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Proposal for a Criteria Set to Protect against Degradation for Sustainable Groundwater Exploitation in High Mountainous Water-Scarce Areas in the South-Central Region of Vietnam

Than Van Don[1*], Pham Thi Thu[1], Nguyen Thi Lan Anh[1], Pham Thi Hong Ngoc[1], Phan Quang Thuc[1], Chu Thi Thu[1], Dang Tran Trung[2]
[1]Center for Water Resources Technology and Data, Vietnam
[2]Center for Water Resources Warning and Forecasting, Vietnam

ABSTRACT

Groundwater plays a crucial role in providing water for domestic use and production. However, continuous extraction pressures have shown signs of degradation and depletion, especially in high mountainous water-scarce areas in Vietnam in general and the South-Central region in particular. The high mountainous water-scarce areas in the South-Central region consist of 28 mountainous regions across 7 provinces: Quang Nam, Quang Ngai, Binh Dinh, Phu Yen, Khanh Hoa, Ninh Thuan, and Binh Thuan. Calculations show that the area contains 8 water-bearing layers/zones, including Pleistocene sedimentary pore aquifers, fissure, fissure-pore sedimentary aquifers ranging from Archeozoic to Mesozoic ages, and water-bearing zones along tectonic faults in intrusive and volcanic rocks. The total groundwater exploitable volume is 50,691 m^3/day, with Khanh Hoa province having the largest volume at 12,758 m^3/day, and Ninh Thuan having the smallest at 1,834 m^3/day. The forecasted total extraction rate is 12,816 m^3/day, capable of supplying 128,160 people with a standard water usage of 100 liters/person/day. To protect and prevent groundwater degradation in this area, the authors propose a criteria set comprising three groups of criteria: Criteria group for preventing degradation in volume (3 criteria with 6 indicators); Criteria group for preventing environmental degradation (4 criteria with 5 indicators); Criteria group for preventing degradation due to socio-economic factors (4 criteria with 6 indicators). The assessment results of groundwater protection against degradation in the area reveal that there are 3 regions with low protection levels and 25 regions with moderate protection levels.

Keywords: criteria for groundwater protection against degradation, South-Central Vietnam

INTRODUCTION

The high mountainous water-scarce areas refer to regions that meet two conditions: having a regional coefficient of ≥ 0.5 and have not yet been surveyed or assessed for groundwater resources; and midland and plain regions with a regional coefficient of 0.2 that have also not been surveyed or assessed for groundwater resources for domestic water supply. The South-Central region has 28 areas across 7 provinces: Khanh Hoa (06 areas in the communes of Son Binh, Son Lam, Khanh Nam, Khanh Binh, Khanh Dong, Khanh Phu); Phu Yen (04 areas in the communes of Xuan Hoa, Krong Hoa, Krong Pa, An Hiep, An Dan); Binh Dinh (03 areas in the communes of Canh Vinh, An Tan, Hoai Son); Quan Nam (06 areas in the communes of Tien Cam, Tien Phong, Tien Tho, Tien My, Que Loc, Tien Hiep); Quang Ngai (04 areas in the communes of Ba Dinh, Ba Bich, Ba To, Ba Xa; Ninh Thuan (01 area in the commune of Phuoc Chien); and Binh Thuan (04 areas in the communes of Son My, Thang Hai, Thuan Quy, Tan Thang) that are identified as water-scarce areas (Figure 1).

