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Evaluating the Effect of the Ecological Restoration of Quarry Slopes in Caidian District, Wuhan City

Yueshu Yang [1], Daxiang Liu [1,*], Hai Xiao [1], Jiangang Chen [2], Yu Ding [3,4], Dong Xia [3,4], Zhenyao Xia [3,4] and Wennian Xu [3,4]

1 Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University, Yichang 443002, China; michael_lewandowski@foxmail.com (Y.Y.); oceanshawctgu@163.com (H.X.)
2 Key Laboratory of Mountain Hazards and Surface Processes, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China; chenjg@imde.ac.cn
3 Key Laboratory of Disaster Prevention and Mitigation (China Three Gorges University), Hubei Province, Yichang 443002, China; thirdding@163.com (Y.D.); xiadong2015@ctgu.edu.cn (D.X.); xzy_yc@126.com (Z.X.); xwn@ctgu.edu.cn (W.X.)
4 Key Laboratory of Geological Hazards on Three Gorges Reservoir Area (China Three Gorges University), Ministry of Education, Yichang 443002, China
* Correspondence: ldx@ctgu.edu.cn

Received: 13 October 2019; Accepted: 20 November 2019; Published: 23 November 2019

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Abstract: Many measures have been applied to quarry slopes for ecological restoration; however, the performance of these measures has not been clearly evaluated. Thus, research evaluating the effects of the ecological restoration of quarry slopes in Caidian District was carried out to quantify the performance of different ecological restoration methods, to evaluate the effect of ecological restoration projects and to learn the applicability of different restoration technologies in Caidian District. The research can provide a reference for scientific decision-making in the follow-up management of ecological environments in Caidian District. First, the ecological restoration process of quarries in Caidian District was described in detail by visiting the relevant design and construction units. Through observational analysis from the aspects of applicable slope gradient, slope flatness requirements, project cost, the vegetation coverage conditions, the species diversity conditions and construction difficulty, the advantages and disadvantages, as well as the applicability of different ecological restoration technologies were preliminarily clarified. Then, the comprehensive evaluation index system of the ecological restoration effects was established by using the fuzzy AHP method. The ecological restoration effects of each sample plot were evaluated quantitatively based on the data of the evaluation indexes obtained by the field investigation and sampling analysis. Finally, according to the evaluation results, the existing problems in the follow-up management of the ecological restoration of quarry slopes in Caidian District were analyzed, and corresponding countermeasures and suggestions were proposed. The results showed that the quantitative evaluation results obtained by the comprehensive evaluation system of ecological restoration were consistent with the observational analysis results, and the validity of the evaluation system was proven.

Keywords: ecological restoration; fuzzy AHP method; quarry slopes; effect evaluation

1. Introduction

Quarries are widespread and have a strong environmental impact on the landscape, causing vegetation losses and soil losses [1,2]. Flora and fauna as well as fundamental ecological relationships have been greatly destroyed by quarries. Quarries destroy soil by modifying the topography of the original site and depleting and altering the soil microbial communities [3–5]. Because of the large number of damaged mountains caused by quarrying and mining, the ecological restoration of damaged mountains is a difficult task in terms of capital, manpower, and technical capability [6].

Regarding "ecological restoration," the concept that the academic community agrees with is based on Diamond [7], Jordon [8], Cairns [9], and other scholars. This process involves restoring a damaged ecosystem to a healthy and stable state through external means. From the perspective of the application scope, the technology for the ecological restoration of slopes has been expanded from the less difficult repair of soil slopes to the more difficult repair of rock slopes, concrete slopes, and masonry slopes widely used in quarrying, water conservancy, transportation, municipal construction, and other fields [10–12]. Technical means have been developed from the original artificial seeding to comprehensive mechanized construction. Plant species configuration has been transformed from a single herb species that can achieve rapid greening effects to a more scientific way for the rational combination of grasses and shrubs [13,14].

At present, various ecological restoration technologies have been developed and applied in the ecological restoration of quarry slopes, such as CS higher-order granulation technology [15], TBS galvanized wire complex grass-shrub planting method [16], and vegetation concrete ecological protection technology [17]. The physical, chemical, and microbial properties of the habitat material have been greatly improved, and the technical application field and application scope have been further expanded. However, these ecological restoration methods have not been effectively evaluated on quarry slopes. Meanwhile, selecting appropriate ecological restoration measures is of great significance for guiding the follow-up ecological restoration work of quarry slopes.

The fuzzy AHP method is the organic combination of the analytic hierarchy process [18,19] and the fuzzy comprehensive evaluation method. The evaluation index system established by the analytic hierarchy process and its weight ranking could solve the quantitative and qualitative problems in the evaluation of effects of the ecological restoration of quarry slopes [20,21]. The fuzzy comprehensive evaluation method comprehensively considers the influencing factors of the research problem and effectively quantifies the determined qualitative indicators through the membership function and fuzzy statistical method [22–24].

