Influence of reservoir construction on surrounding vegetation cover

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Abstract: Vegetation is a significant factor in the energy and water cycles. Changes in vegetation are affected by the natural environment and human activities. In this study, the Dalong Reservoir on the Ningyuan River in Sanya, Hainan, China, was taken as an example to set one type of buffer zone with the reservoir dam site as the center, and two types of horizontal and vertical buffer zones outwards from both banks of the river, and Landsat 5 remote sensing image data and the vegetation data were applied. A coverage estimation model was used to study the temporal and spatial changes in surface vegetation in three types of buffer zones, and the characteristics of the surface vegetation changes in the preterm, midterm and late-term reservoir construction periods were analyzed. The results showed that, (1) During the years 2000 and 2010, the vegetation coverage first decreased and then increased with time in the scope of the research. During preterm construction (2000-2004), the vegetation coverage in the upstream region decreased while that in the downstream region increased. During midterm construction (2004-2006), the declining rate of vegetation coverage downstream was greater than that upstream, but the influence of reservoir construction on vegetation coverage decreased over time in the late-term construction period (2007-2010); (2) Along the direction of the river length, the vegetation coverage showed a downtrend along with the river flow direction during the whole period (2000-2010), and the influence of reservoir construction on vegetation coverage gradually decreased as the distance from the reservoir increased; (3) Along the direction of the river width, the vegetation coverage in the preterm and midterm construction periods (2000-2006) increased with increasing distance from the riverbanks; (4) The vegetation coverage showed a significant increasing trend with increasing distance from the reservoir. The research results can provide a theoretical reference for reducing the risk of vegetation degradation, strengthening the governance of the ecological environment, and promoting the ecological construction of “landscapes, forests, fields, lakes and grass”.

Keywords: reservoir, remote sensing, vegetation coverage, ecological environment, landscapes
DOI: 10.25165/j.ijabe.20211403.5344

Citation: Liu P, Li X R, Zhang R K, Yao M R, Chen J F, Li Y R, et al. Influence of reservoir construction on surrounding vegetation cover. Int J Agric & Biol Eng, 2021; 14(3): 214–220.

1 Introduction

A reservoir is a type of engineering measure that is widely adopted for flood defense. The construction of reservoirs has brought huge economic benefits associated with flood control, irrigation, water supply, and power supply and has made great contributions to the sustainable development of the economy and social stability. It is important to study the influence mechanism of reservoirs on the surrounding environment to protect the structure and function of regional ecosystems[1]. The construction of reservoirs and the policy of returning farmland to forests can effectively reduce soil erosion and have a positive impact on improving the ecological environment[2]. In recent years, with the development of theoretical research, an increasing number of methods have been used to study changes in riparian vegetation. The combination of the normalized difference vegetation index (NDVI) and remote sensing image data has been widely used in vegetation research[3]. Zhang et al.[4] used NDVI data to diagnose the spatiotemporal changes in vegetation coverage in Guangxi by analyzing remote sensing images; Zhang et al.[5] used NDVI data to explore the impact of vegetation restoration on ecosystem services in the Loess Plateau; Kellogg et al.[6] used remote sensing data to analyze the impacts of dams on vegetation at different altitudes; Yi et al.[7] used the difference vegetation index to study the impact of cascade dam construction on riverside vegetation; Saraf et al.[8] used remote sensing and geographic information system (GIS) technology to study the impacts of reservoirs on groundwater and vegetation; Zhang et al.[9] studied the dynamic effects of dam-reservoir-river systems, climate driving factors and human driving factors on vegetation; Eekhout et al.[10] studied the impacts of reservoirs construction, land use and climate change on the ecosystem services of the Mediterranean basin; and Liu et al.[11] used remote sensing technology to analyze the impacts of urban environments and ecosystems on water bodies and the surrounding vegetation coverage. As a basic component of the ecosystem, vegetation plays an important role in climate regulation, soil and