* Corresponding Author

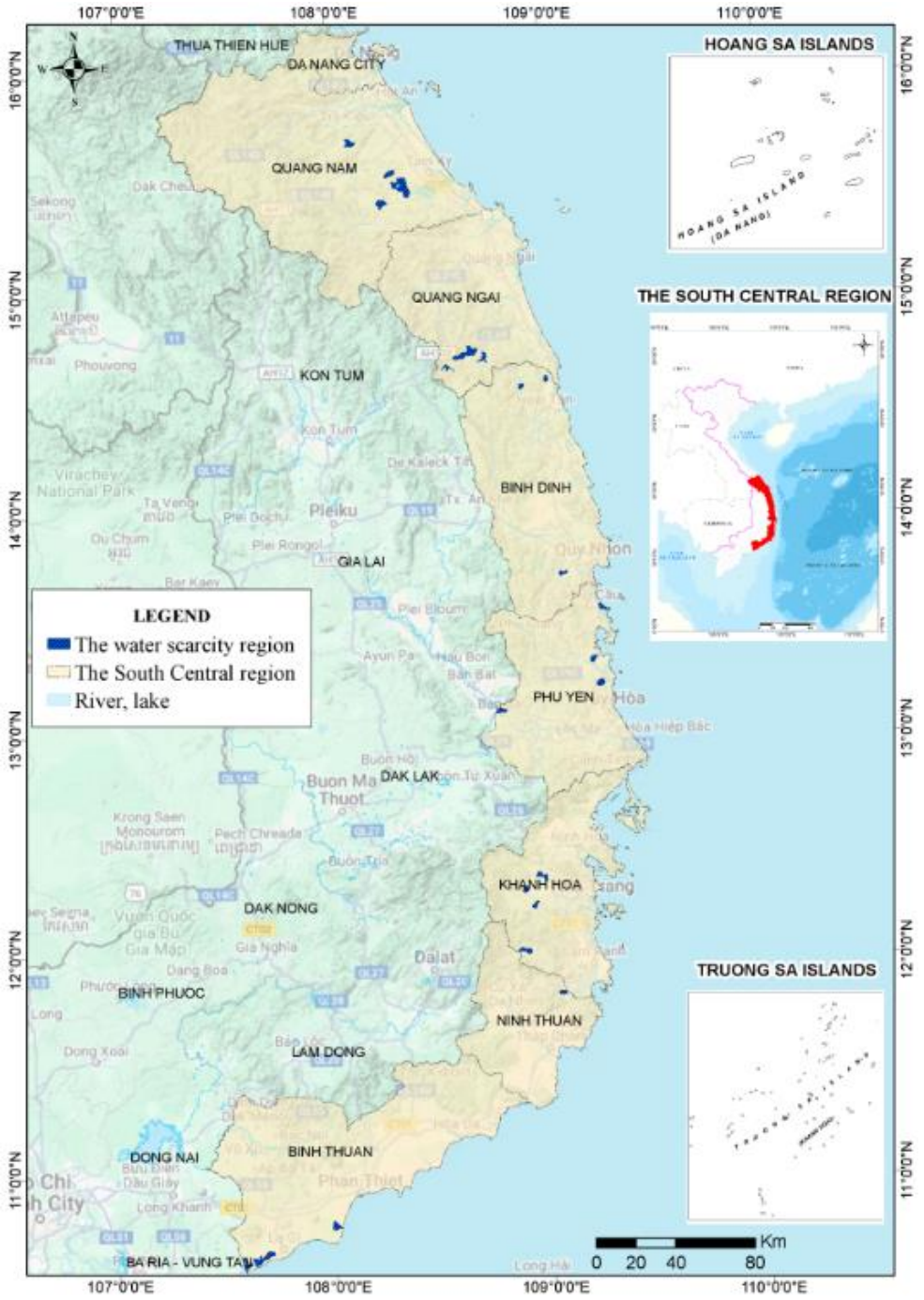

Figure 1. Diagram of water-scarce areas in the South-Central region

DATA USAGE AND RESEARCH METHODOLOGY

Data Usage

The data used in this report is based on the results of test pumping at exploratory drilling sites intended for extraction, based on the water usage needs of various water-scarce regions in the South-Central area (National Center for Water Resources Planning and Investigation, 2020). The survey results supplement hydrometeorological data, current extraction conditions, customs, and impacts on groundwater extraction facilities.

The parameters of the studied aquifers are summarized in Table 1, with values recorded as: minimum - maximum (average) or only the average value.