Therefore, in order to learn the applicability of different restoration measures on damaged slopes in Caidian District, the completed ecological restoration projects of quarry slopes in Caidian District were taken as the study object. This study was conducted to evaluate the effect of ecological restoration projects from two aspects of observational analysis and comprehensive evaluation. The research can provide a reference for scientific decision-making in the follow-up management of ecological environments in Caidian District. This study aims (1) to preliminarily clarify the advantages and disadvantages as well the applicability of different ecological restoration technologies, (2) to establish the comprehensive evaluation index system of the effects of ecological restoration by using the fuzzy AHP method, and (3) to propose the corresponding countermeasures and suggestions according to the existing problems in the follow-up management of ecological restoration of quarry slopes in Caidian District.

2. Methods

2.1. General Description of the Study Region

Caidian District (Figure 1), with a land area of 1093.57 km^2, has a subtropical monsoon climate. The Caidian District is located in southwestern Wuhan City, and its mineral resources are very rich. Since the end of the last century, large-scale quarrying and mining have destroyed the original natural vegetation. Most quarried areas have pure rock slopes with uneven surfaces, and ecological restoration is difficult. Most of the damaged mountains in Caidian District are concentrated on two sides of the Beijing-Zhuhai Expressway, Shanghai-Chengdu Expressway, and 318 National Highway. The total area of the damaged slopes that should be restored is 1.66 million m^2, and the construction fund is approximately USD 36 million. Specifically, the damaged slopes are mainly concentrated in 200,000 m^2 on Ma'an Mountain, 600,000 m^2 on Jiangjia Mountain, 280,000 m^2 on Longni Mountain, 47,000 m^2 on Gaozi Mountain, 500,000 m^2 on Qianzi Mountain, 160,000 m^2 on Tujian Mountain, and 333,000 m^2 on Funiu Mountain.

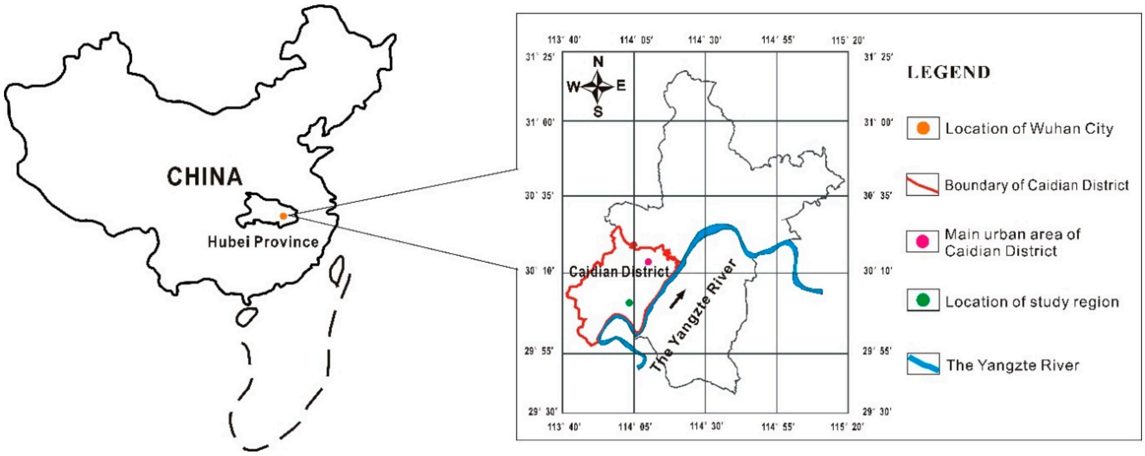

Figure 1. Location map of study region.

Since the beginning of the 21st century, artificial ecological restoration of exposed and damaged mountains has been carried out, and the ecological environment in the area has been significantly improved. Between 2006 and 2013, all large and medium-sized quarries in Caidian District were closed, during which the large-scale ecological restoration of the damaged mountains was carried out. The ecological restoration of three mountains, including Ma'an Mountain, Shiyang Mountain, and Jiangjia Mountain, with a total restoration area of 340,000 m^2 and a total investment of nearly USD 10 million led to a significant improvement in the ecological environment of quarries in Caidian District. According to the time sequence, the ecological restoration process of quarries in Caidian District is shown in Table 1.

Table 1. Ecological restoration process of quarries in the Caidian District.

Time	Position	Ecological Restoration Area (1×10^4 m^2)
April to May 2006	Middle piedmont of Ma'an Mountain	2
March to May 2007	Shiyang Mountain	2
March to May 2008	Tianwan Section, Ma'an Mountain	2
May to September 2009	Tianwan Section, Ma'an Mountain	4
April to August 2010	South piedmont of Ma'an Mountain	4
September to November 2011	North piedmont of Ma'an Mountain	8
July to November 2012	Jiangjia Mountain and Qianzi Mountain	12

2.2. General Situation of the Sample Plots

According to the investigation and data collection of the ecological restoration of quarry slopes in Caidian District, seven sample plots with different restoration technologies were selected for research from the completed ecological restoration projects of quarry slopes. The general description and ecological restoration effects of the sample plots are shown in Table 2.

