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Identifying Areas to Apply Technological Solutions of Groundwater Exploitation and Utilization Using Spring in High Mountainous, Water-Scarce Areas of the Northern Vietnam

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ABSTRACT

Groundwater exploitation through a spring is one of the common solutions for water extraction in the high mountainous and water scarce regions of Northern Vietnam. However, identifying areas where this exploitation solution can be applied for sustainable and long-term operation is a challenging issue that depends on water resources, extraction techniques, social aspects, environment, and the requirement for a large amount of data. In this study, a GIS approach was utilized to delineate the suitable areas for implementing the groundwater extraction through a spring technology in the high mountainous and of Northern Vietnam based on specific criteria. Six criteria were considered, including the hydraulic conductivity of the aquifer, exploitable groundwater reserves, distance to water utilization points, distance to springs, terrain slope, and population distribution/density. Analytical Hierarchy Process (AHP), proposed by Saaty (1980), was integrated to determine the areas suitable for implementing the groundwater extraction through a spring technology in the high mountainous and water-scarce areas of Northern Vietnam. The research results revealed that the areas suitable for implementing the groundwater exploitation through a leaky aquifer technology in the high mountainous and water scarce regions of Northern Vietnam are distributed sustainably and very sustainably in 1,094 communes, wards, and towns across 15 provinces in the study area, with a total area of 3,742 km^2 (accounting for 3.8% of the study area).

Keywords: AHP, GIS, groundwater, spring

INTRODUCTION

Water resources in mountainous areas play a crucial role in meeting the water needs of communities downstream (Somers & McKenzie, 2020). However, these resources face challenges due to declining water storage in snowpack and glaciers. Previously, it was believed that groundwater had a limited contribution to mountain streamflow (Wang & Jeppson, 1969). However, recent understanding recognizes that groundwater plays a significant role as a water source for streams in these regions. The high mountainous and water-scarce areas of Northern Vietnam is the largest territory among the economic regions in Vietnam, and it holds significant importance in the socio-economic development, as well as security and defense.

Due to the complex natural geographical conditions, it is challenging and complicated to search for water sources for domestic and industrial use in high mountainous and water-scarce areas. To ensure the efficient and sustainable operation of water exploitation projects, it is necessary to select appropriate exploitation technologies and management practices that suit the specific water resources and other factors. However, determining the suitable groundwater exploitation technologies for the high mountainous and water-scarce areas to ensure efficient and sustainable operation is difficult and dependent on various factors, including rainfall,

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stream flow, thickness of the cover layer, aquifer depth, groundwater level, permeability coefficient, discharge, exploitable groundwater reserve, water quality, distance to water utilization points, distance to transportation routes, distance to springs, terrain slope, land use, geology, fracture density, population distribution/density, and distance to pollution sources (Enke Hou et al., 2018; Fanao Meng et al., 2021; Indrani Mukherjee et al., 2020; Yu et al., 2019).

Newly emerging technologies such as MIF (Multi-Criteria Decision-Making), AHP (Analytical Hierarchy Process) and remote sensing, and geographical information system (GIS) have proven to be effective in identifying appropriate groundwater areas for watershed development and planning (Javed & Wani, 2009; Pande et al., 2019; Khadri et al., 2016). These technologies enable accurate and precise delineation of suitable groundwater zones, both on small and large scales. Besides, GIS software has become an essential tool in water resources research due to its capabilities in spatial-temporal development and its effectiveness in spatial analysis and data prediction (Ghayoumian et al., 2007).

The main aim of this research investigation has been to prepare various criteria, i.e. hydraulic conductivity of the aquifer, exploitable groundwater reserves, distance to water utilization points, distance to springs, terrain slope, and population distribution/density, etc. The weights of the thematic maps corresponding to the criteria were calculated and normalized using the AHP method (Saaty, 1980). All of these layers were integrated and mapped using the AHP technique and GIS software.

STUDY AREA

Study area is the mountain region and sell-mountain in Northern Vietnam which covers 101.389 km^2. In terms of administration, the study area consists of 15 provinces, namely, Bac Can, Bac Giang, Cao Bang, Dien Bien, Ha Giang, Hoa Binh, Lai Chau, Lang Son, Lao Cai, Phu Tho, Quang Ninh, Son La, Thai Nguyen, Tuyen Quang and Yen Bai.

