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An Attempt to Evaluate the Green Construction of Large-Scale Hydropower Projects: Taking Wudongde Hydropower Station on the Jinsha River, China as an Example

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Abstract: Huge amounts of energy and resources will be consumed, and a large quantity of environmental pollutants will be produced during the construction process of large-scale hydropower projects. As a core link of green supply chain in hydropower projects, green construction is particularly critical. To objectively evaluate the green construction level of large-scale hydropower projects, an evaluation indicator system was constructed in the study. The evaluation system consisted of 30 quantitative indicators and 7 qualitative indicators from the perspectives of environmental protection, resource saving and comprehensive management on the basis of the construction characteristics of large-scale hydropower projects. The quantitative and qualitative evaluation standards were proposed by combining with relevant laws and regulations, specifications and standards, and the environmental management maturity model. Furthermore, taking the second quarter of 2018 in Wudongde Hydropower Station on the Jinsha River, China, as an example, green construction level was assessed by the analytic hierarchy process fuzzy comprehensive evaluation (AHP-FCE) method. The calculation results indicated that the evaluation value of green construction in Wudongde Hydropower Station was 3.697, at "Good" level. The evaluation values of environmental protection, resource saving, and comprehensive management were 3.681, 3.473, and 3.965, respectively, within the range of 3 to 4, so they were all evaluated to be "Good". To further improve the green construction level, it was necessary to supervise some aspects of construction process, i.e., treatment of waste slag in construction, economical and intensive utilization of land, publicity and training, soil erosion control, and saving water resources. In particular, management of soil erosion control should be strengthened. The proposed green construction evaluation system is relatively reliable and practical for professionals in the green hydropower industry, and can provide a reference for other large-scale hydropower projects.

Keywords: green construction; large-scale hydropower projects; AHP-FCE; Wudongde Hydropower Station

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1. Introduction

With rapid economic development and continuous environmental degradation, humans are more and more concerned about the environment and resources. The enterprises are being encouraged to develop sustainably, to reduce the damage to the environment and ecology. Therefore, the green supply chain management which refers to the system that reduces environmental pollution and improves the efficiency of resource utilization during firms' procurement, production, and emissions has been practiced in many industries, such business corporations, electrical and electronics industries, private corporations, retailing industries, etc. [1–6]. It can be concluded from practice that green supply chain management can improve resource efficiency, reduce environmental costs, expand market share,

protect a firm's corporate reputation, and provide companies with greater competitive advantage [7].

Engineering project construction is a human activity that consumes more natural resources, and has a great impact on the environment, resources, and ecology. Therefore, it is essential to implement green supply chain management in the construction of engineering projects. According to the life cycle process, the green supply chain of engineering projects includes green planning, green design, green construction, and green operation. Green construction is the realization stage of green planning and green design, the foundation of green operation, thus green construction is the core link for implementing green supply chain management of engineering projects.

However, despite advocation of green construction, there are many problems in the construction process, such as environmental pollution, huge energy consumption, unhealthy living environments of workers, and so on. Therefore, it is urgent to reasonably evaluate whether the project is green to ensure the sustainability of project construction. At present, the reports on green construction evaluation mainly focus on building projects [8–14], and various scholars have investigated materials, equipment, and methods used in green construction. Scholars in China have evaluated green construction in the engineering of houses, roads, bridges, deep foundation pits, and decoration [15–17]. Lee et al. [13] proposed an energy regeneration system (ERS) to reduce energy consumption required by operating a construction hoist and found that the average energy recovery reached 55.5% through prototype verification. Onubi et al. [14] studied a construction project's implementation of green practices in its site processes influenced its economic performance by meeting environmental performance standards. By testing 168 samples from construction projects completed by class A contractors in Nigeria, it was concluded that not all projects meeting the environmental performance standards would make economic profit. In the green construction, the contractor should be flexible and strive for a balance between environmental performance and economic performance. Zhang et al. [15] established a green construction comprehensive evaluation system of bridges in mountain areas and evaluated a bridge by the grey clustering method. Wang et al. [16] proposed an evaluation system for the green construction of railway subgrade working in north-western cold, arid regions and evaluated green construction levels of different construction schemes by TOPSIS method. However, there are few reports on the green construction evaluation of hydropower projects.

As a clean energy, hydropower provides a strong green power for the development of the national economy [18,19]. The construction of large-scale hydropower projects (the installed capacity exceeding 250,000 kW) is complex, necessitating a long period, and is subject to a wide range of influencing factors. A lot of energy and resources are consumed during construction, and many environmental pollutants, such as sewage, dust, and solid waste, are produced in the construction period [20]. Hence, green construction, the important measure to save resources and energy and protect environment, is the inevitable trend of hydropower industry development. Nevertheless, the green evaluation of hydropower projects mainly focused on the operation period [21], whereas no research was carried out to evaluate the green level during the construction period, especially for large-scale hydropower projects. Thus, establishing an objective and highly operable evaluation system and standard for green construction of large-scale hydropower projects is of practical significance to promote green management of the whole life cycle and improve resource saving and pollution reduction in the hydropower industry.

Therefore, according to the construction characteristics of Wudongde Hydropower Station, a representative large-scale hydropower station under construction in China, we established an evaluation indicator system for green construction in the study. Based on environmental monitoring at construction site and acquired data related to energy and resource consumption, the evaluation indicators were classified, and corresponding evaluation standards were proposed. The essence of the fuzzy comprehensive evaluation method (FCE) firstly presented by Zadeh [22,23] is to determine the value of an evaluation

objective element through the membership matrix and factor weightings. The fuzzy comprehensive evaluation method based on analytic hierarchy process (AHP-FCE) has been effectively applied in many fields, such as mineral prospecting and mapping [24], seawater desalination projects [25], geothermal extraction [26], and mine safety training [27]. Further, the AHP-FCE was introduced in green construction level evaluation of large-scale hydropower projects, and the second quarter of 2018 in Wudongde Hydropower Station was selected as an example. The evaluation results could provide an objective guideline for green construction management of the hydropower station.