Received date: 2019-08-21 **Accepted date:** 2020-12-01
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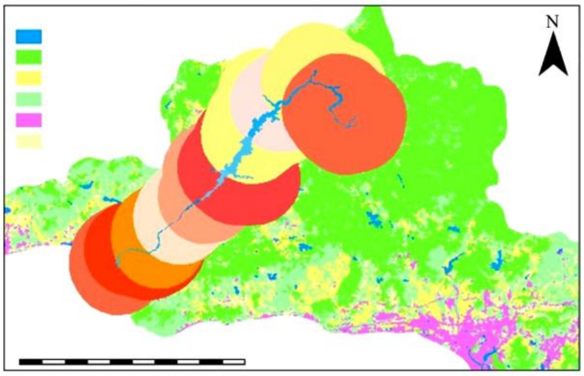
water conservation, and air purification. It is of great practical significance to study the impact of reservoirs on surrounding surface vegetation coverage[12,13]. The Dalong Reservoir in Sanya is located in the middle and lower reaches of the Ningyuan River. It is a large-scale water conservancy hub for flood control, water supply, irrigation, and power generation. It is also the largest water conservancy project in Hainan Province, China[14]. The completion of the reservoir basically solved the problem of engineering water shortages in the central and western parts of Sanya, and the reservoir raised the flood control standard of the middle and lower reaches of River Ningyuan from a 2-year-recurrence flood to a 20-year-recurrence flood. On the other hand, the construction and operation of water conservancy projects inevitably have certain influences on the surrounding ecological environment. From the perspective of an environmental quality evaluation, Zhang et al.[15] used the landscape ecology method to evaluate and predict the impact of the Dalong Reservoir on the regional landscape pattern. Li et al.[16] conducted a comprehensive investigation and research on the ecological-geological environment after the construction of the Dalong Reservoir from four aspects: the geological environment, hydrology and water quality, natural ecological environment, and societies and humanities.

Currently, most published studies have analyzed the effects of reservoirs after construction, but there are few comparative studies relating to the effects that occur before and after the construction of a reservoir[17,18]. This article took the entire construction process of the Dalong Reservoir from 2000 to 2010 as the research period and the surface vegetation in the surrounding area as the research object. The vegetation coverage estimation model was used to analyze the impact of the Dalong Reservoir on the surrounding vegetation in the preterm, midterm and late term of reservoir construction.

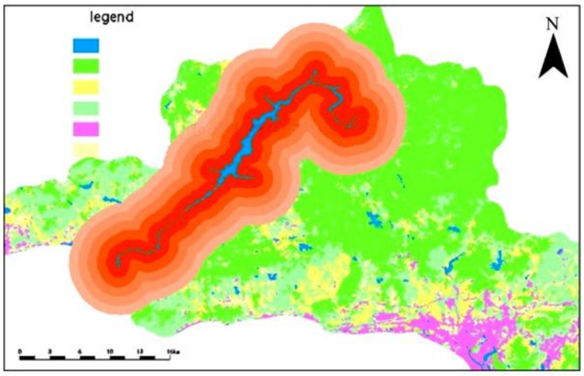
2 Research area overview and data processing

The Dalong Reservoir was built on the Ningyuan River, the fifth-largest river in Hainan Province. The river is located within the longitudes of 109°01′-109°34′ E and latitudes of 18°21′-18°40′ N. The Ningyuan River flows into the South China Sea in the southwest from Wuzhishan in the northeast. The drainage area is small, narrow and long. The upstream section of the river has many mountains with large slopes and tributaries. The water system is tree-shaped, the generation and convergence duration of the river are short, and the floods rise and fall steeply. In terms of climate, the Dalong Reservoir is located in a tropical marine climate zone, with abundant light, heat and rain, and precipitation is concentrated in the rainy season from May to October. Rainstorms in the Ningyuan River Basin are mainly caused by tropical cyclone weather systems, which are affected by the basin area, river system shape and river slope; when floods occur, due to the impacts of the slopes, the flood durations are short, and the flood volumes are concentrated. The vegetation in the basin mostly comprises tropical rainforests and monsoon rainforests. The vegetation types mainly include forests and bushes such as wild tea trees and longan trees. There is no rare vegetation around the reservoir area. The water flow around the reservoir is weak, the water environment is unique, and the fish species are relatively unique. The local social development level is low. There is no large-scale heavy industry, and the supervision and control of domestic sewage and industrial wastewater discharge are strict. The construction of the Dalong Reservoir began in 2004, and the project was formally completed in 2007. The period from 2000 to 2010 was a decade in which the region's ecological environment changed drastically[19].