The study area is bordered by China to the north; Laos to the west; Red River Delta to the southeast; North Central Coast to the southwest; Gulf of Tonkin to the east.

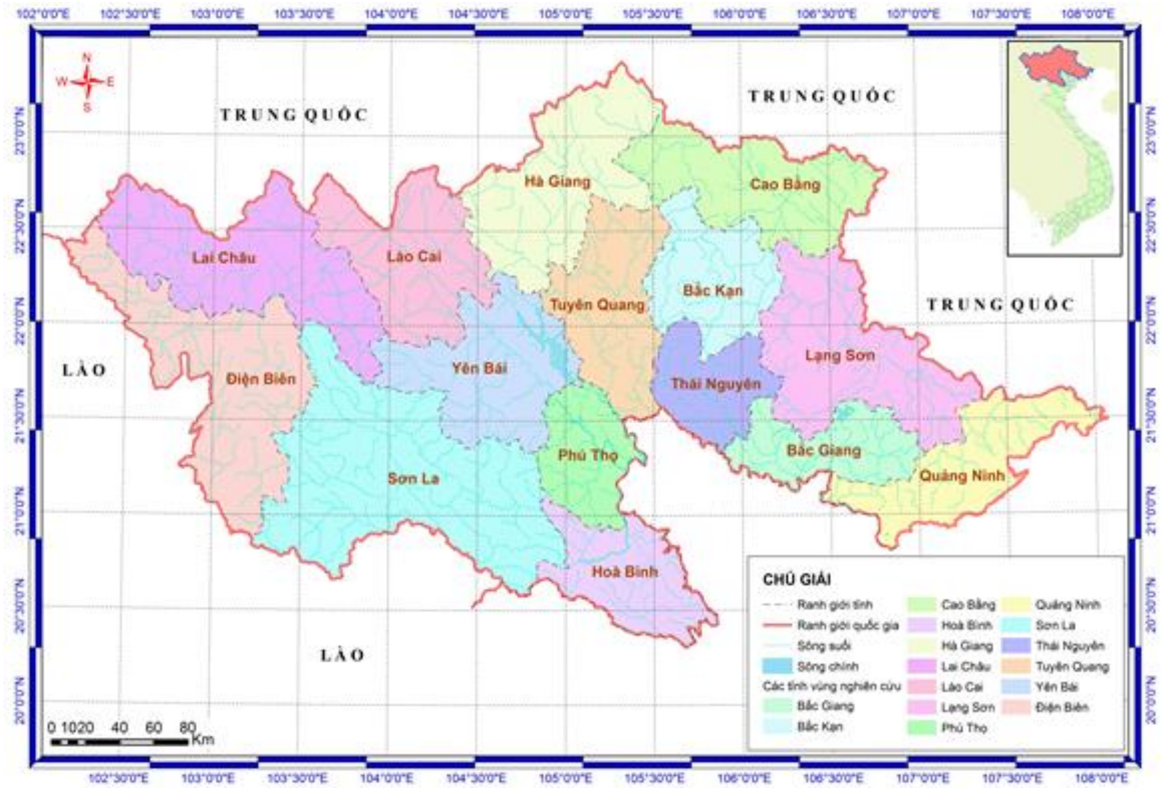

Figure 1. Location of study area

DATA PROCESSING AND METHODOLOGY

In order to establish a map for area identification to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam, a multi-parameter dataset includes the hydraulic conductivity of the aquifer, exploitable groundwater reserves, distance to water utilization points, distance to springs, terrain slope, and population distribution/density which was provided by the National Center for Water Resources Planning and Investigation (NAWAPI).

Hydraulic Conductivity of Aquifers

The hydraulic conductivity of aquifers has been collected and synthesized from previous groundwater resource surveys in the study area. In order to assess the hydraulic conductivity of aquifer layers for determining the sustainability of conduit-based water exploitation technologies in the high mountainous, water-scarce areas of Northern Vietnam, the hydraulic conductivity is divided into the following categories: Very high hydraulic conductivity: > 90 m^2/day; High hydraulic conductivity: from 60 m^2/day to 90 m^2/day; Moderate hydraulic conductivity: from 30 m^2/day to 60 m^2/day; Low hydraulic conductivity: from 15 m^2/day to 30 m^2/day; Very low hydraulic conductivity: < 15 m^2/day.