2. Materials and Methods

2.1. Framework for Green Construction Assessment

The construction of the evaluation indicator system is crucial for multi-criteria analysis. Referring to the mature green construction evaluation system of building engineering which involved construction management, environmental protection, material saving and utilization of material resources, water conservation, and utilization of water resources, land saving and protection of construction land [28], relevant indicators for green construction of large-scale hydropower projects were identified mainly focusing on resource saving and environmental protection based on their construction characteristics. Although the construction management process for large-scale hydropower projects has many similarities with the building engineering, the construction management of hydropower projects involves a more complex social environment and a wider scope of management than building construction. Therefore, taking comprehensive management instead of construction management, three types of indicators were considered for green construction of large-scale hydropower projects, i.e., environmental protection, resource saving, and comprehensive management.

2.1.1. Environmental Protection

In accordance with the environmental impact factors in the construction process of large-scale hydropower projects, the environmental protection indicators cover many aspects, such as water, atmosphere, noise, solid waste, terrestrial organisms, aquatic organisms, and water and soil conservation. In the construction process, the impact of the above factors on environment is expected to be controlled after taking relevant measures, which are reflected as green.

2.1.2. Resource Saving

The construction process of large-scale hydropower projects such as earth and rock excavation and support, concrete production and pouring, grouting engineering and mechanical and electrical installation will consume a lot of energy and resources including steel, cement, sand, diesel, gasoline, electricity, and water. Meanwhile, the construction site of key projects in the large-scale hydropower project (buildings and the permanent management of key projects, stock yards, slag yards, construction enterprises, etc.) occupies a lot of land. How to optimize the construction scheme and layout during construction, reduce energy and resource utilization, strengthen recycling of various resources, and improve the utilization rate of energy and land, is also the embodiment of green engineering.

2.1.3. Comprehensive Management

According to the construction characteristics of large-scale hydropower projects, and based on the principle of full coverage without overlapping, comprehensive management mainly includes organizational management, implementation management, health management among personnel, and external supervision.

Organizational management is an institutional guarantee for smooth progress of the large-scale hydropower project. It is difficult to implement green construction under the disordered organizations. The "three-simultaneousness" system, a system enables the environmental protection facilities in the construction project to be designed, constructed,

and put into use simultaneously with the main project, complements the evaluation system for environmental impact. It is an important institutional guarantee of the effective implementation of pollution prevention and control measures.

Implementation management is designed to control green construction process. The rate of rectification of environmental problems reflects implementation of rectification the problems raised by the environmental regulators during construction, and it is an important symbol reflecting the maturity of the closed-loop plan–do–check act (PDCA) cycle pertaining to the project. A wide range of knowledge about environmental protection is required in the construction area of hydropower projects. As the field management personnel mainly major in hydraulic engineering, metal structures, and geology, they do not know enough about the environmental protection characteristics in hydropower projects. Through field investigation, it is found that some construction management personnel are aware of the importance of environmental protection, whereas they do not know how to do. Therefore, it is necessary to conduct publicity and training to improve the awareness of environmental protection of management personnel. The construction of large-scale hydropower projects may increase the surrounding environmental risks. However, based on environmental risk prevention and emergency management measures, the environmental risk status of the project itself can be mastered and reasonable and feasible prevention, emergency and mitigation measures can be proposed, people's lives and security of property in the construction area and its surroundings can be protected.

Health management of personnel embodies the "people-oriented" concept in green construction. There are many construction personnel gathered in the construction process. If the management of sanitation and epidemic prevention, and hygiene of drinking water is not strengthened, infectious diseases are likely to be spread. In the meanwhile, construction personnel from different regions may bring pathogens from their places of residence and infect each other. If prevention and quarantine measures are not strengthened, disease may be prevalent. In addition, a large-scale hydropower project carries a high construction safety risk and comes with poor environmental conditions, such as construction dust and noise. Therefore, it is particularly important to strengthen the safety and occupational health of construction personnel.

External supervision is an external guarantee of green construction. Supervision by government departments can urge construction units to implement various environmental protection measures, and the relationship with the residents around the construction site can reflect the impact of the construction process on the surrounding environment.

Therefore, the evaluation indicator system for the green construction of large-scale hydropower projects was constructed (Figure 1). The evaluation system contained three rule layer indicators that Environmental protection D, Resource saving E, Comprehensive management F, 16 classification layer indicators of the water environment D_1, Ground water environment D_2, Organizational management F_1, Implementation management F_2, Material Utilization E_1, Utilization of water resources E_2, etc., and 37 indicator layer indicators that Treatment of production wastewater D_{11}, Treatment of domestic sewage D_{12}, Control of production water consumption E_{21}, etc.

2.2. Standards for Evaluation Indicators

The indicator layer indicators in Figure 1 were classified into quantitative and qualitative indicators. Among the 37 indicators, D_{51}, D_{52}, D_{61}, D_{62}, D_{71}, E_{11}, F_{11}, F_{12}, F_{21}, and F_{23} were qualitative, and the others were quantitative. The quantitative indicators were calculated based on monitoring data or relevant statistical data of approved energy and resource consumption, and the evaluation standards referred to relevant national laws, regulations, specifications, and standards, and the literature of Ye in 2012 [29]. The standards for evaluation grades of qualitative indicators are listed in Table 1. Because the qualitative indicators cannot be quantified, the evaluation mainly depends on subjective judgment, so we adopted the maturity levels of environmental management for judgement in the study [30].