Table 1. The parameters of the studied aquifers

No.	Aquifers	Flow rate (l/s)	Transmissivity (m^2/day)	Permeability (m/day)	Static water level depth (m)
1	Pleistocene (qp)	2,25 – 3,05	24,7 - 132,35 (54,0)	0,52 – 2,57 (1,26)	2,4 -9,5
2	Basalt (βn)	1,5 -2,0	34,45	0,52	13,25 - 26
3	Early to Middle Jurassic (J_{1-2})	1,25 - 2,5	9,53 - 34,1 (20,53)	0,15 – 0,36 (0,23)	0,2 – 7,33
4	Proterozoic (pr)	2,0 – 2,55	5,3 - 21,8 (12,55)	0,04 – 0,23 (0,11)	0,2 – 12,78
5	Archeozoic (ar)	1,25 – 1,9	2,72 – 21,0 (12,91)	0,07 – 0,09 (0,08	0,4 – 9,9
6	Late Jurassic to Cretaceous (J_3-K_2)	1,09 – 2,25	7,16 – 62,46 (26,08)	0,1 -1,46 (0,48)	2,46 – 24,54
7	Triassic (γT_2vc)	1,2 – 2,4	14,8	0,16	5,3 – 8,5
8	Late Paleozoic (γPZ_3bg-qs)	1,05-1,43	9,62	0,51	0,5 – 6,0

Research Methodology

- Data collection method: Collecting, compiling, and systematizing documents, as well as conducting field surveys on socio-economic conditions, customs, and identifying specific aquifers and causes of groundwater degradation.
- Inheritance analysis method: Inheriting studies from both domestic and international research.
- Data analysis method: Using statistics and GIS to develop maps of groundwater sources requiring protection.
- Expert method: Used for selecting criteria sets and solutions.
- Analytical Hierarchy Process (AHP): Used to determine weights and evaluate criteria.

RESEARCH RESULTS

Current Status of Groundwater Resources in the South-Central Region

The total potential groundwater resource is 168,960 m^3/day, with Khanh Hoa province having the largest potential at 42,531 m^3/day, and Ninh Thuan province having the smallest potential at 6,112 m^3/day.

The total exploitable reserve is 50,691 m^3/day, with Khanh Hoa having the largest exploitable reserve at 12,758 m^3/day, and Ninh Thuan having the smallest at 1,834 m^3/day.

The projected extraction rate is calculated based on test pumping results at exploratory drillings intended for extraction, aligned with the water usage needs of each region. The projected extraction reserve is calculated for a 27-year exploitation period. The calculated projected extraction rate is 12,816 m^3/day, capable of supplying 128,160 people with a water usage standard of 100 liters/person/day. Among the seven provinces of the South-Central region, Khanh Hoa has the largest projected extraction rate at 2,902 m^3/day, followed by Quang Nam and Binh Thuan provinces; Ninh Thuan has the smallest projected extraction rate of 550 m^3/day in one investigated area.