Exploitable Groundwater Reserve

The exploitable groundwater reserves are expressed in terms of the groundwater exploitable reserve module (unit: m^3/day/km^2). Based on the synthesis of hydrogeological parameters of aquifers, including aquifer thickness, specific yield, permeability, hydraulic conductivity, and groundwater flow module, the storage capacity, recharge volume, groundwater resource potential were calculated, firstly. The exploitable groundwater reserve is estimated by 30% of groundwater resource potential of aquifers in the study area. Finally, the groundwater exploitable reserve module is determined by dividing the exploitable groundwater volume by the spatial distribution area of aquifers. All the calculation steps and procedures mentioned above are carried out using GIS tools through ArcGIS software. To assess the exploitable groundwater reserve for determining the sustainability of technological solutions of groundwater exploitation and utilization using spring in the high mountainous and water scarce regions of Northern Vietnam, the exploitable groundwater reserve is divided into the following categories: Very high exploitable reserve: > 500 m3/day/km2; High exploitable reserve: from 300 m^3/day/km^2 to 500 m^3/day/km^2; Moderate exploitable reserve: from m^3/day/km^2 to 300 m^3/day/km^2; Low exploitable reserve: from 100 m^3/day/km^2 to 200 m^3/day/km^2; Very low exploitable reserve: < 100 m^3/day/km^2.

Distance to Water Utilization Point

The distance to water utilization point is determined by the distance to the central locations of administrative units at the commune, district, and city levels within the provinces in the study area. Based on this, using the Buffer tool in ArcGIS software, the range of distribution areas with corresponding distances to water users is calculated according to the established levels. Accordingly, 2,694 central areas are calculated with distances categorized as follows: very long distance: > 5km; long distance: from 2km to 5km; moderate distance: from 1km to 2km; short distance: from 0.5km to 1km; very short distance: < 0.5km.

Distance to Spring

To determine the distance from exploitable springs to water utilization points, the authors collected and synthesized survey results during the dry season for springs with flow rates above 0.5 l/s, as provided by NAWAPI. The compiled results include 1,917 springs in the high mountainous and water scarce regions of Northern Vietnam. The distance from from exploitable springs to water utilization points is divided into the following categories: very long distance: > 5km; long distance: from 2km to 5km; moderate distance: from 1km to 2km; short distance: from 0.5km to 1km; very short distance: < 0.5km.

Terrain Slope

The terrain slope in the study area is determined based on the digital elevation model (DEM) map. Using the Slope tool in ArcGIS software, the terrain slope is divided into the following categories: Very steep slope: > 20%; Steep slope: from 15% to 20%; Moderate slope: from 10% to 15%; Gentle slope: from 5% to 10%; Very gentle slope: < 5%

Population Distribution/Density

The population distribution/density is compiled based on the natural area and population statistics from the 2020 Statistical Yearbook of the provinces. From this data, the population density within the research area is calculated. To evaluate the population distribution for determining the sustainability of groundwater exploitation using conduit systems in the water-scarce highland region of Northern Vietnam, the population density can be categorized as follows: very high population density: > 400 people/km^2; high population density: from 300 people/km^2 to 400 people/km^2; moderate population density: from 200 people/km^2 to 300 people/km^2; low population density: from 100 people/km^2 to 200 people/km^2; very low population density: < 100 people/km^2.

In order to establish a map for area identification to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam, all six different criteria layers were weighted using the Analytic Hierarchy Process (AHP) method (Saaty, 1980) and determined using the weighted sum method in GIS. The six thematic map layers corresponding to the normalized criteria were assigned scores ranging from 1 to 5, representing the levels from very unsustainable to very sustainably (Table 1).