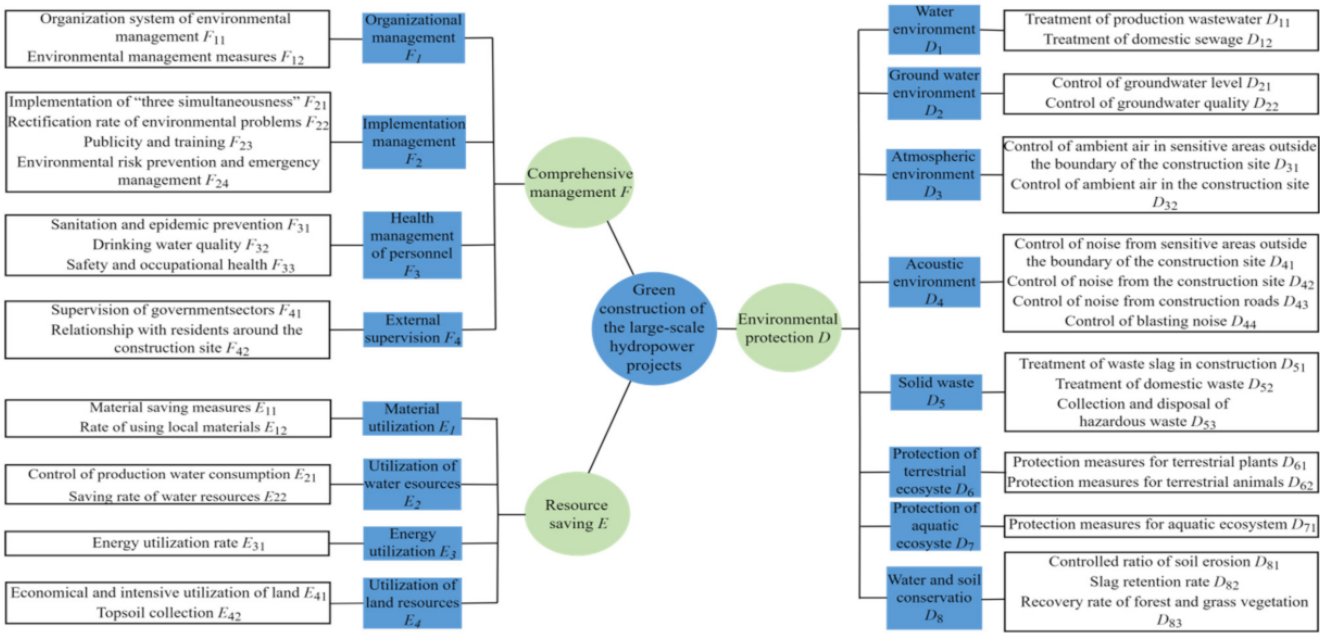


Figure 1. The evaluation system for green construction of large-scale hydropower projects.

2.2.1. Classification Standard for Quantitative Indicators

The five grades describing "Better, Good, Medium, Poor, and Worse" environmental management correspond to the following score ranges of evaluation values: (4, 5], (3, 4], (2, 3], (1, 2], and (0, 1]. The evaluation indicators contained in water environment D_1, groundwater environment D_2, atmospheric environment D_3 and acoustic environment D_4, etc., were generally monitored at multiple sites. Based on the cask theory [30], monitoring sites whose indicators all meet the standard were evaluated as "Better", with the score of 5. For those whose indicators exceeded the standard, they were evaluated as "Worse" and assigned a score of 1. By weighting treatment capacity designed for each pollution source or the number of monitoring sites, the values of indicators were calculated, namely evaluation values in this case. For the evaluation indicators, such as Collection and disposal of hazardous waste D_{53} and Rate of using local materials E_{12}, their values were firstly calculated according to evaluation standards and then converted to the evaluation values by interpolation method.

2.2.2. Classification Standard for Qualitative Indicators

The classification standard of qualitative indicators refers to the environmental management maturity level. The environmental management maturity which reflects the attitude and ability of enterprises to deal with environmental issues can reflect which environmental management level that a construction project reaches [30–33]. According to the project management maturity model [32], a development maturity of 5 levels was constructed, namely "Disordered", "Simple", "Standard", "Improved", and "Lean" levels (Table 2). The maturity was measured using five grades, being "Better", "Good", "Medium", "Poor", and "Worse".

Table 1. Evaluation standards of quantitative indicators for green construction of large-scale hydropower projects.

Classification Layer	Indicator Layer	Evaluation Method and Standard	Better	Good	Medium	Poor	Worse
Water environment D_1	Treatment of production wastewater D_{11}	Integrated Wastewater Discharge Standard or recycling without discharging	Meeting	/	/	/	Exceeding
	Treatment of domestic sewage D_{12}		Meeting	/	/	/	Exceeding
Groundwater environment D_2	Control of groundwater level D_{21}	No impact of cavern excavation on groundwater or surface water	Yes	/	/	/	No
	Control of groundwater quality D_{22}	Quality Standard for Groundwater	Meeting	/	/	/	Exceeding
Atmospheric environment D_3	Control of ambient air in sensitive areas outside the boundary of the construction site D_{31}	Ambient Air Quality Standards	Meeting	/	/	/	Exceeding
	Control of ambient air in the construction site D_{32}		Meeting	/	/	/	Exceeding
Acoustic environment D_4	Control of noise from sensitive areas outside the boundary of the construction site D_{41}	Environmental Quality Standard for Noise	Meeting	/	/	/	Exceeding
	Control of noise from the construction site D_{42}	Emission Standard of Environment Noise for Boundary of Construction Site	Meeting	/	/	/	Exceeding
	Control of noise from construction roads D_{43}		Meeting	/	/	/	Exceeding
	Control of blasting noise D_{44}	The blasting time in summer and winter shall be strictly within the specified time (blasting at night is strictly prohibited)	Yes	/	/	/	No
Solid waste D_5	Collection and disposal of hazardous waste D_{53}	Standardized Management indicator System of Hazardous Waste (No. 99 of the General Office of the Ministry of Environmental Protection in 2015)	55	50~55	43~50	33~43	<32
Water and soil conservation D_8	Controlled ratio of soil erosion D_{81}	Control Standards for Soil and Water Loss on Development and Construction Projects	≥0.7	/	/	/	<0.7
	Slag retention rate D_{82}		≥95%	/	/	/	<95%
	Recovery rate of forest and grass vegetation D_{83}		≥80%	80~60%	60~0%	40~20%	<20%
Material utilization E_1	Rate of using local materials E_{12}	Proportion of building materials that are produced within 500 km of the construction site in the total consumption of building materials (%)	≥70%	70~50%	50~40%	40~20%	<20%
Utilization of water resources E_2	Control of production water consumption E_{21}	Ratio of water consumption indicator per unit gross domestic product (GDP) to national average	≤60%	60~80%	80~120%	120~150%	≥150%
	Saving rate of water resources E_{22}	Ratio of amount of recycled wastewater to water consumption	≥90%	90~70%	70~50%	50~30%	<30%