Table 2. General description and ecological restoration effects of the sample plots.

No.	General Description	Ecological Restoration Technology	Implementation Time	Ecological Restoration Effects
I	The slope is located on Zhaxin Road, northwest of Ma'an Mountain, with a length of 180 m at the bottom, a maximum height of approximately 90 m, a slope gradient of 70°–80°, and a total area of 10,000 m^2. The slope rock is undeveloped mudstone.	Soil spray-sowing technology	2011	Within 180 days after project completion, the vegetation coverage increased from 5% to over 95%. After 1 year, the coverage decreased to less than 40% because of the impact of a rainstorm. The unconfined compressive strength of the habitat material was approximately 0.15 MPa. In a rainstorm in July 2012, a large area of the habitat material layer collapsed.
II	The slope is located in the middle of Jiangjia Mountain in Yuxian town, with a length of 600 m at the bottom, a maximum height of 90 m, a slope gradient of 65°–80°, and a total area of nearly 50,000 m^2.	TBS galvanized wire complex grass-shrub planting method	2011	Within 60 days after the project completion, the vegetation coverage increased from zero to over 50%, and the growth height of the shrubs was less than 10 cm. After 2 years, the coverage rate exceeded 85%, and the growth height of the shrubs exceeded 30 cm, which basically realized the ecological restoration of the damaged slope and achieved the expected effect.
III	The slope is located in the middle section of Ma'an Mountain, with a length of 130–150 m at the bottom, a maximum height of approximately 50 m, a slope gradient of 60°–70°, and a total area of over 5500 m^2.	CS higher-order granulation technology	2012	There was almost no vegetation coverage on the slope surface at first. Two years after project completion, the vegetation coverage was over 90%, among which the growth height of the shrubs was more over 50 cm. The slope ecosystem with a sustainable succession function was initially constructed. In addition, the ecological restoration target of the damaged slope was well achieved.
IV	The slope is located in the western part of the middle piedmont of Ma'an Mountain, with a length of 120–150 m at the bottom, a maximum height of approximately 80 m, a slope gradient of 60°–70°, and a total area of 9000 m^2.	Tape planting slope technology	2012	Two years after the project completion, the vegetation coverage increased from complete exposure to 95%, and the growth height of the shrubs exceeded 50 cm. The ecological restoration target of the damaged slope was initially achieved, but the plant community structure was relatively simple and the species diversity was insufficient.
V	The exposed weathered rock slope is located in a brick factory at the northwest foot of Ma'an Mountain, with a length of 100 m at the bottom, a maximum height of approximately 80 m, a slope gradient of 65°–75°, and a total area of 12,000 m^2. The upper part of the slope is hard marl, and the lower part is debris generated by local collapse of the mountain.	Building widening network method	2010	One year after project completion, the vegetation coverage increased from almost no vegetation to 40%. After three years, the vegetation coverage decreased to less than 40%. Because of the poor stability of the planting platform and the corrosion of steel bars with the increase in age, many planting platforms no longer existed.
VI	The slope is located at the middle foot of Ma'an Mountain, with a length of 50–80 m at the bottom, a maximum height of 80 m, a slope gradient of 75°–85°, and a total area of 4500 m^2. The irregular slope is a fault-generated schist.	Floating panels trenching method	2011	One year after project completion, the vegetation coverage increased from approximately 20% to over 60%, among which the contribution rate of vines accounted for 40%. After two years, the vegetation coverage decreased to less than 50%, and most of the shrubs grew well. However, problems such as low vegetation coverage and insufficient species diversity still existed.
VII	The slope is located in the eastern part of the middle piedmont of Ma'an Mountain, with a length of 100–120 m at the bottom, a maximum height of 60 m, a slope gradient of 65°–75°, and a total area of 5000 m^2. The damaged rock surface is undeveloped limestone.	Vegetation concrete ecological protection technology	2010	Fifty days after project completion, the slope surface was fully covered by vegetation. After two years, with the introduction of local species, especially local small shrubs, formed a natural landscape in harmony with the surrounding environment. Two days after completion of spraying, the unconfined compressive strength of the habitat material reached 0.26 MPa.

2.3. The Evaluation Index System of Ecological Restoration of Quarry Slopes by Using the Fuzzy AHP Method

2.3.1. Establishment of the Evaluation System

The selection of the evaluation indexes should reflect the overall effect of comprehensive ecological restoration on the quarry slopes, considering not only the physical, mechanical, and chemical properties of the habitat material but also the contribution of the vegetation to soil fixation, water retention capacity, and the slope landscape pattern. Therefore, a comprehensive evaluation index system from the four aspects of the effect of habitat material improvement, the effect of ecology, the effect of soil and water conservation, and the effect of landscape was established.