Table 1. The normalized results of the criteria

No.	Criteria group	Criteria	ID	Description	Value (from - to)	Weight
1	Sources of water	Hydraulic conductivity of aquifers	HSD	Very high	> 90 m^2/day	5
				High	60 ÷ 90 m^2/day	4
				Moderate	30 ÷ 60 m^2/day	3
				Low	15 ÷ 30 m^2/day	2
				Very low	< 15 m^2/day	1
		Exploitable groundwater reserve	TLCTKT	Very high	> 500 m^3/day/km^2	5
				High	300 ÷ 500 m^3/day/km^2	4
				Moderate	200 ÷ 300 m^3/day/km^2	3
				Low	100 ÷ 200 m^3/day/km^2	2
				Very low	< 100 m^3/day/km^2	1
2	Technical economic	Distance to water utilization point	KCSDN	Very high	> 5 km	1
				High	2 ÷ 5 km	2
				Moderate	1 ÷ 2 km	3
				Low	0,5 ÷ 1 km	4
				Very low	< 0,5 km	5
		Distance to spring	KCML	Very high	> 5 km	1
				High	2 ÷ 5 km	2
				Moderate	1 ÷ 2 km	3
				Low	0,5 ÷ 1 km	4
				Very low	< 0,5 km	5
		Terrain slope	DD	Very high	> 20 %	1
				High	15 ÷ 20 %	2
				Moderate	10 ÷ 15 %	3
				Low	5 ÷ 10 %	4
				Very low	0 ÷ 5 %	5
3	Society	Population distribution/ density	PBDC	Very high	> 400 people/km^2	5
				High	300 ÷ 400 people/km^2	4
				Moderate	200 ÷ 300 people/km^2	3
				Low	100 ÷ 200 people/km^2	2
				Very low	< 100 people/km^2	1

The weights of the thematic maps corresponding to the criteria were calculated and normalized using the AHP method (Saaty, 1980). The determined weights of the criteria for area identification to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam are as follows: W_{HSD} = 0.234; W_{TLCTKT} = 0.215; W_{KCSDN} = 0.166; W_{KCML} = 0.140; W_{DD} = 0.090; W_{PBDC} = 0.155, with consistency ratio (CR) according to the AHP method being 1.29%.

The index for assessing technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam is calculated using the following formula:

$$P = \sum_{i=1}^{n} w_i X_i \qquad (1)$$

Where P is the index for assessing technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam; X_i is the score of criterion i; w_i is the weight of criterion i in the overall set of criteria influencing the sustainability of the groundwater exploitation technology solution (the sum of all weights equals 1); n is the number of criteria.

The map of technological solutions of groundwater exploitation and utilization in the water-scarce highland region of Northern Vietnam is constructed based on the index of applying sustainable groundwater exploitation technology using conduit systems in the water-scarce highland region of Northern Vietnam. This is done using GIS technology. The Weighted Sum tool in ArcGIS is utilized, using the raster format of each criterion map after normalization. The map theoretically represents the value of each pixel, ranging from 1 (indicating very low sustainability of the groundwater exploitation technology solution) to 5 (indicating very high sustainability of the groundwater exploitation technology solution). This value depends on the values of each criterion map, where 1 represents the lowest value and 5 represents the highest value. The framework applied in this study is presented in Figure 2.