Table 1. *Cont.*

Classification Layer	Indicator Layer	Evaluation Method and Standard	Better	Good	Medium	Poor	Worse
Energy utilization E_3	Energy utilization rate E_{31}	Ratio of the comprehensive energy consumption indicator of the project to the comprehensive energy consumption indicator of GDP formulated by the central or local governments	≤60%	60~80%	80~120%	120~150%	≥150%
Utilization of land resources E_4	Economical and intensive utilization of land E_{41}	Ratio of GDP per unit construction land to national average	≤60%	60~80%	80~120%	120~150%	≥150%
	Topsoil collection E_{42}	Ratio of collected topsoil to that required in the Report for Soil and Water Conservation Plan	≥90%	90~70%	70~50%	50~30%	<30%
Implementation management F_2	Rectification rate of environmental problems F_{22}	Rectification and solving rate of problems found on site	100%	100~90%	90~70%	70~50%	<30%
	Environmental risk prevention and emergency management F_{24}	Whether the environmental emergency plan has been filed and drilled on site?	Yes	/	/	/	No
Health management of personnel F_3	Sanitation and epidemic prevention F_{31}	Whether there are infectious diseases and endemic diseases induced by environmental changes caused by the project and whether there are cross-infections or epidemic infectious diseases due to poor living and sanitary conditions?	No	/	/	/	Yes
	Drinking water quality F_{32}	Standards for Drinking Water Quality	Yes	/	/	/	No
	Safety and occupational health F_{33}	Standardization of Safety Production of Power Engineering Construction Projects and Rating Standard (No. 247 document of South China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China in 2012)	≥90	90~80	80~70	70~60	<30
External supervision F_4	Supervision of government sectors F_{41}	Whether the problems found by government supervision are rectified in time as required?	Yes	/	/	/	No
	Relationship with residents around the construction site F_{42}	Whether smooth communication and problem-solving channels are established, and whether complaints are handled timeously?	Yes	/	/	/	No

Table 2. The characteristics of environmental management maturity levels.

Maturity Level	Score	Grade	Main Characteristics
Disordered	0~1	Worse	The project is completely economic-interest-oriented, without awareness of environmental management.
Simple	1~2	Poor	With the awareness of environmental management, the impact on the ecological environment is only considered in theoretical analysis while being applied less in implementation and evaluation.
Standard	2~3	Medium	The influence on the ecological environment is assessed and appropriate countermeasures are taken according to standards during the construction of the project. Moreover, the environmental benefits of the project are well considered.
Improved	3~4	Good	The ecological environment factors are profoundly analyzed qualitatively and quantitatively, and corresponding measures are taken in each stage of implementation.
Lean	4~5	Better	Environmental management means is constantly improved and optimized, and the goal of ecological and environmental protection is achieved at an appropriate cost to the economic benefits.

The qualitative indicators were scored by the expert scoring method based on the environmental management maturity levels. The expert group (number m) evaluated the qualitative indicators according to the maturity levels: (0, 1] refers to "Disordered" maturity level and the maximum value is $N_1 = 1$; (1, 2] indicates the "Simple" maturity level and the maximum value is $N_2 = 2$. In a similar fashion, the maximum value is recorded as N_i. The number of votes of the expert group on the indicator A_{ij} at the ith level is N_j ($0 \leq j \leq m$). According to Equation (1), the values of qualitative indicators were calculated, because the maturity level was consistent with the division of grades; therefore, the calculated values were the evaluation values.

$$X_{ij} = \frac{\sum_{i=1}^{5} (N_i \times N_j)}{m} (i = 1,2,3,4,5;\ 0 \leq j \leq m) \quad (1)$$

2.3. AHP-FCE Method

The analytic hierarchy process fuzzy comprehensive evaluation method (AHP-FCE) is a comprehensive evaluation method based on fuzzy mathematics. A flowchart through the integrated AHP-FCE method procedure is depicted in Figure 2, and the basic steps can be summarized as follows:

Step 1. Construct a fuzzy membership matrix of evaluation indicators.

According to the original values of indicators $U = (u_1, u_2, \ldots, u_n)$ (n represents the number of indicators) and the classification standard, an evaluation matrix was calculated based on the membership function.

$$R = \begin{vmatrix} r_{11} & \cdots & r_{15} \\ \vdots & r_{ij} & \vdots \\ r_{n1} & \cdots & r_{n5} \end{vmatrix} \quad (2)$$

where r_{ij} is the membership degree that the i-th indicator belongs to the j-th evaluation grades. The membership function R was established to depict the membership degree of evaluation factors to certain evaluation grades through certain functional operation

to visualize the original fuzzy mathematical concept. According to the thresholds of evaluation standards as inflection points, a linear membership function was built by using the lower semi-trapezoid method (Table 3).