According to the types of indexes available in total, in combination with expert advice, the primary evaluation indexes were as follows. Evaluation indexes for the effect of habitat material improvement include organic matter (X_1), available N (X_2), available P (X_3), available K (X_4), soil bulk density (X_5), total N (X_6), total P (X_7), and pH (X_8). Evaluation indexes for the effect of ecology include vegetation coverage (Y_1), Gleason richness index (Y_2), Shannon–Wiener diversity index (Y_3), Pielou evenness index (Y_4), drought resistance of vegetation (Y_5), barren resistance of vegetation (Y_6), and proportion of native species (Y_7). Evaluation indexes for the effect of soil and water conservation include shearing strength of the root-soil composite (Z_1), permeability (Z_2), soil erosion intensity (Z_3), sewage flow interception (Z_4), root weight density (Z_5), and root tensile strength (Z_6). Evaluation indexes for the effect of landscape include landscape coordination (W_1), regional characteristics (W_2), landscape capacity for visitors (W_3), and green period (W_4).

The principal component analysis method of SPSS was used to compare the importance of each index. It was found that the scores of X_1, X_2, X_3, X_4, and X_5 in the effect of habitat material improvement; Y_1, Y_3, Y_4, and Y_5 in the effect of ecology; Z_1, Z_2, Z_3, and Z_5 in the effect of soil and water conservation; and W_1 and W_3 in the effect of landscape were higher than the average, which can be incorporated into the evaluation index system.

2.3.2. Determination of Index Weight

According to the expert advice, the important values of each index were compared with each other by the 1–9 scale method [25,26], and the judgement matrix was formed. Then, the weight vector was calculated, and the consistency test was performed. The index weights of the evaluation index system of ecological restoration of quarry slopes are shown in Table 3.

Table 3. The index weights of the evaluation index system of ecological restoration of quarry slopes.

First-Class Index	Weight	Second-Class Index	Weight	Total Weight Sequencing	Rank
The effect of soil and water conservation	0.296	Shearing strength of root-soil composite	0.289	0.0853	4
		Permeability	0.180	0.0531	9
		Soil erosion intensity	0.440	0.1300	2
		Root weight density	0.091	0.0270	12
The effect of ecology	0.418	Vegetation coverage	0.446	0.1862	1
		Drought resistance of vegetation	0.164	0.0687	8
		Shannon–Wiener diversity index	0.285	0.1190	3
		Pielou evenness index	0.105	0.0439	10
The effect of habitat material improvement	0.143	Organic matter	0.498	0.0713	7
		Available N	0.219	0.0315	11
		Available P	0.111	0.0159	13
		Available K	0.107	0.0154	14
		Soil bulk density	0.065	0.0093	15
The effect of landscape	0.143	Landscape coordination	0.500	0.0717	5
		Landscape capacity for visitors	0.500	0.0717	5

2.3.3. Determination of Grading Standard

According to the relevant research results and the functional characteristics of ecological restoration of quarry slopes, combined with expert advice, the grading standard can be divided into five levels (v_1-Very good, v_2-Good, v_3-Normal, v_4-Poor and v_5-Very poor). The grading standard of the evaluation indexes of ecological restoration of quarry slopes is shown in Table 4.

Table 4. The grading standard of the evaluation indexes of ecological restoration of quarry slopes.

Index	The Standard of Different Grades				
	v_1	v_2	v_3	v_4	v_5
Shearing strength of root-soil composite/(kPa)	>60	60~50	50~40	40~30	<30
Permeability/(mm·h^{-1})	>30	30~20	20~10	10~5	<5
Soil erosion intensity/(g·cm^{-3}·a^{-1})	<5	5~15	15~25	25~35	>35
Root weight density/(kg·m^{-3})	>3.5	3.5~2.5	2.5~1.5	1.5~0.5	<0.5
Vegetation coverage/%	>95	95~80	80~65	65~40	<40
Drought resistance of vegetation	Very good	Good	Normal	Poor	Very poor
Shannon–Wiener diversity index	>3.0	3.0~2.5	2.5~2.0	2.0~1.5	<1.5
Pielou evenness index	>1.0	1.0~0.8	0.8~0.6	0.6~0.4	<0.4
Organic matter/(g·kg^{-1})	>30	30~20	20~10	10~5	<5
Available N/(mg·kg^{-1})	>75	75~55	55~35	35~15	<15
Available P/(mg·kg^{-1})	>30	30~20	20~10	10~5	<5
Available K/(mg·kg^{-1})	>205	205~150	150~95	95~40	<40
Soil bulk density/(g·cm^{-3})	<1.5	1.5~2.0	2.0~2.5	2.5~3.0	>3.0
Landscape coordination	Very good	Good	Normal	Poor	Very poor
Landscape capacity for visitors	Very good	Good	Normal	Poor	Very poor

Note: The shearing strength of root-soil composite is under saturated conditions with a vertical pressure of 75 kPa.