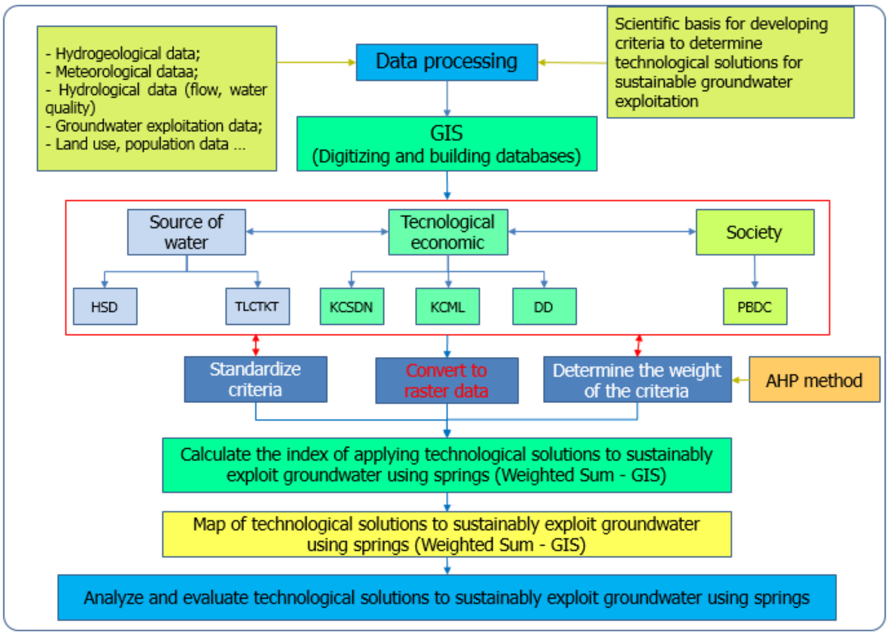

Figure 2. Framework of the study

Data partitioning can be done in various ways, with three common methods being: equal interval, natural breaks, and standard deviation. In the equal interval method, the data is grouped into intervals with equal value ranges, except for the values at the upper and lower bounds. The natural breaks method determines thresholds based on the inherent natural grouping present in the dataset, aiming to maximize similarity within groups and maximize the distance between classes. The standard deviation method represents the variation of attribute values from the mean value. The dividing thresholds are created with value ranges proportional to the standard deviation, often using intervals of 1, 1/2, 1/3, or 1/4 of the standard deviation. Based on the index of area identification to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam, the data can be divided into five categories: Very Low Sustainability, Low Sustainability, Moderate Sustainability, High Sustainability, and Very High Sustainability.

RESULTS AND DISCUSSION

All six thematic layers (hydraulic conductivity of aquifer, groundwater storage capacity, distance to water demand, distance to conduit system, terrain slope, population distribution/ density) with their spatial distribution in the study area are presented as follows.

Hydraulic Conductivity of Aquifers

The hydraulic conductivity of the aquifer reflects the capacity and movement of groundwater within the aquifer. A higher hydraulic conductivity indicates a greater potential for groundwater extraction, and vice versa (Do Ngoc Anh et al., 2019; Pham Ba Quyen et al., 2017). The hydraulic conductivity values for the aquifer layers were collected and synthesized from previous basic groundwater resource surveys in the study area. Accordingly, the hydraulic conductivity values for the aquifer layers range from 0 m^2/day to 6,429 m^2/day, with an average of 132 m^2/day. These values were compiled for each aquifer layer in each province within the study area (Figure 3).

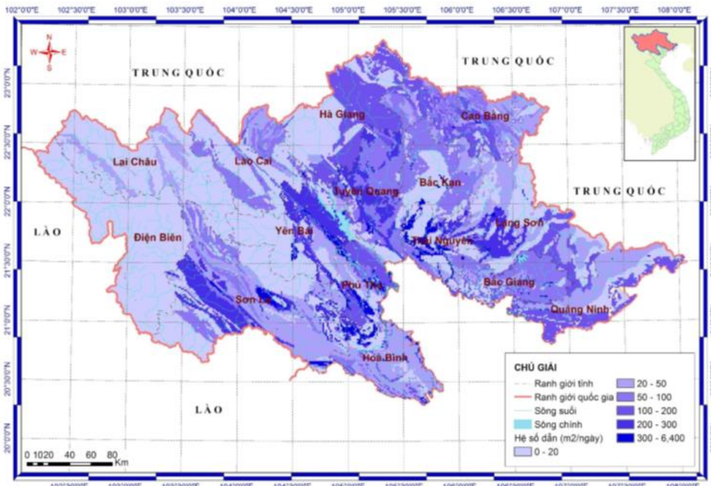

Figure 3. The map illustrating the zoning of hydraulic conductivity of the aquifer in the high mountainous, water-scarce areas of the Northern Vietnam

Exploitable Groundwater Reserve

The exploitable groundwater reserve reflects the water richness or abundance of the aquifers. The exploitable groundwater reserve is expressed through the module of exploitable groundwater reserve (in units of m^3/day/km^2). The aquifer layers with a larger module of exploitable groundwater reserve are considered to be more water-rich, and groundwater extraction facilities operate more stably, and vice versa (Do Ngoc Anh et al., 2019; Pham Ba Quyen et al., 2017).