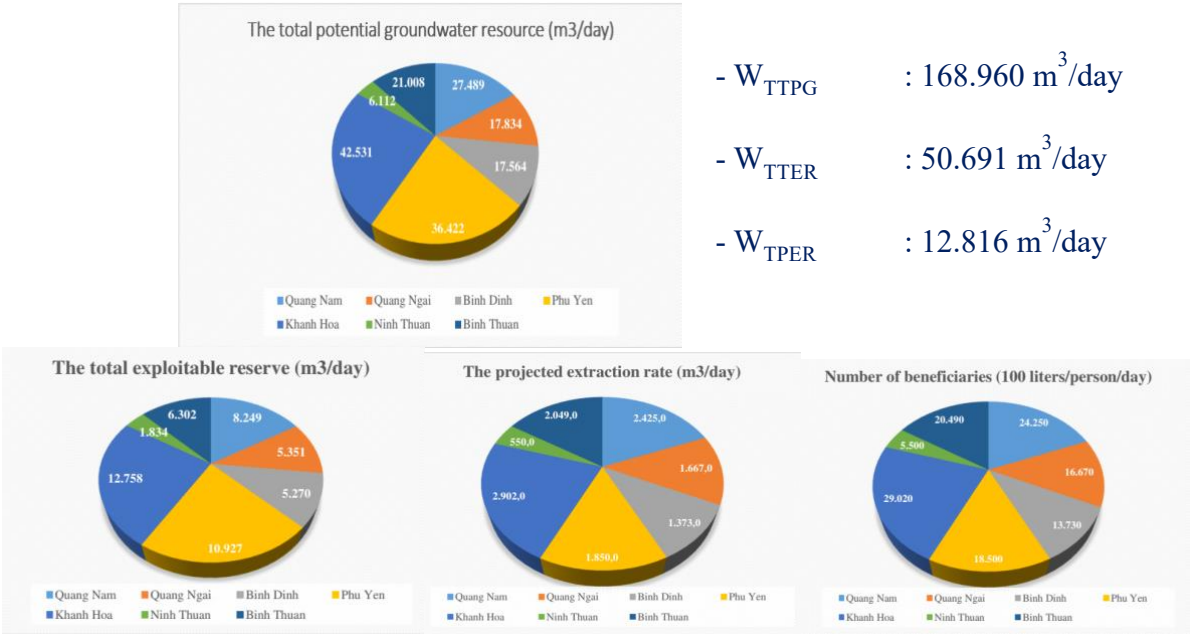

Figure 2. Groundwater Status in High Mountainous Water-Scarce Areas in the South-Central Region

Proposal for a Criteria Set to Protect Against Groundwater Degradation

Scientific and Practical Basis

Based on the hydrogeological characteristics and groundwater resources in high mountainous water-scarce areas of the South-Central region, combined with survey results and data analysis, the causes of groundwater degradation are identified as follows: The area has overlapping recharge zones with aquifer distribution zones, facilitating the infiltration of pollutants into groundwater; Soil erosion due to heavy rain may carry surface pollutants into groundwater; Saltwater intrusion; Flooding and drought can alter flow paths and infiltration of pollutants into groundwater; Changes in land use; Overexploitation of groundwater leading to depletion; Use of chemical fertilizers and pesticides in agriculture; Waste from livestock activities; Incomplete standardization of water extraction operation procedures; Limitations in customs and community awareness in water extraction and usage.

This analysis is based on studies conducted globally and in Vietnam, including those by Ajit Pratap Singh and Prashant Bhakar (2019); Wang Z. & Wu Q.I.A.N.G. (2006); Associate Professor Dr. Doan Van Canh (2015).

Proposed Criteria Set

Based on research findings on the causes of groundwater degradation in high mountainous water-scarce areas in the South-Central region and expert consultations, the research team has developed a detailed criteria set for protecting against groundwater degradation as follows:

1) Group of Criteria for Preventing Degradation of Water Reserves

**** Criterion 1: Source Assessment***

Evaluates changes in recharge levels for groundwater due to impacts from rainfall, vegetation cover, and forest land changes. This criterion is assessed through indicators including:

Indicator 1 (I_1): Evaluation of vegetation cover degradation. This is assessed by the reduction in forest area over 5 years from the study year. >5%: 3 points, 1-5%: 2 points, <1%: 1 point.

$$I_1 = (\text{Forest area in 2016} - \text{Forest area in 2021}) \times 100\%.$$

Indicator 2 (I_2): Evaluation of rainfall levels. Assessed by the decrease in rainfall over 10 years from the studied year. >500mm: 3 points, 100-500mm: 2 points, <100mm: 1 point.

I_2 = (Total rainfall in 2011 - Total rainfall in 2021).

Indicator 3 (I_3): Evaluation of water table depth. Assessed by the static water level depth. >20m: 3 points, 10-20m: 2 points, <10m: 1 point.

The score for the criterion is calculated as the sum of (criterion points x indicator weight).

**** Criterion 2: Safe Extraction Capacity to Prevent Pollution, Saltwater Intrusion, and Land Subsidence***

This criterion assesses the capability to extract water without causing pollution, saltwater intrusion, or land subsidence. Assessed through Indicator I_4: Safe Extraction Capacity Indicator.

$$I_4 = \frac{\text{Total extracted groundwater}}{\text{Safe extraction capacity}} * 100\%$$

There are three possible scenarios:

Scenario 1: Total extraction < Safe groundwater extraction capacity, i.e., <80%, 1 point.

Scenario 2: Total extraction ≈ Safe groundwater extraction capacity, i.e., 80%-100%, 2 points.

Scenario 3: Total extraction > Safe groundwater extraction capacity, i.e., >100%, 3 points.

**** Criterion 3: Extraction Limits for Structures***

The extraction water table limit is the maximum level that groundwater can be extracted from an aquifer or specific groundwater source without causing negative impacts on the environment and water resources. Calculated by:

$$I_5 = \frac{\text{Total extracted groundwater}}{\text{Total natural recharge}} * 100\%$$

There are three possible scenarios:

Scenario 1: Safe extraction: Total withdrawal ≤ Total natural recharge, I_5 <80%: 1 point.