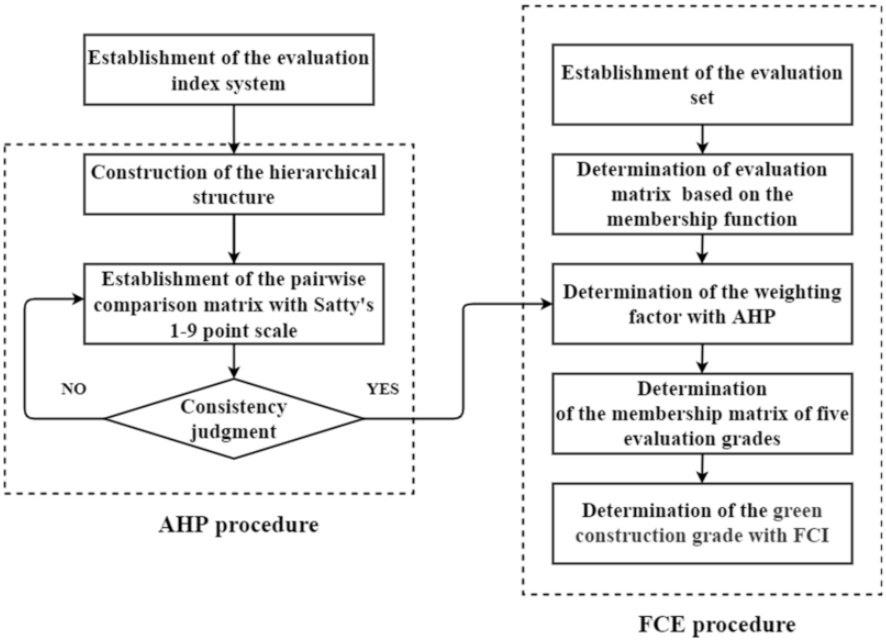


Figure 2. Flowchart through the integrated AHP-FCE process.

Table 3. The calculation of membership degrees.

x_i Interval	Calculation of Membership Degrees in Different Intervals				
	5	**4**	**3**	**2**	**1**
$x_i > c_5$	1	0	0	0	0
$c_4 < x_i \leq c_5$	$(x_i - c_4)/(c_5 - c_4)$	$(c_5 - x_i)/(c_5 - c_4)$	0	0	0
$c_3 < x_i \leq c_4$	0	$(x_i - c_3)/(c_4 - c_3)$	$(c_4 - x_i)/(c_4 - c_3)$	0	0
$c_2 < x_i \leq c_3$	0	0	$(x_i - c_2)/(c_3 - c_2)$	$(c_3 - x_i)/(c_3 - c_2)$	0
$c_1 < x_i \leq c_2$	0	0	0	$(x_i - c_1)/(c_2 - c_1)$	$(c_2 - x_i)/(c_2 - c_1)$
$c_0 < x_i \leq c_1$	0	0	0	0	1

Notes: x_i indicates the evaluated value; c_i represents the inflection point of the corresponding evaluation intervals (4, 5], (3, 4], (2, 3], (1, 2], and (0, 1].

Step 2. Weight of each indicator was calculated using the AHP method

The analytic hierarchy process (AHP) established by Saaty is a decision-making method combined qualitative and quantitative assessments [4,34,35]. The process is explained below. To evaluate the weight of each indicator, a pair-wise comparison matrix was formed as follows:

$$A = (P_{ij})_{n \times n} \begin{vmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{vmatrix} \quad (3)$$

where P_{ij} is the relative importance value of indicator i in comparison with indicator j, calculated by Satty's 1–9 points scale [34,36]. $P_{ij} > 0$ and $P_{ij} \times P_{ji} = 1$.

In the next step, the elements of matrix A were normalized using Equation (4).

$$P_{ij}{}^{*} = \frac{P_{ij}}{\sum_{j=1}^{n} P_{kj}} \forall i \xi j = 1, 2, \cdots, n \quad (4)$$

To obtain the relative importance of each criterion, Equation (5) was applied.

$$w_i{}^* = \sum_{j=1}^{n} P_{ij}{}^* \ \forall i = 1, 2, \cdots, n \tag{5}$$

In the fourth step, the criteria weight vector, $w = (w_1, w_2, \ldots, w_n)$ was calculated using Equation (6):

$$w_i = \frac{w_i{}^*}{\sum\limits_{k=1}^{n} w_k{}^*} \ \forall i = 1, 2, \cdots, n \tag{6}$$

To determine the reliability of compaction performed between criteria in each branch of the hierarchy tree, the consistency rate CR presented in Equation (7) has to be examined. If CR < 0.1, it means that the judgement matrix exhibits good consistency, otherwise the elemental values thereof should be adjusted.

$$CR = \frac{CI}{RI} \tag{7}$$

where *CI* is the consistency indicator calculated by Equation (8).

$$CI = \frac{\xi_{max} - n}{n - 1} \tag{8}$$

where λ_{max} (the maximum eigenvalue) is calculated by using Equation (9):

$$\xi_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(pw)_i}{w_i} \tag{9}$$

where *RI* in Equation (7) is a random indicator. The value of *RI*, changing with variations in the dimensions, is given in Table 4.

Table 4. *RI* values.

Dimension	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Step 3. Based on the weight vector w and evaluation matrix R, FCE was conducted.

$$B = w \cdot R = (w_1, w_2, \cdots, w_n) \cdot \begin{vmatrix} r_{11} & \ldots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \ldots & r_{\mathrm{n5}} \end{vmatrix} = (b_1, b_2, \cdots b_n) \tag{10}$$

where B indicates the membership matrix of five evaluation grades. The calculated result for evaluation is shown as follows:

$$FCI = B \cdot S = (b_1, b_2, \cdots b_n) \cdot \begin{vmatrix} 5 & 4 & 3 & 2 & 1 \end{vmatrix}^{-1} \tag{11}$$

where S represents the vector of evaluation standards, *FCI* indicates the fuzzy comprehensive result. $FCI \leq 1$, $1 < FCI \leq 2$, $2 < FCI \leq 3$, $3 < FCI \leq 4$, and $4 < FCI$ represent green construction with "Worse, Poor, Medium, Good, and Better" evaluation results, respectively.

