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Criteria for selection of technology to exploit groundwater in water-scarce area in Vietnam

Trieu Duc Huy, Bui Du Duong, Pham Ba Quyen, and Vu Manh Hai

National center for Water resources Planning and Investigation (NAWAPI), Hanoi, Vietnam

Correspondence: Trieu Duc Huy (trieuduchuy@gmail.com)

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Abstract. Water extraction solutions in the high mountainous areas of Northern Vietnam commonly include rainwater harvesting, dug wells, drilled wells, groundwater springs, and hanging lakes. However, many water supply systems operate inefficiently and lack flexibility. This study established 10 criteria for selecting groundwater exploitation technology, divided into three groups: water resources, economic and technical, social, and environmental criteria. These criteria aim to identify appropriate water extraction technologies suitable for high mountainous and water-scarce regions, ensuring the long-term and efficient operation of water supply systems. The Geographic Information System (GIS) approach was utilized, integrating the criteria using the Analytical Hierarchy Process (AHP) method to select suitable water extraction technologies. The research results indicate that the evaluation criteria for determining suitable areas for implementing sustainable water extraction technologies, and the weights assigned to these criteria, ensure a consistent ratio (CR) $<10\,\%$ according to the hierarchical analysis method. This article presents the results of identifying areas suitable for implementing groundwater extraction technologies using drilled wells, based on seven criteria within three groups: water resources, economic and technical, and social criteria. The GIS approach has been employed, and the criteria have been integrated using the AHP to select and determine the areas suitable for implementing groundwater extraction technologies using drilled wells.

1 Introduction

The Northern region is the largest economic territory in Vietnam, characterized by complex natural geographical conditions, making it challenging to find water sources for daily life and production. To ensure effective and sustainable long-term water exploitation, it is essential to select appropriate technology and operational management tailored to each water source condition and other relevant factors. However, determining the right technology for water extraction in high mountainous and water-scarce areas is particularly difficult and depends on numerous factors. Many studies have focused on identifying areas suitable for implementing sustainable water extraction technologies using GIS techniques. Most of these studies use index calculation methods, leveraging GIS technologies to create maps that highlight suitable areas for sustainable water extraction technology (Ghayoumian et al., 2007; Suman et al., 2018).

2 Materials and Methods

2.1 Criteria for selecting groundwater exploitation technology in water-scarce areas in the Northern region

Scientific and practical research has established 10 criteria suitable for the study area and available data sets, divided into three groups: water source criteria, technical and economic criteria, and social criteria (Hou et al., 2017; Fanao et al., 2021; Indrani et al., 2020; Anh et al., 2018; Quyen et al., 2017). Currently, the technological solutions for exploiting groundwater in the high mountainous areas of Northern Vietnam include drilled wells, dug wells, springs, caves, and underground dams. These solutions are outlined as follows:

- Drilled Wells: Drilled wells are the most popular solution for exploiting groundwater. They often feature submersible pumps installed to extract water. The evaluation of zoning and application of technological solutions using drilled wells is based on seven criteria: Aquifer

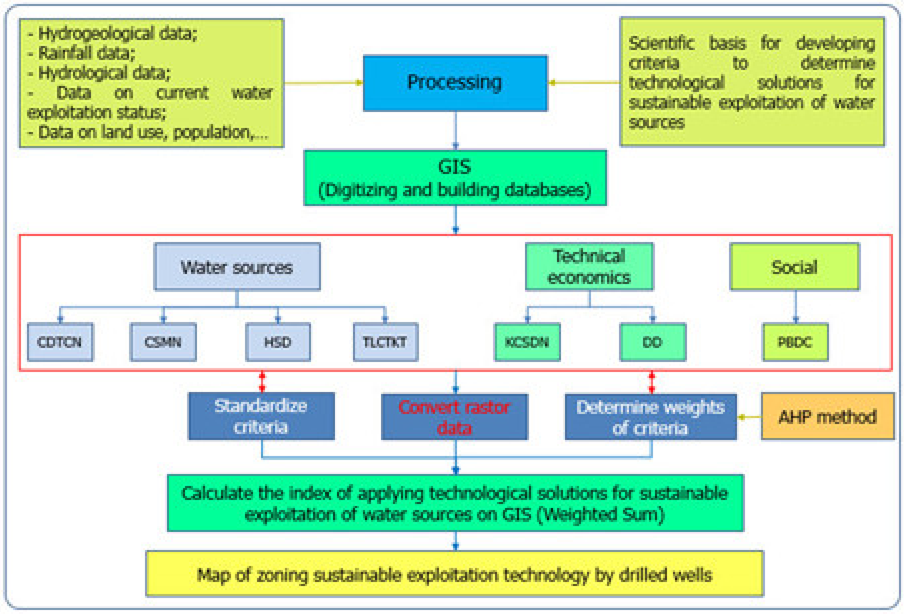

Figure 1. Diagram of methodology on identifying the locations applying sustainable groundwater exploitation technology solutions through drilled wells in the mountainous of the Northern area of Vietnam.

