water area in the study region, especially the permanent water area, is primarily related to the water conveyance volume in the lower Tarim River [Figure 6: see original paper].

From a regional perspective, the surface water areas in the upper, middle, and lower segments all showed positive correlations with ecological water conveyance volume, with correlation coefficients ( $r$  values) of 0.73 (strong positive correlation), 0.58 (moderate positive correlation), and 0.54 (moderate positive correlation), respectively. Seasonal water areas also showed positive correlations with water conveyance volume, with  $r$  values of 0.58 (moderate positive correlation), 0.56 (moderate positive correlation), and 0.36 (extremely weak positive correlation), respectively. Permanent water areas showed positive correlations as well, with  $r$  values of 0.73 (strong positive correlation), 0.78 (strong positive correlation), and 0.71 (strong positive correlation), respectively. These correlation results indicate that, overall, the upper segment's surface water area has a relatively strong correlation with water conveyance volume, while the lower segment's permanent water area is most strongly influenced by water conveyance volume. This is primarily because water released from Daxihaizi Reservoir must pass through the upper and middle segments before reaching the Lake Taitema area in the lower segment, and as water conveyance volume increases, the wa-

ter area continues to expand. Additionally, the extremely low water conveyance volume during 2007–2009 (with only  $1.75 \times 10^8 \text{ m}^3$  in 2007) directly caused the surface water area and seasonal water area in the study region to decrease to their lowest points in 2008.

### 3 Discussion

Based on remote sensing imagery and ecological water conveyance data from the lower Tarim River over the past 20 years, this study analyzed the spatiotemporal variation characteristics of regional surface water area and discussed the impacts of ecological water conveyance on surface water area, providing reference significance for understanding the ecological and environmental effects of ecological water conveyance in the lower Tarim River. The lower Tarim River region from Daxihaizi Reservoir to Lake Taitema is characterized by scarce precipitation and high evaporation, with water resources primarily consisting of discharge from Daxihaizi Reservoir—that is, the ecological water conveyance volume for the lower Tarim River. Water resources are the primary limiting factor for ecological environmental security and sustainable socioeconomic development in arid regions. With increasing ecological water conveyance, the expanding surface water area in the lower Tarim River has led to gradual and significant vegetation recovery and continuous ecological improvement.

Due to water loss along the river channel, the initial water conveyance efforts did not reach Lake Taitema, so the permanent and seasonal water areas in Lake Taitema did not increase significantly after the first few conveyance events. The low discharge from Daxihaizi Reservoir in 2007 directly caused significant decreases in both permanent and seasonal water areas in the study region, reducing the total surface water area to its minimum value in 2008. Among the upper, middle, and lower segments of the lower Tarim River, river- and lake-dominated surface water bodies are concentrated in the Lake Taitema area of the lower segment. The expansion of water area in Lake Taitema is the main factor contributing to the increased water area in the lower Tarim River. However, due to potential quality defects in the imagery data and possible influence of water from the Cherchen River on Lake Taitema, the results of this study contain some uncertainties that require further comprehensive consideration of other influencing factors in future research.

### 4 Conclusions

Through the above analysis and discussion, the main conclusions of this study are as follows:

From 2000 to 2019, the total surface water area, seasonal water area, and permanent water area in the lower Tarim River all exhibited fluctuating upward trends, increasing from  $49.00 \text{ km}^2$ ,  $48.93 \text{ km}^2$ , and  $0.06 \text{ km}^2$  in 2000 to  $498.54 \text{ km}^2$ ,  $300.76 \text{ km}^2$ , and  $197.78 \text{ km}^2$  in 2019, respectively. In the first year after water conveyance began (2000), the total surface water area and seasonal water

area increased sharply from 48.58 km<sup>2</sup> and 48.02 km<sup>2</sup> to 491.26 km<sup>2</sup> and 475.30 km<sup>2</sup>, respectively. The surface water areas in the upper segment (Daxihaizi Reservoir-Yingsu), middle segment (Yingsu-Alagan), and lower segment (Alagan-Lake Taitema) all showed fluctuating upward trends, with increase rates of 0.31 km<sup>2</sup>/a, 1.75 km<sup>2</sup>/a, and 13.48 km<sup>2</sup>/a, respectively. The surface water area in the lower Tarim River region shows obvious spatial heterogeneity, being mainly distributed in the lower segment. The increase in surface water area caused by ecological water conveyance was primarily manifested in the Lake Taitema area (defined as the area below 39°39'54" N). In 2019, the permanent water area and seasonal water area in Lake Taitema were approximately 267.27 km<sup>2</sup> and 188.00 km<sup>2</sup>, respectively, with a total water area of about 455.27 km<sup>2</sup>—an increase of 417.08 km<sup>2</sup> compared to 2000. From 2000 to 2019, the average proportions of permanent water area in the upper, middle, and lower segments were 0.36%, 1.30%, and 98.34%, respectively. The total surface water area, seasonal water area, and permanent water area in the lower Tarim River region showed correlation coefficients with ecological water conveyance volume of 0.54 (moderate positive correlation), 0.07 (extremely weak positive correlation), and 0.71 (strong positive correlation), respectively, indicating that surface water area, especially permanent water area, is primarily related to water conveyance volume. The middle segment's surface water area showed a relatively strong correlation with water conveyance volume, while the lower segment's permanent water area was most strongly influenced by water conveyance volume. The extremely low water conveyance volume during 2007–2009 directly caused the surface water and seasonal water areas to decrease to their minimum values in 2008.

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

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