2.3.4. Calculation Method

The expert scoring method is used to determine the membership degree of qualitative indexes, and the membership degree function is used to calculate the membership degree of quantitative indexes. If the value of the membership function of an element belonging to a fuzzy set is large, the degree of membership of the element is high, and the degree to which it belongs to the set is also high. The value of the membership is a number between [0, 1]. A value closer to 1 indicates a better degree of membership. First, the membership degree of the second-level index is calculated, and the calculation method of the membership degree of the quantitative index is as follows [27]:

The positive index (the higher the index value is, the better it is for the project):

$$r_{im(j+1)} = \frac{V_{imj} - x_{imj}}{V_{imj} - V_{im(j+1)}}, j = 0, 1, 2, 3, 4 \quad (1)$$

The reverse index (the smaller the index value is, the better it is for the project):

$$r_{im(j+1)} = \frac{x_{imj} - V_{imj}}{V_{im(j+1)} - V_{imj}}, j = 0, 1, 2, 3, 4 \quad (2)$$

where $r_{im(j+1)}$ is the membership degree of the index to the effect for level $j + 1$; x_{imj} is the actual index value of the effect for level j of the m index under level i; V_{imj} is the index value standard of the effect for level j of the m index under level i; and $V_{im(j+1)}$ is the index value standard of the effect for level $j + 1$ of the m index under level i.

The comprehensive evaluation set of the first-level index layer is set as $B = \begin{pmatrix} B_1 & B_2 & B_3 & B_4 \end{pmatrix}^T$. The second-level index weight matrix can be multiplied by the corresponding membership degree matrix to obtain the first-level index membership degree. By multiplying the first-level index weight matrix with the corresponding membership degree matrix, the membership degree of the target layer can be obtained. According to Equation (3), the comprehensive evaluation results can be obtained as follows:

$$S = W * \begin{pmatrix} B_1 & B_2 & \ldots & B_N \end{pmatrix}^T = \begin{pmatrix} w_1 & w_2 & \ldots & w_N \end{pmatrix} * \begin{pmatrix} B_1 & B_2 & \ldots & B_N \end{pmatrix}^T \quad (3)$$

3. Results

3.1. Observational Analysis of the Ecological Restoration Effect on Quarry Slopes

Based on the field investigation and visiting the relevant design and construction units of seven typical sample plots, the ecological restoration technologies were compared from the aspects of applicable slope gradient, slope flatness requirements, project cost, the vegetation coverage conditions, the species diversity conditions, and construction difficulty. The vegetation coverage conditions and the species diversity conditions were mainly based on field observation and analysis. The advantages, disadvantages, and applicability of different ecological restoration technologies were analyzed (Table 5).

Table 5. Comparison of different ecological restoration technologies.

No.	Ecological Restoration Technology	Applicable Slope Gradient/(°)	Slope Flatness Requirements	Project Cost/ (USD/m^2)	The Vegetation Coverage Conditions	The Species Diversity Conditions	Construction Difficulty
Sample plot I	Soil spray-sowing technology	40–70	Relatively high	8.6–12.9	Medium	Relatively high	Medium
Sample plot II	TBS galvanized wire complex grass-shrub planting method	60–80	Relatively high	14.3–21.5	High	Relatively high	Medium
Sample plot III	CS higher-order granulation technology	50–80	Relatively high	12.9–22.9	High	Relatively high	Relatively high
Sample plot IV	Tape planting slope technology	40–70	Very high	10.0–17.2	High	Medium	Relatively high
Sample plot V	Building widening network method	60–80	High	15.8–22.9	Low	Low	High
Sample plot VI	Floating panels trenching method	60–80	High	12.9–21.5	Low	Relatively low	High
Sample plot VII	Vegetation concrete ecological protection technology	50–85	Relatively high	14.3–21.5	High	Relatively high	Medium

In addition, *Indigofera amblyantha* Craib, *Medicago sativa* Linn., *Indigofera pseudotinctoria* Matsum, *Festuca elata* Keng ex E. Alexeev, *Cynodon dactylon* (Linn.) Pers., and *Lolium perenne* Linn. had good growth in the ecological restoration projects from the perspective of species suitability, which played a role in quickly covering the slopes with the pioneer species. *Paspalum notatum* Flugge, *Rhus chinensis* Mill., *Robinia pseudoacacia* Linn., and several vines did not seem adaptable.

It can be concluded from the observational analysis of the seven technologies (Figure 2) that the applications of the TBS galvanized wire complex grass-shrub planting method, CS higher-order granulation technology, tape planting slope technology, and vegetation concrete ecological protection technology for the ecological restoration of quarry slopes in Caidian District were successful, which was worthy of further promotion. However, the soil spray-sowing technology easily collapsed in cases of heavy rain. Because of the complexity and difficulty of construction, as well as the low vegetation coverage and poor species diversity, the building widening network method and floating panels trenching method should be used with caution in later projects.