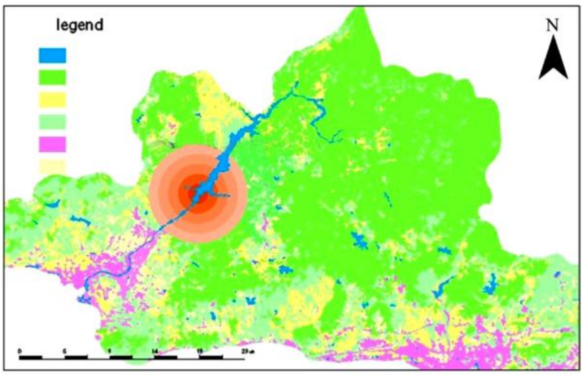
The Landsat 5 satellite's Phase 4 TM products and comprehensive seasonal data with low cloud cover collected in 2001, 2004, 2006 and 2010 were used in this research. The images were preprocessed on the ENVI 5.1 platform, and the 5-km buffer area around the Ningyuan Riverbank was extracted from each image using the spatial analysis tool of the GIS system as the study area. In this study, three types of buffer areas are applied to study the vegetation around the reservoir[20]. First, the reservoir is taken as the center, and areas along the river are delineated at the same distance interval to make a buffer zone with a 5-km radius; second, the river is taken as the center, and the area from the shoreline outwards is delineated to form five buffer subbelts with bandwidths of 1 km; third, the dam site is taken as the center, and five buffer rings are formed outwards, each with a bandwidth of 1 km. The surrounding area of the reservoir is the study area analyzed in this paper; specifically, the study area refers to the area covered by the above three types of buffer zones. The three types of buffer zones are shown in Figure 1.



a. Schematic diagram of the vertical buffer (with the reservoir as the center)



b. Schematic diagram of the horizontal buffer (with the river as the center)



c. Schematic diagram of the buffer zone near the dam site

Figure 1 Schematic diagrams of three buffer types

3 Vegetation coverage estimation model

Vegetation coverage is the specific expression of vegetation growth and distribution and is defined as the percentage of the vertical projection area of leaves, stems, branches, etc., on the ground to the total statistical area[21]. NDVI and dimidiate pixel models are currently the most widely used methods for estimating vegetation coverage. In this paper, NDVI was used as a parameter, and the vegetation coverage model designed based on the dimidiate pixel model was used to estimate the vegetation coverage in the preterm (2000-2004), midterm (2004-2007) and late-term (2007-2010) of Dalong Reservoir construction.

3.1 Dimidiate pixel model

The dimidiate pixel model[22,23] is a simple and practical remote sensing estimation model. It assumes that the surface of a pixel is composed of vegetation and nonvegetation. The spectral information observed by a remote sensing instrument is also linearly weighted and synthesized by these two component factors. The weight of each factor is the ratio of the respective area in the pixel.