Scenario 2: Extraction with artificial recharge supplementation: Total withdrawal approximately equals total natural recharge, i.e., I_5 = 80-100%: 2 points.

Scenario 3: Unsafe extraction, requiring limitation: Total withdrawal > Total natural recharge, i.e., I_5 >100%: 3 points.

The indicator for the extraction water table limit is calculated as the percentage of the drawdown depth of the borehole water level compared to the allowed extraction water table threshold.

$$I_6 = \frac{\text{Drawdown depth of the borehole}}{\text{Allowed extraction water table threshold}} * 100\%$$

Indicator I_6 is classified into three levels:

I_6 >60%: 3 points.

30% < I_6 ≤ 60%: 2 points.

0% < I_6 ≤ 30%: 1 point.

The criterion score is calculated as the sum of (criterion points x indicator weight).

According to Clause 2, Article 32 of Decree 53/2024/NĐ-CP dated May. 16, 2024, of the Prime Minister, detailing the implementation of some provisions of the Law on Water Resources, the permitted groundwater extraction threshold for the South-Central region should not exceed 50m.

2) Group of Criteria for Preventing Environmental Degradation

**** Criterion 4: Risk of Groundwater Saline Intrusion***

This criterion assesses the risk of saline intrusion into groundwater by measuring the distance from the 1.5 g/l salinity boundary to the nearest extraction structure. Indicator I_7 is classified into three levels: I_7 ≤ 1km: 3 points, 1km < I_7 ≤ 2km: 2 points; I_7 > 2km: 1 point.

**** Criterion 5: Pollution Risk***

This criterion is evaluated based on two indicators: Indicator 8 (I_8): Pollution Impact Indicator and Indicator 9 (I_9): Potential Pollution Source Impact Indicator.

Indicator 8 (I_8): Evaluated by analyzing groundwater samples compared to Standard 09:2023/BTNMT, the national technical standard on groundwater quality, classified into three levels:

Trace element pollution (As, Cd, Pb, Cr, Cu, Zn, Mn, Hg, CN, Phenol), Pesticides, Radiation, TDS: 3 points.

Nitrogen, iron, and microbiological pollution (Coliform, E. Coli): 2 points.

No pollution detected: 1 point.

Indicator 9 (I_9): Evaluated based on the distance from a potential pollution source to the study area, classified into three levels: $I_9 \leq$ 1km: 3 points; 1km < $I_9 \leq$ 2km: 2 points; I_9 >2km and areas not affected: 1 point.

The criterion score is calculated as the sum of (criterion points x indicator weight).

**** Criterion 6: Groundwater Self-Protection Capability***

This criterion assesses the self-protection capability of aquifers, evaluated through Indicator 10 (I_{10}): Groundwater Self-Protection Indicator.

To calculate I_{10}, the authors use the GOD method to map aquifer protection levels, introduced by Foster in 1987. The acronym GOD represents:

G: Aquifer pressure characteristics (confined, semi-confined, unconfined, etc.).

O: Overlying layer composition.

D: Depth to groundwater level.

Indicator I_{10} is classified into three levels: Good self-protection: 1 point; Moderate self-protection: 2 points; Poor and very poor self-protection: 3 points.

3) Criteria for Counteracting Degradation Due to Socio-Economic Factors

**** Criterion 7: Operation and Maintenance of Exploitation Works***

This criterion is evaluated based on Index 11 (I_{11}): Operation index of the work. The index is scored based on the principle that longer operation times result in higher operation and maintenance costs. I_{11} < 6 hours/day: 1 point; 6 $\leq I_{11}$ < 12 hours/day: 2 points; I_{11} > 12 hours/day: 3 points.

**** Criterion 8: Customs and Practices in Water Exploitation***

This criterion is evaluated based on the number of ethnic minorities (according to Vietnam's 2019 population statistics from the General Statistics Office) living in the study area. This criterion is assessed through Index I_{12}, categorized into three levels: <10,000 people: 3 points; 100,000 – 1 million people: 2 points; > 1 million people: 1 point.