(**a**)

(**b**)

(**c**)

Figure 2. *Cont*.

Figure 2. The original appearance and restoration effect on the sample plots. (**a**) Sample plot I; (**b**) sample plot II; (**c**) sample plot III; (**d**) sample plot IV; (**e**) sample plot V; (**f**) sample plot VI; (**g**) sample plot VII.

3.2. Comprehensive Evaluation of the Ecological Restoration Effect Based on the Fuzzy AHP Method

3.2.1. Acquisition of Index Data

From June to July 2014, the data of the evaluation indexes for each sample plot were obtained by field investigation and sampling analysis, as shown in Table 6.

Table 6. The data of the evaluation indexes of ecological restoration of quarry slopes.

Index	The Data of Different Sample Plots						
	Sample Plot I	**Sample Plot II**	**Sample Plot III**	**Sample Plot IV**	**Sample Plot V**	**Sample Plot VI**	**Sample Plot VII**
Shearing strength of root-soil composite/(kPa)	39.82	50.26	54.36	58.79	35.28	49.85	75.66
Permeability/(mm·h^{-1})	17.15	15.25	21.36	29.86	19.82	14.26	26.87
Soil erosion intensity/(g·cm^{-3}·a^{-1})	33.87	34.26	28.35	11.56	22.58	29.65	17.26
Root weight density/(kg·m^{-3})	2.27	2.58	2.32	3.08	2.39	2.06	3.26
Vegetation coverage/%	30.51	86.36	90.28	97.27	35.06	48.36	95.55
Drought resistance of vegetation	Very poor	Normal	Good	Good	Very poor	Poor	Good
Shannon–Wiener diversity index	1.46	2.86	2.36	2.83	1.55	1.64	2.68
Pielou evenness index	0.65	0.95	0.83	0.95	0.7	0.68	0.86
Organic matter/(g·kg^{-1})	9.87	16.54	22.57	29.85	10.24	12.34	26.57
Available N/(mg·kg^{-1})	38.58	50.21	58.57	68.56	35.67	45.62	63.27
Available P/(mg·kg^{-1})	8.67	18.52	20.06	26.58	13.65	10.15	23.56
Available K/(mg·kg^{-1})	100.25	130.25	132.52	186.52	90.42	88.67	176.53
Soil bulk density/(g·cm^{-3})	2.6	2.06	2.12	1.32	2.65	2.31	1.38
Landscape coordination	Poor	Good	Good	Very good	Normal	Normal	Very good
Landscape capacity for visitors	Normal	Good	Normal	Good	Poor	Normal	Good

Note: The shearing strength of root-soil composite is under saturated conditions with a vertical pressure of 75 kPa.

3.2.2. Evaluation Results and Analysis

The comprehensive evaluation results of the sample plots can be obtained according to Equation (3) (Table 7). Based on the principle of maximum membership degree judgement, it can be concluded that the ecological restoration effects of the tape planting slope technology and vegetation concrete ecological protection technology were very good; the ecological restoration effects of the TBS galvanized wire complex grass-shrub planting method and CS higher-order granulation technology were good; the ecological restoration effect of the floating panels trenching method was normal; and the ecological restoration effects of the soil spray-sowing technology and building widening network method were poor. The quantitative evaluation results were consistent with the observational analysis results, which proved the effectiveness and applicability of the evaluation system.

Table 7. Evaluation results of ecological restoration of quarry slopes.

No.	v_1-Very Good	v_2-Good	v_3-Normal	v_4-Poor	v_5-Very Poor
Sample plot I	0.0000	0.0643	0.3129	0.3153	0.3074
Sample plot II	0.0332	0.3041	0.2489	0.2926	0.1212
Sample plot III	0.0000	0.3467	0.2289	0.2734	0.1510
Sample plot IV	0.6896	0.2999	0.0105	0.0000	0.0000
Sample plot V	0.0313	0.0107	0.1867	0.5263	0.2449
Sample plot VI	0.0072	0.2324	0.3848	0.3756	0.0000
Sample plot VII	0.5157	0.4620	0.0143	0.0080	0.0000

4. Discussion

4.1. Ecological Restoration Technologies and Effect Evaluation of Ecological Restoration for Quarry Slopes

4.1.1. Ecological Restoration Technologies for Quarry Slopes

The commonly used ecological restoration technologies for quarry slopes have not only improved the local ecological environment, but also formed a good landscape effect [28–30]. The frequency of disasters such as soil erosion and landslides has been significantly reduced in the ecologically restored areas [31]. Moreover, the efficient eco-industry model can promote the development of local economy and enhance the environmental protection awareness among the general public [32,33].