thickness (CDTCN); Aquifer conductivity (HSD); Water depth (CSMN); Exploitable reserves (TLCTKH); Distance to water use location (KCSDN); Terrain slope (DD); Population density (PBDC).

- Dug wells: Dug wells are a manual and common method for extracting groundwater. They typically target shallow groundwater in surface karst zones covered by partially or completely weathered sediments. These surfaces are often large and located in the lower parts of the terrain or karst valleys.
- Springs: Exploiting groundwater from springs involves a spontaneous approach where people collect water from natural streams and water bodies with small flows, channeling it for use through troughs or pipes.
- Caves: Groundwater exploitation in caves is popular in limestone areas, where water is pumped directly from the cave. Depending on the water level difference between the cave and the surface terrain, either a suction pump or a push pump is used. The flow rate of the suction pump depends on the allowable extraction flow and pump capacity.
- Underground Dams: This method involves constructing dams to block the flow and raise the groundwater level in the fractured karst zone, facilitating easier groundwater extraction.

2.2 Identify areas to apply technological solutions for exploiting groundwater resources by drilling wells in the Northern region of Vietnam

To establish a map for applying technological solutions to the sustainable exploitation of groundwater resources using drilled wells, a multi-parameter data set provided by State-level projects was utilized by the National Center for Water Resources Planning and Investigation. The data set includes the following:

- Water Source Criteria Group: Data on aquifer thickness, groundwater level depth, and aquifer conductivity coefficients were collected and synthesized from State-level project results. Data on exploitable groundwater reserves were calculated based on the hydrogeological parameters of aquifers (Tam et al., 2018).
- Technical and Economic Criteria Group: To determine the distance to water use locations, technological solutions for exploiting and using groundwater sources by drilled wells in high mountainous and water-scarce areas were evaluated. The centers of administrative units at commune, district, and city levels within the study area were identified. Using the Buffer tool in ArcGIS software, the distribution range of areas relative to water use locations was calculated and determined according to established levels. Terrain slope data were determined based on the digital elevation model (DEM). Using the Slope tool in ArcGIS software, terrain slopes were classified according to division levels (Tam et al., 2018).