According to the principle of the pixel binary model, it is assumed that the spectral information S of a pixel is obtained by adding the spectral information S_v contributed by the vegetation and the spectral information S_s contributed by the nonvegetation[24]. The formula is shown in Equation (1).

$$S=S_v+S_s \tag{1}$$

Suppose that the proportion of the area covered by vegetation in a pixel is f_c, that is, the vegetation coverage of the pixel, and that the proportion of the area without vegetation coverage is $(1–f_c)$. If the spectral information of a pixel that is completely covered by vegetation of a certain thickness is S_{veg}, the vegetation spectral information S_v in a mixed pixel is the product of S_{veg} and the area occupied by the vegetation component (vegetation coverage) f_c in that pixel. The formula is shown in Equation (2).

$$S_v=F_c\, S_{veg} \tag{2}$$

Similarly, if the spectral information of a pixel that is completely covered by a certain thickness of nonvegetation is S_{soil}, then the nonvegetation spectral information S_s in the mixed pixel is the product of S_{soil} and $(1–f_c)$, as shown in Equation (3).

$$S_s=(1-f_c)\, S_{soil} \tag{3}$$

Substituting Equation (2) and Equation (3) into Equation (1), the spectral information S of a pixel can be obtained.

$$S=f_c\, S_{\rm veg}+(1-f_c)\, S_{\rm soil} \tag{4}$$

After transforming Equation (4), the vegetation coverage equation is as follows.

$$f_c=\frac{(S-S_{\rm soil})}{(S_{\rm veg}-S_{\rm soil})} \tag{5}$$

Due to the noise in the remote sensing data, [5%, 95%] is selected as the confidence interval. In other words, the value of a pixel with a cumulative pixel percentage of 5% is $S_{\rm soil}$ and that with a cumulative pixel percentage of 95% is $S_{\rm veg}$ [25].

Equation (5) expresses the relationship between spectral information and vegetation coverage. $S_{\rm soil}$ and $S_{\rm veg}$ are the spectral information reflected by the pure soil and vegetation pixels; these pure pixels weaken the influence of the atmosphere and vegetation types.

3.2 Using NDVI to estimate vegetation coverage

The vegetation index model commonly used to estimate vegetation coverage is NDVI, which comprises a long sequence of remotely sensed observation data. Because of its advantages, such as its wide coverage and easy accessibility, NDVI has been an important data material used to study changes in vegetation coverage for a long time[26]. NDVI is a quantitative value that reflects the status of vegetation on the ground and is derived from the spectral information of ground features received by remote sensing sensors. According to the dimidiate pixel model, the NDVI of a pixel can be expressed as the information contributed by the green vegetation $\rm NDVI_{veg}$ and the information contributed by the nonvegetation coverage $\rm NDVI_{soil}$; this also satisfies Equation (4). Thus, S can be substituted with NDVI in Equation (5) to obtain the following equation:

$$f_c=\frac{(NDVI-NDVI_{soil})}{(NDVI_{veg}-NDVI_{soil})} \tag{6}$$

where, $NDVI_{veg}$ represents the NDVI value when a pixel is completely covered by vegetation of a certain thickness; $NDVI_{soil}$ represents the $NDVI$ value when a pixel is completely covered by a certain thickness of nonvegetation.

4 Results and discussion

In this paper, the interannual dynamics of vegetation around the studied reservoir and the vegetation changes in the three buffer zones were studied, and data were analyzed for each of the four cases.