Based on the ecological restoration of quarry slopes in Caidian District, the applicability as well as the advantages and disadvantages of seven ecological restoration technologies were preliminarily clarified in this study. The applicability of other commonly used ecological restoration technologies and the physical and chemical properties of the habitat material have also been compared for the quarries in different regions [34–37]. On the basis of these research outcomes, the ecological restoration technologies suitable for different types of quarry slopes can be chosen, so as to realize the function of ecological restoration and protection for shallow layer of quarry slopes.

4.1.2. Effect Evaluation of Ecological Restoration for Quarry Slopes

The ecosystem constructed by the ecological restoration of quarry slopes can be regarded as the unity of the interaction between the habitat material, vegetation, and environment, which determines the stability and effect of the ecological restoration of slopes [38,39]. If the dynamic monitoring and comprehensive evaluation can be carried out on the ecological restoration of slopes, it could contribute to know the real-time effect of the ecological restoration of quarry slopes.

Many methods have been used to evaluate the effect of ecological restoration of quarries [10,40–42], however, most of them just focused on qualitative analysis. Compared with qualitative analysis, the follow-up manual regulation can be guided according to the evaluation results, so as to achieve the sustainable development of the ecosystem of quarry slopes. In order to comprehensively reflect the effect of ecological restoration of quarries, the comprehensive evaluation index system for effect of the ecological restoration of quarry slopes was established by using the fuzzy AHP method from four aspects in this study. By using the established evaluation system to quantitatively evaluate the effect of the ecological restoration of quarry slopes in Caidian District, it can provide theoretical and scientific basis for ecological construction and restoration countermeasures.

4.2. Existing Problems and Countermeasures

4.2.1. Existing Problems

According to the above evaluation results, the existing problems in the follow-up management of the ecological restoration of quarry slopes in Caidian District from the perspective of technology were analyzed. The existing problems mainly focus on the four aspects of stability of the habitat material, pioneer species, durability of some components, and maintenance management, as follows.

Insufficient stability of the habitat material: The lack of stability of the habitat material was mainly reflected in the weak adhesion between the habitat material layer and the slope surface, which led the habitat material to easily collapse under the action of rainfall. For example, compared with the CS higher-order granulation technology and vegetation concrete ecological protection technology, the mechanical properties of the soil spray-sowing technology had not been improved because it used a mixture of pure planting soil, fertilizer, and organic materials. According to the field investigation and sampling analysis, the shearing strength of root-soil composite of sample plot I by using the soil spray-sowing technology was only 39.82 kPa, while the shearing strength of root-soil composite of sample plot III by using the CS higher-order granulation technology and sample plot VII by using the vegetation concrete ecological protection technology was 54.36 kPa and 75.66 kPa. Therefore, a large area of the habitat material layer collapsed because of a rainstorm soon after the completion of sample plot I in July 2012. In addition, the ability of resisting rainfall and runoff erosion for the surface of sample plot I was also poor. In the initial stage without vegetation cover, soil erosion was easy to occur. Even if the vegetation covers the slope in the later stage, the thickness of the habitat material layer will become thinner with the passage of time, which makes it difficult to achieve long-lasting effect of ecological restoration.

Strong pioneer species: The species survey and monitoring of sample plots showed that a single vegetation community structure and the species diversity was poor, and a stable ecosystem with self-sustainability had not yet been formed. For example, the Shannon–Wiener diversity index of sample plot I by using the soil spray-sowing technology, sample plot V by using the building widening network method, and sample plot VI by using the floating panels trenching method was only 1.46, 1.55, and 1.64, respectively, which was significantly lower than those of the other sample plots. A stable ecosystem has a high species diversity and thus has a strong ability to adapt to changes in the external environment. Otherwise, even if the current vegetation coverage is high but the species diversity is low, the ecosystem is prone to degradation.

Poor durability of some components: Bamboo scaffolding was widely used in the floating panels trenching method. However, bamboo easily aged, and the steel wire used for tying also easily corroded. After the bamboo scaffolding was completed, it became unstable, and the vegetation coverage was reduced. Rebar was the main stress component of the planting platform. Some of the planting platforms had been damaged because of corrosion of the steel bars and reduction in mechanical properties, which influenced the effect of the ecological restoration.

Inadequate maintenance management: For the sample plot of the building widening network method, planting platforms were distributed sporadically, and irrigation systems were not set up separately, leading to planting platforms with low water conservation capacity. Because of the small scale of the planting platforms and the weakness of the self-sustainability of the ecosystem, the vegetation died.

4.2.2. Countermeasures and Suggestions

Based on the existing problems and the development of ecological restoration of quarry slopes, the following corresponding countermeasures and suggestions were proposed.