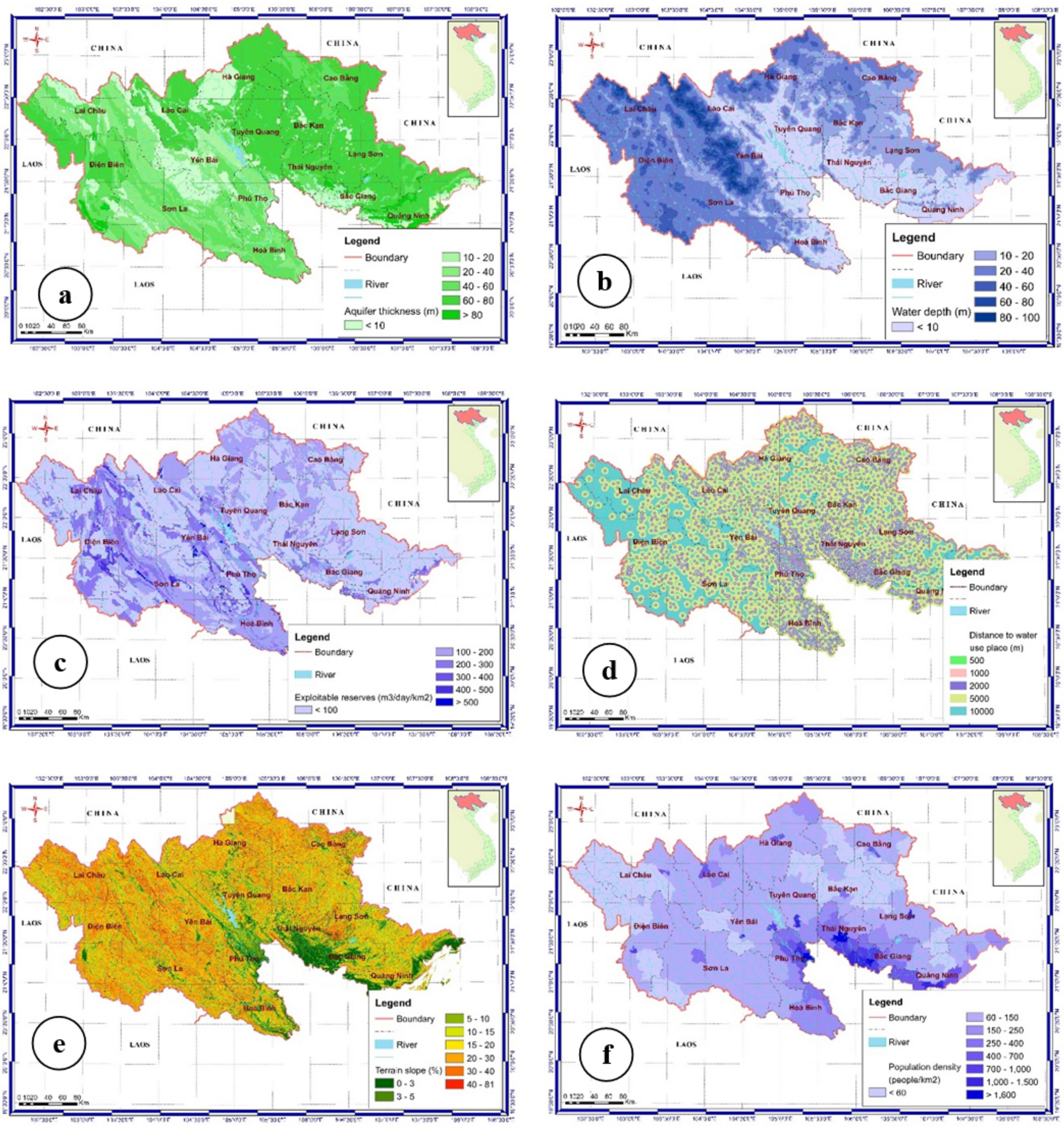

Figure 2. Distribution maps of criteria's value: **(a)** Saturation thickness (of aquifers), **(b)** Depth to groundwater level, **(c)** Exploitable reserve, **(d)** Distance to the groundwater usage point, **(e)** Terrain slope, **(f)** Population density.

– Social Criteria Group: Population density data were used to evaluate and determine technological solutions for exploiting and using groundwater sources by drilled wells. This data was synthesized from the natural area and current population status in the 2020 Statistical Yearbook of the provinces (Statistics, 2020), from which the population density ratio in the study area was calculated.

The Geographic Information System (GIS) approach has been utilized, and the criteria have been integrated using the Analytical Hierarchy Process (AHP) method (Saaty, 1980) to select suitable water extraction tech-