The calculated results of groundwater storage for the entire study area determine the following: total storage capacity is approximately 13,557,116 m^3/day; recharge volume is around 20,093,875 m^3/day; Natural discharge potential is approximately 33,650,991 m^3/day; exploitable groundwater reserve is estimated to be around 10,095,297 m^3/day. The results of establishing the module map are shown in Figure 4.

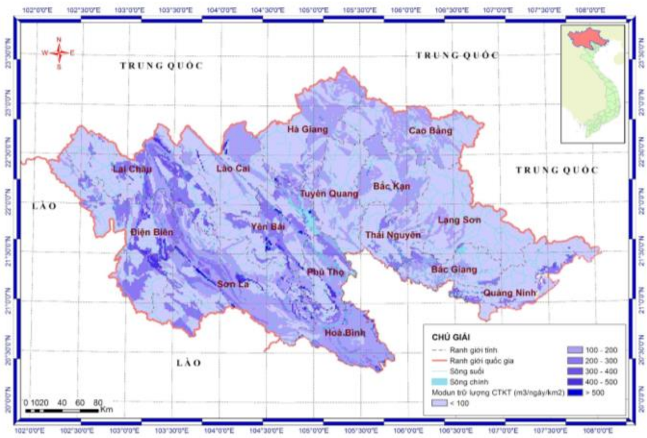

Figure 4. The map illustrating the zoning of exploitable groundwater reserve of the aquifer in the high mountainous, water-scarce areas of the Northern Vietnam

Distance to Water Utilization Point

The distance to water utilization point is crucial in constructing water extraction facilities. Central areas are often densely populated and have high water demand, thus prioritizing the construction of water extraction facilities is necessary. However, the sustainability of these facilities largely depends on the distance from the construction site to the water consumption areas. The closer the distance to residential and water usage areas, the better the investment efficiency and the effectiveness of water extraction and utilization. Areas far from water sources will incur higher costs for pipeline installation and pumping stations, along with maintenance and protection expenses, leading to inefficient operations. To determine the distance to water utilization points for evaluating and determining technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam, the administrative centers of commune-level, district, and city units in the provinces were identified within the study area.

Using the Buffer tool in ArcGIS software, the range of distribution for areas with corresponding distances to water demand at various levels was determined. Accordingly, 2,694 central areas were calculated with distances categorized as follows: very high distance: > 5km; large distance: 2km to 5km; medium distance: 1km to 2km; small distance: 0.5km to 1km; very small distance: < 0.5km. The results were compiled into a raster map and illustrated in Figure 5.

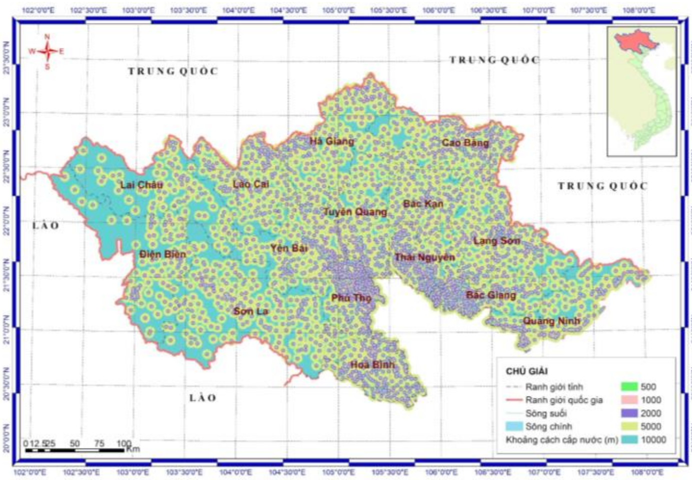

Figure 5. The map illustrating the distance to water ultilization points in the high mountainous, water-scarce areas of the Northern Vietnam

Distance to Spring

Springs usually emerge at specific locations. In fractured aquifer layers composed of sedimentary, igneous, metamorphic rocks, the density of springs is typically high, but the flow rates are low. Conversely, in karst regions, springs often have high flow rates but low density. The flow rates of springs can vary significantly over time and are dependent on rainfall. Some springs may have high flow rates during the rainy season but can run dry during the dry season, making them unsuitable for water extraction. When the distance between exploitable springs (springs with flow rates above 0.5 l/s) and water demand areas is large, the costs of constructing water pipelines, as well as maintenance and protection expenses, increase, leading to less sustainable infrastructure (Do Ngoc Anh et al., 2019; Pham Ba Quyen et al., 2017).