3. Results and Discussions

3.1. Case Analysis

Wudongde Hydropower Station, the most upstream among the four cascade hydropower stations (Wudongde, Baihetan, Xiluodu, and Xiangjiaba) in the lower reaches of the Jinsha River, China, has a normal storage level of 975 m and installed capacity of 10, 200 MW. Moreover, the annual average power generation is 3.891 × 1010 kW·h, and the maximum dam height is 270 m. The hydropower station ranking seventh in the world in terms of installed capacity is mainly responsible for power generation and takes into consideration of flood control, shipping, and promotion of local economic and social development. Due to the large scale of Wudongde Hydropower Station, green construction can save a lot of resources and protect the ecological environment.

The second quarter of 2018 was the construction peak period for Wudongde Hydropower Station. Various environmental protection measures were under construction or operation, and the indicators were relatively complete and representative. Thus, the green construction level of Wudongde Hydropower Station in the second quarter of 2018 was evaluated.

3.2. Evaluation Values of Indicators for Green Construction

Quantitative indicators were calculated according to monitoring reports and construction statistics of Wudongde Hydropower Station in the second quarter of 2018. For qualitative indicators, fifteen engineers familiar with the site conditions from the building, design, environmental supervision, environmental impact assessment, supervision, and construction units were selected to score maturity, and then the value of each indicator was calculated according to Equation (1). The evaluation value between (0, 5] of each indicator is summarised in Table 5.

Table 5. Calculation and evaluation values of each indicator for green construction assessment of Wudongde Hydropower Station.

Indicator	D_{11}	D_{12}	D_{21}	D_{22}	D_{31}	D_{32}	D_{41}	D_{42}	D_{43}	D_{44}
Calculation value	4.83	3.71	5	5	5	3	3.67	3.67	5	5
Evaluation value	4.83	3.71	5	5	5	3	3.67	3.67	5	5
Indicator	D_{51}	D_{52}	D_{53}	D_{61}	D_{62}	D_{71}	D_{81}	D_{82}	D_{83}	E_{11}
Calculation value	2.16	3	38	2.5	3	3	0.62	97.16%	87.77%	3.16
Evaluation value	2.16	3	2.5	2.5	3	3	1	5	5	3.16
Indicator	E_{12}	E_{21}	E_{22}	E_{31}	E_{41}	E_{42}	F_{11}	F_{12}	F_{21}	F_{22}
Calculation value	0.74	110.08%	24%	0.407	102.82%	88.22%	4.33	4.33	2.66	71.43%
Evaluation value	5	2.75	1	5	2.43	4.911	4.33	4.33	2.66	2.072
Indicator	F_{23}	F_{24}	F_{31}	F_{32}	F_{33}	F_{41}	F_{42}			
Calculation value	2.33	5	5	5	96.6	5	5			
Evaluation value	2.33	5	5	5	5	5	5			

3.3. Comprehensive Evaluation of Green Construction

3.3.1. Determination of Indicator Weight

In accordance with the indicator system for green construction established in Figure 1, indicators in the rule, classification and indicator layers were scored in pairs by six engineers familiar with the site conditions from the building, design, environmental supervision, environmental impact assessment, supervision, and construction units. For example, in the indicator layer, the relative importance of the controlled ratio of soil erosion D_{81}, slag

retention rate D_{82}, and recovery rate of forest and grass vegetation D_{83} were measured by the expert scoring method, and the pair-wise judgment matrix was constructed as follows

$$A = \begin{vmatrix} 1 & 4 & 1 \\ 0.25 & 1 & 0.25 \\ 1 & 4 & 1 \end{vmatrix} \quad (12)$$

It was obvious to find that D_{81} and D_{83} were more relatively important than D_{82}. According to Equations (4)–(6), the weight coefficients of D_{81}, D_{82}, and D_{83} were calculated as 0.444, 0.112, and 0.444, respectively. Then, the maximum eigenvalue λ_{max}, the consistency indicator CI, and the consistency rate CR was calculated according to Equations (7)–(9), that $\lambda_{max} = 3$, $CI = -4.4409 \times 10^{-16}$, $RI = 0.58$, $CR = -8.6248 \times 10^{-16}$. Since $CR < 0.1$, the judgment matrix of the indicator layer had complete consistency. Similarly, the weight coefficients of the indicator layer, classification layer and rule layer indicators were calculated, which all passed the consistency test. The final weight of each indicator relative to the overall objective was determined and illustrated in Table 6.

Table 6. Weight of each indicator for green construction of large-scale hydropower projects.

Rule Layer	Weight	Classification Layer	Weight	Indicator Layer	Weight	Final Weight	Ranking
D	0.667	D_1	0.239	D_{11}	0.667	0.106	1
				D_{12}	0.333	0.053	4
		D_2	0.089	D_{21}	0.750	0.045	5
				D_{22}	0.250	0.015	24
		D_3	0.089	D_{31}	0.500	0.030	14
				D_{32}	0.500	0.030	15
		D_4	0.089	D_{41}	0.300	0.018	20
				D_{42}	0.300	0.018	21
				D_{43}	0.300	0.018	22
				D_{44}	0.100	0.006	36
		D_5	0.171	D_{51}	0.333	0.038	8
				D_{52}	0.333	0.038	9
				D_{53}	0.333	0.038	10
		D_6	0.042	D_{61}	0.800	0.022	19
				D_{62}	0.200	0.006	37
		D_7	0.042	D_{71}	1.000	0.028	16
		D_8	0.239	D_{81}	0.444	0.071	2
				D_{82}	0.111	0.018	23
				D_{83}	0.444	0.071	3
E	0.167	E_1	0.250	E_{11}	0.800	0.033	11
				E_{12}	0.200	0.008	34
		E_2	0.250	E_{21}	0.750	0.031	12
				E_{22}	0.250	0.010	25
		E_3	0.250	E_{31}	1.000	0.042	7
		E_4	0.250	E_{41}	0.750	0.031	13
				E_{42}	0.250	0.010	26
F	0.167	F_1	0.190	F_{11}	0.750	0.024	18
				F_{12}	0.250	0.008	35
		F_2	0.420	F_{21}	0.625	0.044	6
				F_{22}	0.125	0.009	31
				F_{23}	0.125	0.009	32
				F_{24}	0.125	0.009	33
		F_3	0.269	F_{31}	0.200	0.009	29
				F_{32}	0.200	0.009	30
				F_{33}	0.600	0.027	17
		F_4	0.210	F_{41}	0.500	0.010	27
				F_{42}	0.500	0.010	28