**** Criterion 9: Water Pricing***

This criterion evaluates the variation in water pricing across regions compared to the ceiling water price for rural areas as stipulated in Circular 44/2021/TT-BTC. It is assessed through Index 13 (I_{13}), divided into three levels: 0 $\leq$ I13 $\leq$ 2000 VND: 3 points; 2000 < I13 $\leq$ 5000 VND: 2 points; I_{13} > 5000 VND: 1 point.

**** Criterion 10: Mechanisms and Policies for Water Resource Management***

This criterion assesses the level of attention to water resource management by reviewing the issuance of water resource management documents by the province, including: Water resource planning; Prohibition zones, restricted exploitation zones; Water resource inventory; List of water sources needing protection; List of intra-provincial water sources; List of ponds and lakes not to be filled, etc. It is categorized into three levels: I_{14} < 4 documents - Low management level: 3 points; 4 $\leq I_{14} \leq$ 6 documents - Medium management level: 2 points; I_{14} > 6 documents - High management level: 1 point.

**** Criterion 11: Community Awareness***

This criterion is evaluated through three indexes:

Index 15 (I_{15}) - CF: Financial Capacity

This index is assessed by observing the surplus revenue compared to expenditure in relation to the national minimum and maximum levels. The minimum and maximum values are used as benchmarks to calculate the financial indicator (CF), as shown in the formula:

$$I_{15}(C_F) = 100 - \left(\frac{F_{max} - s}{F_{max} - F_{min}} \times 100\right)$$

Where F_{min} is the minimum per capita surplus of the country,

F_{max} is the maximum per capita surplus of the country,

s is the average per capita surplus of the study area.

Index 16 (I_{16}) - CE: Education

The value of this index is calculated based on the educational level in society.

The score for this index (I_{16}) is calculated based on the percentage of the population aged 18 - 50 who have achieved at least high school education:

$$I_{16}(C_E) = 100 - \left(\frac{E_{max} - e}{E_{max} - E_{min}} \times 100\right)$$

Where E_{max} is the region with the highest percentage of the population with at least high school education in the country,

E_{min} is the region with the lowest percentage of the population with at least high school education in the country,

e is the percentage of the population with at least high school education in the study area.

CE = 100 if e = 76.56%; CE = 0 if e = 54.86%; if 54.86% < e < 76.56%, then the formula above is used.

Index 17 (I_{17}) - PTV: Training

This index reflects the societal capacity for handling freshwater resources after being empowered with basic training on resource management. To score this index (PTV), the percentage of trained and empowered individuals is calculated and multiplied by a coefficient for various fields, as shown in the formula with the industrial training coefficient being 1, other training coefficient being 0.5, and no training coefficient being 0:

$$I_{17}\ (P_{TV}) = (n + 0.5t) \times 100$$

Where:

n is the percentage of trained individuals with industrial skills,

t is the percentage of individuals trained in other relevant areas.

Scoring for I_{15}, I_{16}, I_{17} is as follows: < 50%: 3 points; 50% - 75%: 2 points; > 75%: 1 point.

The criterion score is the average score of the indexes.

Selection of Criterion Weights

Proposed Weights for the Criterion Set

The purpose is to use the Criterion Set to evaluate the degree of resistance to degradation for sustainable groundwater exploitation in the study area.

The Analytic Hierarchy Process (AHP) method is used to select weights for the criteria in the criterion set.

For criteria with 2 indexes, expert judgment is used to choose the more important criterion.

For criteria with 3 or more indexes, the AHP method is used to determine the weights for the indexes within the criterion.

Table 2. Criterion Set for Protection and Counteraction of Degradation for Sustainable Groundwater Exploitation in the High Mountains and Water-Scarce Areas of the South-Central Region

No.	Current status of water resources degradation						Current status of environmental degradation						Current status of degradation due to socio-economic factors						
	C1			C2		C3	C4		C5		C6		C7	C8	C9	C10	C11		
Index	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}		I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}	
Weighting of Criteria Groups	1						1						1						
Weighting of Criteria	0,51			0,19		0,31	0,443		0,3873		0,17		0,07	0,14	0,11	0,25	0,44		
Weighting of Index	0,22	0,46	0,32	1	0,4	1	1	0,6	0	1	1		1	1	1	1	1	1	1
Total Score for Protection and Anti-Degradation of Water Resources	< 4: Rate of Protection and Anti-Degradation of Water Resources is Good																		
	4 - 6: Rate of Protection and Anti-Degradation of Water Resources is Moderate																		
	> 6: Rate of Protection and Anti-Degradation of Water Resources is Poor																		