4.1 Interannual dynamic changes in vegetation coverage upstream and downstream of the reservoir

The changes in vegetation coverage upstream and downstream of the reservoir from 2000 to 2010 are shown in Figure 2. It can be observed that the vegetation coverage first decreased and then increased with the passage of time in the scope of the research, especially upstream, and there was a significant negative correlation between the vegetation coverage and time. In the preterm construction period (2000-2004), the vegetation coverage decreased at a rate of 0.4225% per year, and the coverage rate increased to 2.02% per year in the midterm construction period (2004-2006) for the scope of the research. It is worth noting that for the downstream area, the vegetation coverage increased during preterm construction but decreased during midterm construction. This result indicated that during the construction of the Dalong Reservoir, water storage formed a falling zone, and the sediment loss downstream of the reservoir hindered the normal growth of vegetation. Therefore, the downstream ecological environment was more affected during the construction of the reservoir than the upstream area was[27,28]. In addition, the downstream resettlement that occurred during reservoir construction was significantly larger than that upstream[29]. Deforestation of the local vegetation, vegetation removal, and resettlement activities (such as land reclamation, etc.) were also direct factors affecting vegetation coverage. To repair the downstream ecosystem after reservoir construction, ecological compensation policies must be implemented to control the frequency and intensity of human disturbances. If a certain ecological compensation policy is not adopted and the frequency and intensity of human disturbances downstream of a reservoir are not reasonably controlled, it will be difficult for the downstream ecosystem to repair itself after a reservoir is constructed. Between 2006 and 2010, vegetation coverage recovered in both the upstream and downstream areas. The surrounding vegetation coverage before reservoir construction decreased yearly; however, the vegetation coverage in the upstream and downstream areas improved annually. The secondary plants grew rapidly when the main vegetation was destroyed during midterm construction, so the ecological environment in this area was restored in a short time. Moreover, the microclimate surrounding the reservoir caused the rainfall amount to increase, which contributed to the growth of local vegetation[30,31].

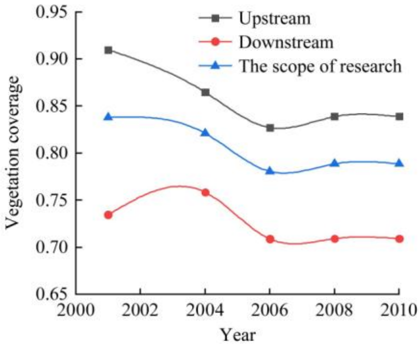


Figure 2 Vegetation coverage changes in the upstream and downstream reservoir areas from 2000 to 2010

4.2 Changes in vegetation coverage along the river-length direction

Taking the Dalong Reservoir dam site as the boundary between the upstream and downstream regions of the river, the upstream river length was found to be 182.52 km, and the downstream river length was 93.49 km. The upstream and downstream rivers were equally divided into five segments. Figure 3 shows the vegetation coverage variations with the distance from the dam site in different periods (i.e., preterm, midterm, and late-term). The trend with which the vertical vegetation coverage varies with distance is similar among different periods, showing that the vegetation coverage decreases from the upstream to downstream regions. Compared with the curve changes of the "preterm construction" and "midterm construction" periods, the results show that the difference between the "preterm construction" and "midterm construction" curves tends to decrease as the distance from the dam increases. This indicates that the influence of reservoir construction on vegetation gradually decreases as the distance from the dam increases. Compared with the "midterm construction" and "late-term construction" curve changes, in the downstream area, within 50 km of the reservoir, the "late-term construction" value was higher than the "midterm construction" value, and the vegetation could be restored; in the areas 50 km away from the reservoir, the "midterm construction" value was higher than the "after construction" value, and the vegetation situation continued to deteriorate, which was related to urban expansion in the coastal areas. In the downstream region within 50-70 km from the dam, the vegetation coverage was higher in the preterm construction period but was lower in the late-term construction period compared with that in the midterm construction period. The vegetation coverage downstream within 70-90 km of the dam was higher in the midterm construction period but lower in the late-term construction period than in the preterm construction period. This likely resulted from the vegetation damage and land leveling that was conducted around the reservoir during the construction of the reservoir. The destruction of the upstream vegetation affected the interception capacity for rainwater, and land leveling increased the convergence capacity, thus enhancing the water supply downstream and contributing to vegetation growth. During the late-term construction period, most of the upstream water accumulated in the reservoir, and the water supply was regulated by the reservoir, according to local irrigation and residential water consumption data. Therefore, the amount of water supplied to the downstream vegetation was significantly reduced compared to that before dam construction, and the vegetation coverage correspondingly declined. The vegetation coverage farther than 90 km downstream of the reservoir was equivalent between the preterm and late-term construction periods, indicating that the reservoir hardly affected vegetation outside this distance.