The indicator weight implies the influence degree of the indicator on the evaluation results of green construction. The indicators ranked in the top ten according to the weight values were as follows: treatment of production wastewater (D_{11}), controlled ratio of soil erosion (D_{81}), recovery rate of forest and grass vegetation (D_{83}), treatment of domestic sewage (D_{12}), control of groundwater level (D_{21}), implementation of "three simultaneousness" (F_{21}), and energy utilization rate (E_{31}), as well as treatment of waste slag in construction (D_{51}), disposal of domestic waste (D_{52}), and collection and disposal of hazardous waste (D_{53}) which had the same weight. It could be concluded that construction wastewater, water and soil conservation, and treatment of solid waste were closely related to green construction of the large-scale hydropower projects, which confirmed to the nature of their environmental impact during construction period.

3.3.2. Comprehensive Evaluation

Firstly, the membership degrees of the indicator layer indicators were obtained according to their evaluation values. For example, the evaluation values of D_{11} and D_{12} were 4.83 and 3.71, respectively, so the membership matrix were $\begin{vmatrix} 0.83 & 0.17 & 0 & 0 & 0 \\ 0 & 0.71 & 0.29 & 0 & 0 \end{vmatrix}$. Since the weights of D_{11} and D_{12} were $\begin{vmatrix} 0.667 & 0.333 \end{vmatrix}$, the evaluation value FCI of the classification layer indicator water environment D_1 corresponding to D_{11} and D_{12} was $\begin{vmatrix} 0.667 & 0.333 \end{vmatrix} \times \begin{vmatrix} 0.83 & 0.17 & 0 & 0 & 0 \\ 0 & 0.71 & 0.29 & 0 & 0 \end{vmatrix} \times \begin{vmatrix} 5 & 4 & 3 & 2 & 1 \end{vmatrix}^{-1} = 4.457$. The evaluation values of classification layer indicators were calculated according to the corresponding indicator layer indicators evaluation values and weights, and the membership degrees of classification layer indicators were obtained (Table 7).

Table 7. The evaluation values and membership degrees of the classification layer indicators for green construction.

Classification Layer Indicator	Evaluation Value	5	4	3	2	1
Water environment D_1	4.457	0.457	0.543	0	0	0
Groundwater environment D_2	5.000	1	0	0	0	0
Atmospheric environment D_3	4.000	0	1	0	0	0
Acoustic environment D_4	4.202	0.202	0.798	0	0	0
Solid waste D_5	2.551	0	0	0.551	0.449	0
Protection of terrestrial ecosystem D_6	2.600	0	0	0.600	0.400	0
Protection of aquatic ecosystem D_7	3.000	0	0	1.000	0	0
Water and soil conservation D_8	3.219	0	0.219	0.781	0	0
Material utilization E_1	3.528	0	0.528	0.472	0	0
Utilization of water resources E_2	2.313	0	0	0.313	0.687	0
Energy utilization E_3	5.000	1	0	0	0	0
Utilization of land resources E_4	3.050	0	0.050	0.950	0	0
Organizational management F_1	4.330	0.330	0.670	0	0	0
Implementation management F_2	2.838	0	0	0.838	0.162	0
Health management of personnel F_3	5.000	1	0	0	0	0
External supervision F_4	5.000	1	0	0	0	0

Similarly, the evaluation values and membership degrees of the rule layer indicators for green construction could be calculated, and the results are demonstrated in Table 8. The evaluation values of environmental protection D, resource saving E, and comprehensive management F were 3.681, 3.473 and 3.965, respectively. In accordance with the membership degrees of the rule layer indicators in Table 8 and the weights of the rule layer indicators, FCE was conducted such that B = (0, 0.694, 0.307, 0, 0) according to Equation (3). By using Equation (4), the fuzzy evaluation result of the green construction level was calculated as FCI = 3.697.

Table 8. The evaluation values and membership degrees of the rule layer indicators for green construction.

Rule Layer Indicator	Evaluation Value	5	4	3	2	1
Environmental protection *D*	3.681	0	0.681	0.319	0	0
Resource saving *E*	3.473	0	0.473	0.527	0	0
Comprehensive management *F*	3.965	0	0.965	0.035	0	0

3.4. Analysis of Evaluation Results

3.4.1. Evaluation Results

According to the standards for evaluation grades of green construction, the green construction level of Wudongde Hydropower Station in the second quarter of 2018 was deemed to be "Good". The evaluation values of Environmental protection D, Resource saving E, and Comprehensive management F in the rule layer were 3.681, 3.473, and 3.965, within the range of 3 to 4, thus they were evaluated to be "Good".

For indicators in the classification layer, the evaluation values of water environment D_1, groundwater environment D_2, acoustic environment D_4, energy utilization E_3, organizational management F_1, health management of personnel F_3 and external supervision F_4 were between 4 and 5, at the "Better" grade. Of them, the evaluation values of groundwater environment D_2, energy utilization E_4, health management of personnel F_3, and external supervision F_4 reached 5. Atmospheric environment D_3, water and soil conservation D_8, material utilization E_1, and utilization of land resources E_4 were scored between 3 and 4, at the "Good" grade, of which the evaluation value of atmospheric environment D_3 reached 4. In addition, the evaluation values of solid waste D_5, protection of terrestrial ecosystem D_6, protection of aquatic ecosystem D_7, utilization of water resources E_2, utilization of land resources E_4, and implementation management F_2 were scored between 2 and 3, at the "Medium" grade (the score for protection of aquatic ecosystem D_7 reached 3).