For the problem of insufficient stability of the habitat material, it is recommended to select habitat material with cement as the cementing material, which is appropriately mixed with plant fibers [17]. The cement can enhance the bonding force between the habitat material and the slope surface [43] and can improve the ability of the habitat material to resist erosion by rainfall and runoff, which is conducive to the successful adhesion of the habitat material on steep slopes. In addition, gouging and wetting flat rock slopes first is suggested to further enhance the bonding force between the slope surface and the habitat material.

For the problem of strong pioneer species, a reasonable matching of pioneer species and native species should be considered in the selection and allocation of mixed plant seeds [44,45]. Bush seeds that are pretreated and easily germinate can be properly configured. After the implementation of the project, it is recommended that performance tracking and regulation according to the succession of the vegetation community be carried out and that measures, such as removing some dominant species, transplanting competing species, and replanting shrubs, be taken.

For the problem of the poor durability of some components, selection of steel members after anti-corrosion treatment is recommended. Ageing materials, such as bamboo, should be avoided as structural members. The structural form should be optimized to ensure the sustainability of the ecological restoration projects of quarry slopes.

For the problem of inadequate maintenance management, the water demand for plant growth should be fully considered in the design and construction, and the storage and irrigation system should be reasonably established [46,47]. It is suggested that a water-saving micro-irrigation system in the form of drip irrigation be set up [48], especially for the characteristics of poor water conservation ability of the building widening network method. In addition, repair of the habitat material is an important part of maintenance management. If the habitat material collapses, repair measures should be taken in time to prevent geological disasters caused by accelerated weathering of bare slope surfaces.

Furthermore, scientific planning and mountain-friendly policies are necessary. Combined with the actual situation, the damaged mountain should be rationally developed and utilized according to local conditions [49–53]. First, it could be built into a landfill in areas where the gentle slopes can form a closed loop. For example, in the Qianzi Mountain of Caidian District, the excavation area is 200,000 m^2 at the bottom of the mountain and the depth is 50 m, and approximately 10 million m^3 of domestic garbage can be landfilled according to preliminary estimates. Second, combined with the tourism industry of Caidian District [33], many existing damaged rock slopes can be transformed into mine parks [54,55]. Third, the existing Yushun Mountain Cemetery and Weiwu Cemetery in Caidian District are connected to Jiangjia Mountain and Funiu Mountain, respectively. By combining the construction of the cemetery, the pressure on land resources brought about by the growth of the cemetery can be greatly alleviated.

5. Conclusions

A comprehensive evaluation index system from four aspects of the effect of habitat material improvement, the effect of ecology, the effect of soil and water conservation, and the effect of landscape was established. The ecological restoration effect of each sample plot was evaluated quantitatively based on the data of the evaluation indexes obtained by the field investigation and sampling analysis. The results show that the quantitative evaluation results obtained by the comprehensive evaluation system of ecological restoration are consistent with the observational analysis results, and the validity of the evaluation system is proven.

According to the observational analysis and the evaluation results, the existing problems in the follow-up management of the ecological restoration of quarry slopes in Caidian District were analyzed. The corresponding countermeasures and suggestions were proposed. Additionally, it may be considered to rely on the evaluation results to decide whether to carry out the follow-up manual regulation and specific regulation measures. Through the continuous monitoring of each index before and after the regulation, the comprehensive evaluation system of ecological restoration proposed in this study can be used to quantitatively evaluate the effect of manual regulation, which can achieve the sustainable development of the ecosystem of quarry slopes.

In the next step, the real-time evaluation results of ecological restoration projects should be taken into consideration to guide the formulation of subsequent regulatory schemes and the selection of regulatory opportunities. In addition, how to supplement and select indexes that can comprehensively and objectively reflect the effects of ecological restoration and establish a more perfect evaluation system needs further research.

Author Contributions: Conceptualization, Y.Y., D.L., and W.X.; data curation, D.L. and Y.D.; formal analysis, Y.Y. and H.X.; investigation, Y.Y., D.L., H.X., and D.X.; methodology, Y.Y., D.L., and J.C.; resources, Z.X.; writing—review and editing, Y.Y.

Funding: This study was supported by the CRSRI Open Research Program (Program SN: CKWV2019753/KY), the National Natural Science Foundation of the People's Republic of China (Grant Nos. 51708333, 51678348 and 41807068), the National Key R&D Program of China (Grant No. 2017YFC0504902-02), the Open Fund of the Key Laboratory of Geological Hazards on Three Gorges Reservoir Area (China Three Gorges University), Ministry of Education (Grant No. 2018KDZ11), the Natural Science Foundation of Hubei Province (Grant Nos. 2016CFA085 and 2017ACA189), the Open Fund of the Key Laboratory of Disaster Prevention and Mitigation, Hubei Province (Grant No. 2016KJZ13), the Open Fund of Key Laboratory of Mountain Hazards and Surface Processes, Chinese Academy of Sciences (Grant No. 2019001), the open fund of Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education (Grant No. KF2019-11).

Conflicts of Interest: The authors declare no conflict of interest.

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