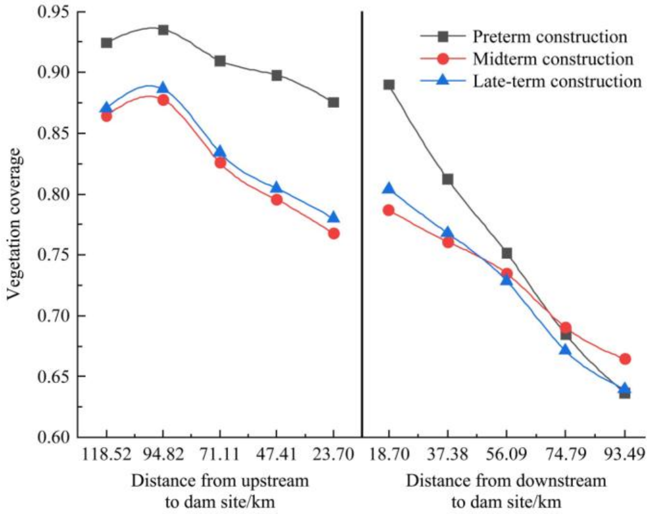


Figure 3 Variation trends of vegetation coverage in the upstream and downstream region in the preterm, midterm and late-term construction periods of the Dalong Reservoir

Figure 4 shows the changes in vegetation coverage with distance from the dam site in different periods. It can be observed that the slope of the "pre-intermediate construction" curve is steeper than that of the "late-intermediate construction" curve both the upstream and downstream regions, indicating that the destruction process of vegetation is more sensitive to the distance from the dam than the restoration process.

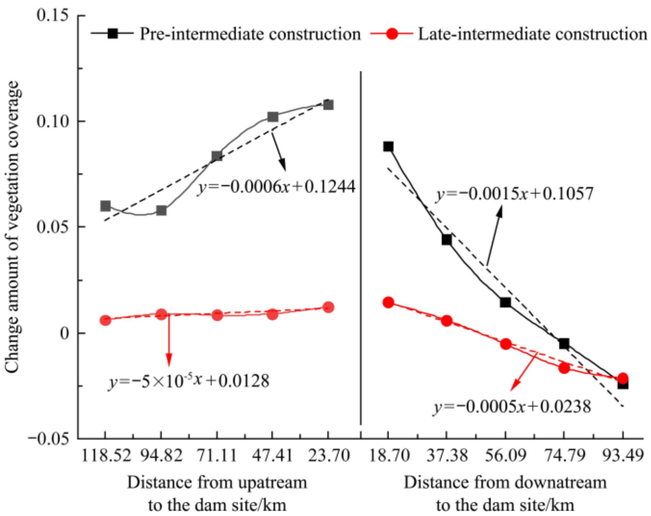


Figure 4 Variation trends of the vegetation coverage change amount with the distance to the dam in the pre-intermediate and late-intermediate construction periods of the Dalong Reservoir

4.3 Change in vegetation coverage perpendicular to the river length

Figure 5 shows the vegetation coverage variations with distance from the shore in different periods. The vegetation coverage within 5 km of the shoreline in the midterm construction period was lower than that in the preterm construction period. In addition, the vegetation coverages of "preterm construction" and "midterm construction" periods had significant positive correlations with the distance from the shore, indicating that vegetation coverage increased with the distance from the riverbank (p<0.05) in the preterm and midterm construction periods. In the late-term construction period, the vegetation coverage within 5 km of the shoreline was higher than that in the midterm construction period but was lower than that in the preterm reservoir construction period. The vegetation coverage increased with increasing distance from the shoreline in the range of 0-3 km but decreased and tended to stabilize in the range of 3-5 km in the late-term reservoir construction. Therefore, in the late-term reservoir construction, the vegetation within 5 km of the shoreline was slowly repaired, but it still did not reach the vegetation coverage level of the preterm period of reservoir construction, and the vegetation restoration of the area within the range of 0-3 km from the shoreline was faster than that within the range of 3- 5 km.