To determine the distance from exploitable springs to water utilization areas, the authors collected and compiled survey results during the dry season provided by NAWAPI for springts with flow rates above 0.5 l/s. The results were compiled for 1,917 springs in the high mountainous, water-scarce areas of the Northern Vietnam. Using the Buffer tool in ArcGIS software, the author identified areas with spring distances categorized into the following levels: very large distance: > 5km; large distance: 2km to 5km; medium distance: 1km to 2km; small distance: 0.5km to 1km; very small distance: < 0.5km. The distribution diagram of distances to exploitable springs is shown in Figure 6.

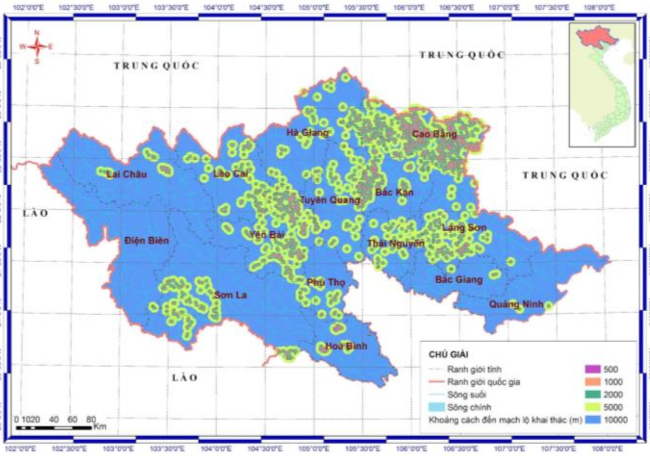

Figure 6. The map illustrating the distance to springs in the high mountainous, water-scarce areas of the Northern Vietnam

Terrain Slope

The terrain slope determines whether the construction of water extraction facilities is feasible. Flat terrain is highly favorable for constructing water extraction facilities, while steep terrain does not allow for the construction of such facilities (Do Ngoc Anh et al., 2019). The Slope tool in ArcGIS software was used to determine the terrain slope based on established categorizations. The resulting distribution diagram of terrain slopes in the study area is shown in Figure 7.

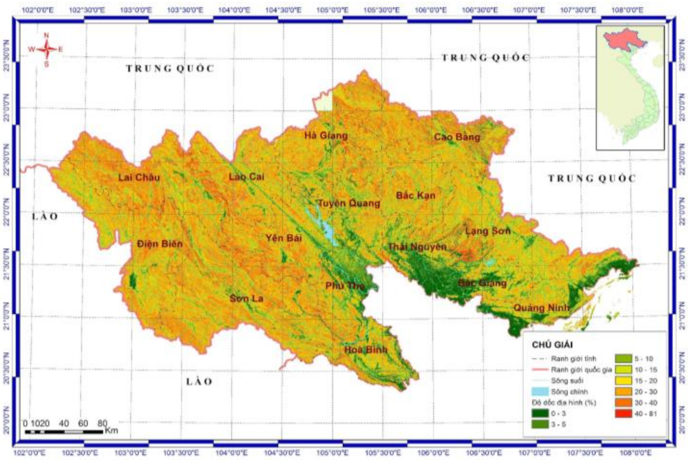

Figure 7. The map illustrating the terrain slope in the high mountainous, water-scarce areas of the Northern Vietnam

Population Distribution/Density

In densely populated areas, the construction of centralized water supply systems is prioritized. The distribution diagram of population in the study area was established in raster format to facilitate calculations for determining groundwater extraction and utilization technological solutions using categorized springs. The population density levels used for categorization are as follows: Very high population density: > 400 people/km²; High population density: 300 to 400 people/km²; Medium population density: 200 to 300 people/km²; Low population density: 100 to 200 people/km²; Very low population density: < 100 people/km². The results are illustrated in Figure 8.