Validity Check of Proposed Weights

a) Criteria Group 1:

The results of Validity of Weights for Criteria Group 1 are performed:

Table 3. Validity of Weights for Criteria Group 1

Largest Eigenvalue of the Pairwise Comparison Matrix	ymax=	3,01
Random Index	RI=	0,58
Consistency Index	CI=	0,01
Consistency Ratio	CR=	0,92

Conclusion: CR = 0.92% < 10%, meets the requirement.

Table 4. Calculation of the suitability of the weight for Criterion 1

Largest Eigenvalue of the Pairwise Comparison Matrix	ymax=	3,09
Random Index	RI=	0,58
Consistency Index	CI=	0,05
Consistency Ratio	CR=	8,14

Conclusion: CR = 8,14 % < 10%, meets the requirement.

b) Criteria Group 2:

Table 5. Validity of Weights for Criteria Group 2

Largest Eigenvalue of the Pairwise Comparison Matrix	ymax=	3,02
Random Index	RI=	0,58
Consistency Index	CI=	0,01
Consistency Ratio	CR=	1,78

Conclusion: CR = 1,78% < 10%, meets the requirement.

c) Criteria Group 3:

Table 3. Validity of Weights for Criteria Group 3

Largest Eigenvalue of the Pairwise Comparison Matrix	ymax=	5,19
Random Index	RI=	1,12
Consistency Index	CI=	0,05
Consistency Ratio	CR=	4,27

Conclusion: CR = 4,27% < 10%, meets the requirement.

Quantification of the Criteria Set

Based on the set of criteria, the authors have quantified them for the high mountainous and water-scarce areas in the South-Central Region, as shown in the following chart:

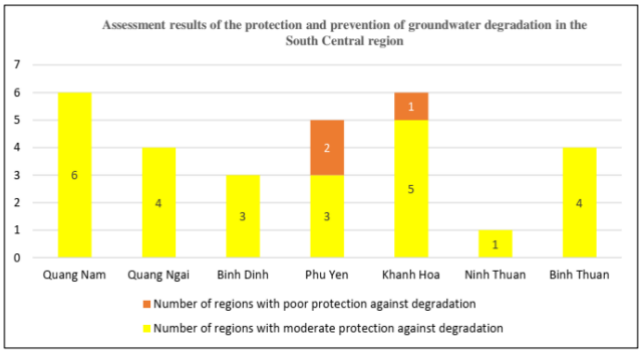

Figure 3. Chart of assessment results on the protection and prevention of groundwater degradation in high mountain areas and water-scarce regions in the South-Central Region

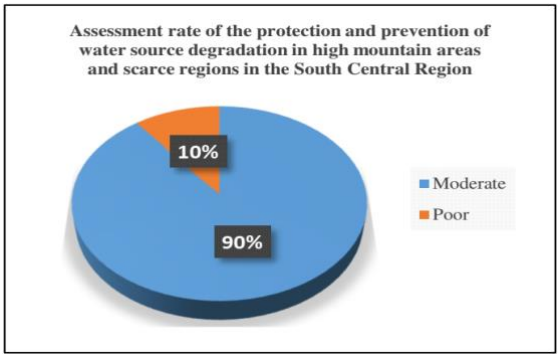

Figure 4. Chart showing the assessment rate of groundwater protection and prevention of degradation in high mountain areas and water-scarce regions in the South-Central Region