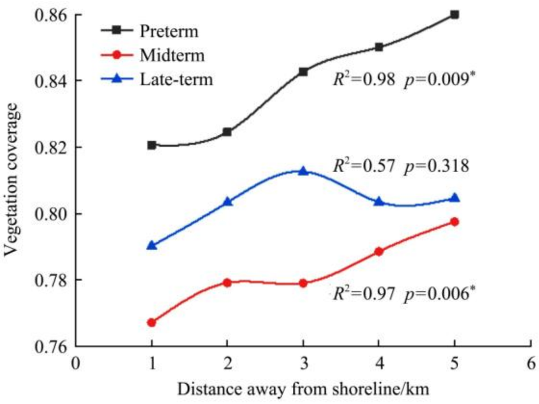


Figure 5 Variation trends of vegetation coverage with distance from the shore in the preterm, midterm and late-term construction of the Dalong Reservoir

4.4 Change in vegetation coverage with the reservoir as the center

To eliminate the impact of downstream urbanization on vegetation coverage, a 5-km buffer zone was created with the dam site as the center, and the effect of reservoir construction on vegetation was analyzed in this area. Figure 6 shows the variation curve of vegetation coverage in the core area of the reservoir between 2000 and 2010. It can be observed that the 10-year vegetation coverage variation in the core area of the reservoir is consistent with the vegetation coverage variations within 5-km of the banks of the Ningyuan River; however, the magnitude of the variation in the former is greater than the latter, with decline rates of 0.7475%/a in the preterm construction period and 4.045%/a in the midterm construction period, while the increase rate was 1.18%/a in the late-term construction period.

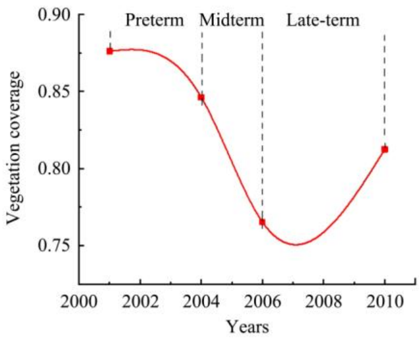


Figure 6 Variation curve of vegetation coverage in the core area of the reservoir from 2000 to 2010

Figures 7 and 8 show the variation trends of vegetation coverage and the vegetation coverage change amounts in the core area of the Dalong Reservoir in different periods, respectively. Figure 7 shows that in the preterm construction period, the vegetation coverage did not change significantly with the distance from the center of the reservoir (p>0.05). This implies that before the construction of the reservoir, the vegetation coverage centered on the reservoir did not change much within the range of 0-5 km. In the midterm construction period, the vegetation coverage rate showed a significant increase around the reservoir (p<0.05), and this increase was consistent with the variation rule of the vegetation coverage rate along with the riverbank distance in the midterm construction period, as discussed in Section 4.3. However, in the late-term construction period, the vegetation coverage rate showed an increasing trend around the reservoir (p<0.05). Compared to that described in Section 4.3, the vegetation coverage in the late-term construction period at distances larger than 3 km increased (Figure 7). This was because reservoirs have water storage functions, and reservoir construction is advantageous to the restoration of vegetation surrounding reservoirs. This indicates that the studied reservoir was conducive to the restoration of vegetation around the reservoir.