In the indicator layer, the evaluation values of the controlled ratio of soil erosion D_{81} and Saving rate of water resources E_{22} were 1, indicating that they were deemed to be "Worse". The evaluation values of control of ambient air in the construction site D_{32}, treatment of waste slag in construction D_{51}, treatment of domestic waste D_{52}, collection and disposal of hazardous waste D_{53}, protection measures for terrestrial plants D_{61}, protection measures for terrestrial animals D_{62}, protection measures for aquatic ecosystem D_{71}, control of production water consumption E_{21}, economical and intensive utilization of land E_{41}, implementation of "three simultaneousness" F_{21}, rectification rate of environmental problems F_{22}, and publicity and training F_{23} were found in the range of 2–3, at the "Medium" grade. The evaluation values of the other 23 indicators were greater than 3, which were evaluated above the level of "Good". There were 15 indicators with evaluations of 5, at the "Better" level, i.e., control of groundwater level D_{21}, control of groundwater quality D_{22}, and control of ambient air in sensitive areas outside the boundary of the construction site D_{31}.

In the indicators ranked in the top ten by weight values, the treatment of production wastewater D_{11} (first), control of groundwater level D_{22} (fifth), recovery rate of forest and grass vegetation D_{83} (third), and energy utilization rate E_{31} (seventh) were at the "Better" grade. The treatment of domestic sewage D_{12} (fourth) belonged to the "Good" grade. The treatment of waste slag in construction D_{51} (eighth), treatment of domestic waste D_{52} (ninth), collection and disposal of hazardous waste D_{53} (tenth) and Implementation of "three simultaneousness" (sixth) were found at the "Medium" grade, of which the evaluation value of treatment of waste slag in construction D_{51} approached 2, at the "Poor" grade. The controlled ratio of soil erosion D_{81} (second) was evaluated as "Worse".

3.4.2. Application of Evaluation Results

Based on the above analysis, the controlled ratio of soil erosion, saving rate of water resources, treatment of waste slag in construction, treatment of domestic waste, collection

and disposal of hazardous waste, and implementation of "three simultaneousness" should be well managed in the next stage of the project construction.

For the controlled ratio of soil erosion, the focus was to strengthen control, and consistent with the main project, the bare ground should be afforested and improved timeously, thus further undue soil erosion should be avoided. As for the saving rate of water resources, in this stage, it was necessary to strengthen recovery and utilization of reclaimed water, and water used for aggregate mixing, and for pouring and cooling dam concrete (each of which entails significant water consumption). Meanwhile, water saving measures should be promulgated and economic measures should be adopted in the construction site to encourage the construction unit to save water. In the treatment of water slag in construction, it was necessary to strengthen management of slag-transporting trucks, require the waste slag to be transported to the designated slag yard, and prohibit littering and dumping along both sides of the road. Otherwise, slag-transporting trucks shall be paid, and penalties shall be imposed on them. Meanwhile, in the slag yard, slag should be stockpiled according to the design requirements and protected timeously. In the treatment of domestic waste, refuse bins should be increased in each area of the construction site, and the waste should be classified for recycling. At the same time, domestic waste should be transported to a designated landfill according to the requirements of clearing waste on the same day of its production, thus avoiding its accumulation. The collection and disposal of hazardous waste should mainly focus on the management of waste engine oil in the construction site. Discarded waste engine oil should be collected in a storage for hazardous waste, and the corresponding protection and records should be kept. When managing implementation of "three simultaneousness", the environmental protection measures should be deconstructed, and a progress plan should be prepared. The process control should be strengthened using progress management software, such as Oracle Primavera P6. In addition, it was necessary to make continuous improvements and take effective optimisation steps to ensure that each measure was designed, constructed, and implemented simultaneously across the main project.

With the development of green construction evaluation in engineering projects, the study contributed to construct the green construction evaluation indicator system of large-scale hydropower projects. The evaluation indicator system used in the study was proposed by combining with the actual engineering construction situations, which can provide reference for other hydropower projects. Nevertheless, there are some differences in the geographical location and construction conditions of different hydropower stations. Although the evaluation indicator system constructed in our study can provide reference for the green construction evaluation of other hydropower stations, it was suggested that more in-depth studies be undertaken according to the actual influence range and construction conditions of projects, so that the evaluation system will become more rational and widely applicable. Aside from the AHP fuzzy comprehensive evaluation method, there are many other evaluation methods, such as set pair analysis and artificial neural network evaluation methods, which should be mutually verified in future research.

4. Conclusions

The green construction assessment of large-scale hydropower projects was to objectively evaluate the construction influence on energy, resource consumption and the environment. The overall standard is designed to minimize the negative influence in the construction process and protect the environment. At present, the green construction evaluation indicator system of large-scale hydropower projects is lacking. Therefore, in the study, an evaluation system containing 37 indicators for green construction of large-scale hydropower projects was proposed regarding environmental protection, resource saving, and comprehensive management. The fuzzy comprehensive evaluation method based on analytic hierarchy process (AHP-FCE) widely used in multi-indicator and multi-level complex evaluations was employed to evaluate the green construction level. Furthermore,

the green construction level evaluation was performed by taking the second quarter of 2018 in Wudongde Hydropower Station on Jinsha River as an example.

The result of weight calculation by AHP method was that the treatment of production wastewater (D_{11}), the controlled ratio of soil erosion (D_{81}), recovery rate of forest and grass vegetation (D_{83}), and treatment of domestic sewage (D_{12}) had higher weights; therefore, construction wastewater, water and soil conservation, and the treatment of solid waste were closely related to green construction of the large-scale hydropower projects. The evaluation value of Wudongde Hydropower Station by FCE was 3.697, indicating that the green construction level was at the "Good" grade. The evaluation values of comprehensive management, environment protection, and resource saving approached 4, at the "Good" grade. However, in order to further improve the green construction level of the station, it was necessary to strengthen the management of some construction processes, such as treatment of waste slag in construction, economical and intensive utilization of land, publicity and training, and the controlled ratio of soil erosion and the saving rate of water resources. Since the controlled ratio of soil erosion accounted for a large weight, its management should be particularly strengthened.

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