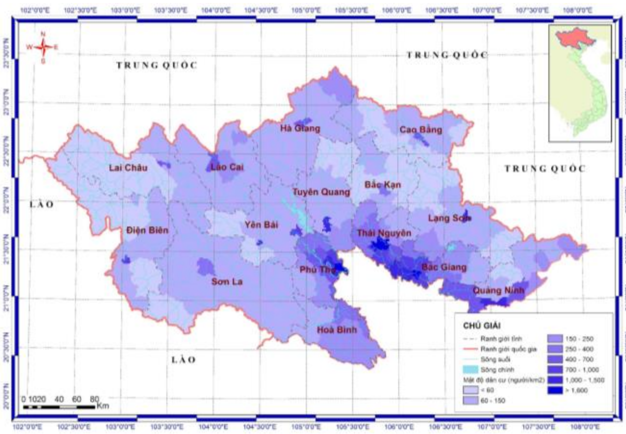

Figure 8. The map illustrating the population distribution/density in the high mountainous, water-scarce areas of the Northern Vietnam

Based on the calculated and standardized data for each criterion within the ArcGIS environment, the Weighted Sum tool was applied using formula (1) to overlay maps. This process determined the areas suitable for applying technological solutions of groundwater exploitation and utilization using spring for domestic water supply in high mountainous, water-scarce areas of the Northern Vietnam at different levels. The areas of each zone were computed within the ArcGIS software and exported as an Excel file. Subsequently, the data was processed to classify the levels of applicability for each commune, ward, and town within the study area.

The results of identifying areas to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam are presented in Table 2 and Figure 9. In these results, the areas where the groundwater exploitation technology using categorized springs can be applied at sustainable to highly sustainable levels are distributed across 1,094 communes, wards, and towns in 15 provinces within the study area, covering an area of 3,742 km² (which accounts for 3.8% of the study area's total area).

Table 2. Results of zoning technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam

No.	Level of sustainability	Distributed area (km^2)	Ratio (%)
1	Very Low Sustainability	10.594	10,6%
2	Low Sustainability	52.630	52,9%
3	Moderate Sustainability	32.550	32,7%
4	High Sustainability	3.732	3,8%
5	Very High Sustainability	10	0,01%

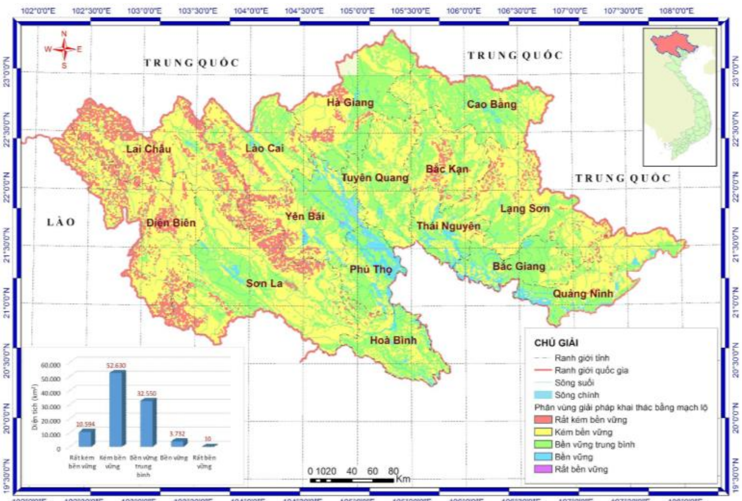

Figure 9. The map illustrating the area identification to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam

CONCLUSIONS

The determination of areas suitable to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam has utilized GIS techniques to provide an effective solution for sustainable water resource management. The research results indicate that the areas where this technology can be applied at sustainable to highly sustainable levels are distributed across 1,094 communes, wards, and towns in 15 provinces within the study area, covering an area of 3,742 km² (which accounts for 3.8% of the study area's total area).

The distribution map of the areas suitable to apply technological solutions of groundwater exploitation and utilization using spring in high mountainous, water-scarce areas of the Northern Vietnam, along with the research methodology employed in this study, will serve as a guiding principle for future projects and management programs aimed at the rational utilization of water resources, particularly in high mountainous, water-scarce regions in Vietnam where living conditions remain challenging.

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