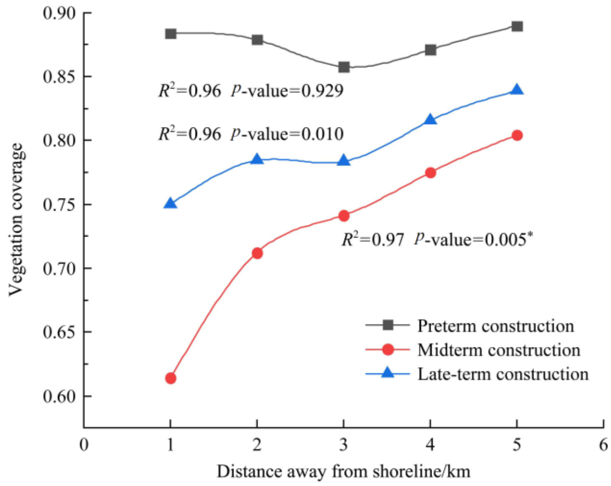


Figure 7 Variation trends of vegetation coverage with the distance from the dam in the core area of the Dalong Reservoir

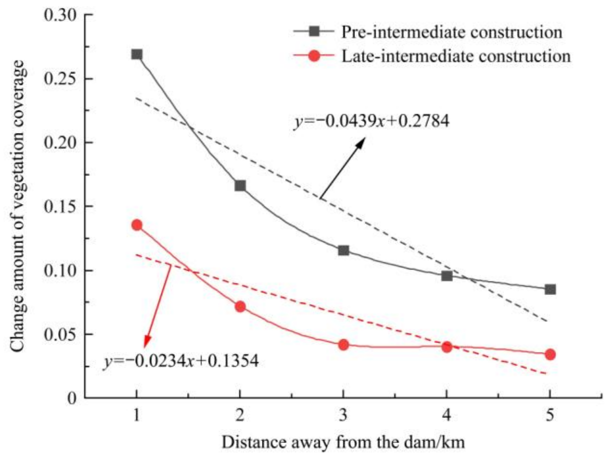


Figure 8 Variation trends of the change amounts of vegetation coverage with the distance from the dam in the core area of Dalong Reservoir5 Conclusions

Figure 8 shows that the vegetation coverage change shown in the "pre-intermediate construction" curve decreased by 0.0439 per kilometer, while the vegetation coverage change in the "late-intermediate construction" curve decreased by 0.0234 per kilometer. The slope of the "late-intermediate construction

(2004-2010)" curve is smaller than the slope of the "pre-intermediate construction (2000-2007)" curve, indicating that the destruction process of vegetation during reservoir construction is more sensitive to the distance from the reservoir than the restoration process.

5 Conclusions

In this study, a vegetation coverage estimation model was used to analyze the temporal and spatial characteristics of the surrounding vegetation coverage during the preterm, midterm and late-term construction of the Dalong Reservoir from 2000 to 2010. The following conclusions were drawn.

(1) From 2000 to 2010, the vegetation coverage first decreased and then increased with time in the scope of the research, and, especially in the upstream region, there was a significant negative correlation between vegetation coverage and time. In the process of reservoir construction, the local environment was inevitably destroyed. However, if the reservoir was reasonably developed in combination with the local ecological conditions, the growth environment of vegetation would be improved after completion of the reservoir construction and the vegetation would recover annually at a slow rate.

(2) With the reservoir at the center, an analysis was carried out along the river. The influence of reservoir construction on vegetation decreased gradually with increasing distance from the reservoir. This phenomenon was more obvious in the process of vegetation destruction and was not obvious in the process of vegetation restoration.

(3) With the river as the center, an analysis was carried out perpendicularly to the river length, and the vegetation coverage increased with increasing distance from the riverbank in the preterm and midterm reservoir construction periods. In the late-term reservoir construction period, the vegetation was repaired slowly, but the coverage still did not reach the level of preterm reservoir construction.

(4) Taking the dam site as the core for analysis, within a 5-km range of the buffer zone, the vegetation coverage showed a significant increasing trend from the reservoir at the center to the surrounding area, and the construction of the reservoir was conducive to the restoration of vegetation around the reservoir.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant No. 41877276), the Chinese Natural Science Foundation of Shanxi Province (Grant No. 201901D111052).

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