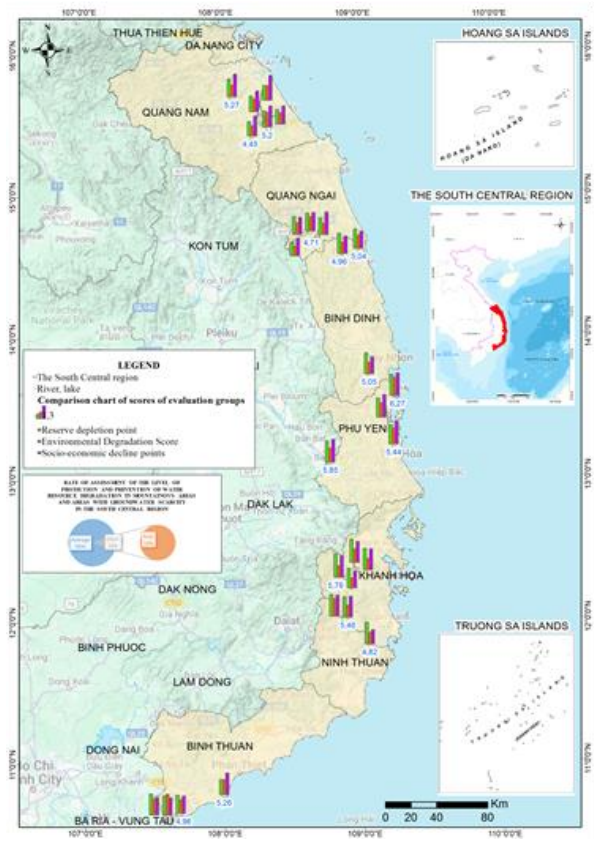

Figure 5. Map showing the assessment of groundwater protection and degradation prevention by regional groups in the South-Central Region

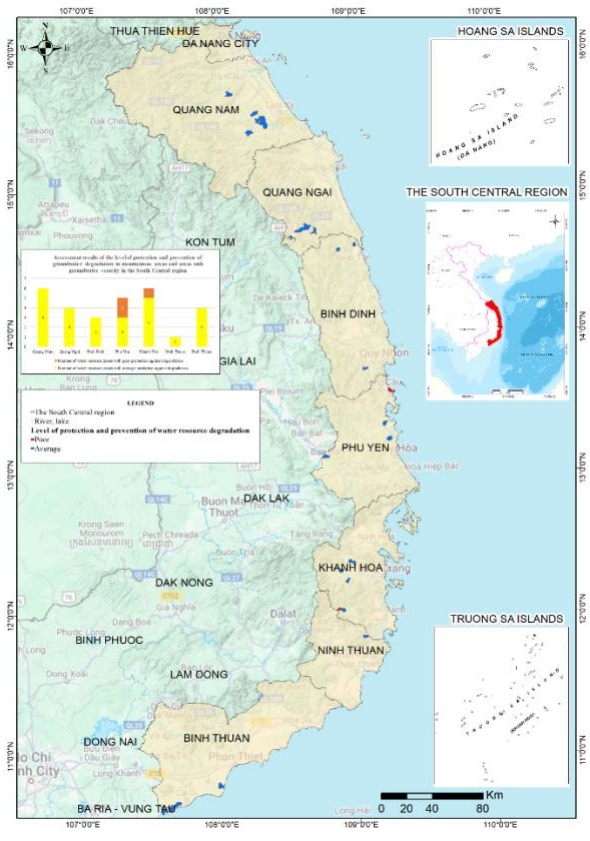

Figure 6. Map showing the results of the assessment of groundwater protection and anti-degradation in the high mountainous and water-scarce regions of the South-Central Region

CONCLUSIONS AND RECOMMENDATIONS

The research results indicate that the water-scarce areas in the South-Central Region have 8 aquifer layers/zones, including Pleistocene sedimentary aquifer layers, fracture aquifers, fracture-sedimentary aquifers from Archean to Mesozoic age, and aquifer zones along tectonic faults in intrusive and volcanic rocks. The forecasted extraction capacity is 12,816 m³/day, which can supply a total of 128,160 people with a water usage standard of 100 liters/person/day. To protect and prevent the degradation of groundwater resources, artificial recharge solutions and reasonable groundwater extraction regimes are needed, as well as sanitary protection zones for water abstraction areas and recharge protection areas for each facility, with a minimum radius of 20 meters and recharge protection areas ranging from 3.0 to 12.0 km².

Relevant ministries, departments, and local authorities should consider developing a water supply system appropriate to the characteristics of water resources and water usage practices based on groundwater research results to ensure sustainable and safe water supply for the people in high mountainous and water-scarce areas of the South-Central Region.

ACKNOWLEDGMENTS

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