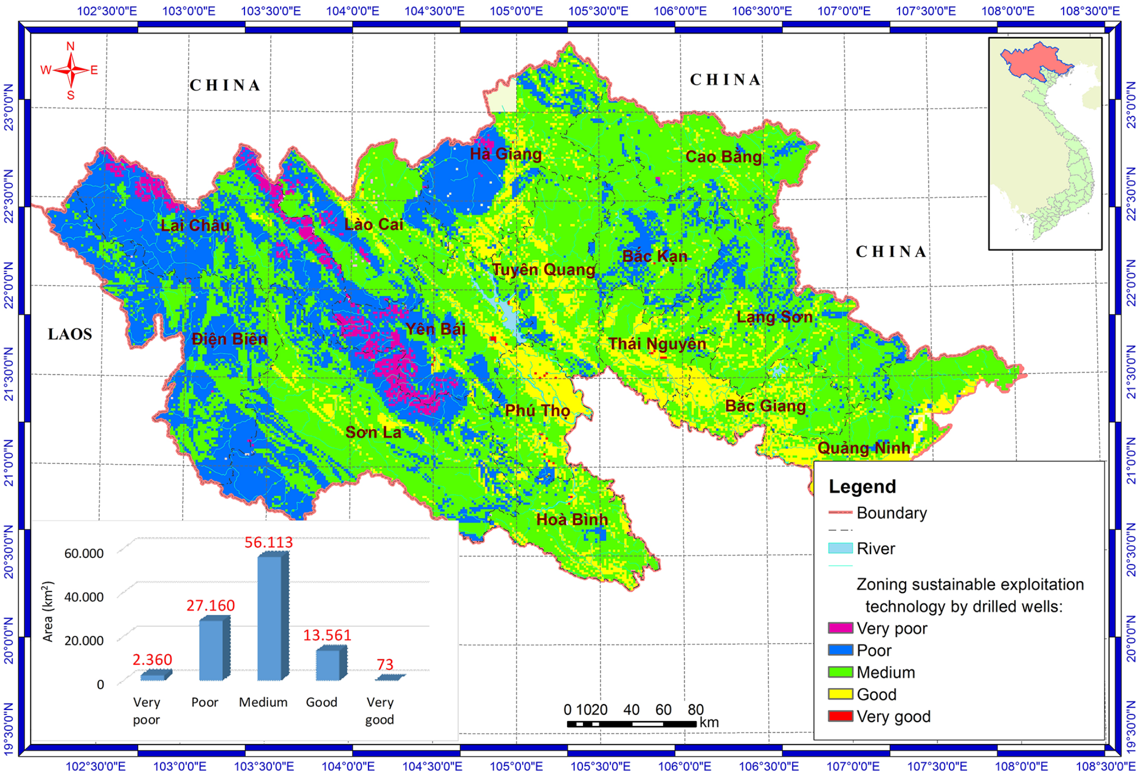

Figure 3. Maps of zoning sustainable exploitation technology by drilled wells.

nologies through drilled wells for the high mountainous and water-scarce areas.

3 Results

The spatial distribution of all seven criteria across the three groups (aquifer thickness, water depth, aquifer conductivity, exploitable reserves, distance to water use place, terrain slope, and population density) in the study area is detailed as follows:

- Aquifer thickness: The average thickness of aquifers in the study area is divided into regions with aquifer thickness ranges as follows: <10 m, from 10 to 20 m, from 20 to 30 m, from 30 to 50 m and >50 m.

- Water depth: The results of establishing a diagram of groundwater depth distribution in high mountainous, water-scarce areas in the Northern region have divided into areas with groundwater depth as follows: <10 m, from 10 to 20 m, from 20 to 30 m, from 30 to 50 m and >50 m.

- Aquifer conductivity: The conductivity coefficient of aquifers is divided into the following regions: $<15\,m^2\,d^{-1}$, from 15 to $30\,m^2\,d^{-1}$, from 30 to $60\,m^2\,d^{-1}$, from 60 to $90\,m^2\,d^{-1}$ and $>90\,m^2\,d^{-1}$.

- Exploitable reserves: The larger the exploitable reserve module of the aquifer, the richer it is in water, and the more stable the groundwater exploitation works are, and vice versa. The results of establishing the exploitable reserve module diagram of the aquifers have been divided into regions with the following values: $<100\,m^3\,d^{-1}\,km^{-2}$, from 100 to $200\,m^3\,d^{-1}\,km^{-2}$, from 200 to $300\,m^3\,d^{-1}\,km^{-2}$, from 300 to $500\,m^3\,d^{-1}\,km^{-2}$ and $>500\,m^3\,d^{-1}\,km^{-2}$.

- Distance to water use place: The distribution of areas with distance to the water use place is calculated by distance according to the following levels: <0.5 km, from 0.5 to 1 km, from 1 to 2 km, from 2 to 5 km and >5 km.

- Terrain slope: determines whether the ground allows the construction of water exploitation works or not. Flat terrain is very favorable for the construction of water exploitation and use works, the terrain is too steep and does not allow the construction of water exploitation works. Terrain slope is divided into the following zones: <5 %, from 5 % to 10 %, from 10 % to 15 %, from 15 % to 20 % and >20 %.

- Population density: The population density map in the study area is divided into the following levels: <100 people km^{-2}, from 100 to 200 people km^{-2}, from

200 to 300 people km^{-2}, from 300 to 400 people km^{-2} and >400 people km^{-2}.

Based on the data for each criterion (Fig. 2), calculations and standardizations were performed in the ArcGIS environment. The map superposition method, using the Weighted Sum tool in ArcGIS (Suman et al., 2018), was applied to determine the suitability of areas for groundwater exploitation using drilled wells. This process aimed to identify suitable areas for domestic water supply in the high mountainous and water-scarce regions of Northern Vietnam at various levels. The area of each region was calculated in ArcGIS software, and the data was exported to Excel for further processing and classification of applicability levels for each commune, ward, and town in the study area.

The results, shown in Fig. 3, indicate the following distribution of areas suitable for groundwater exploitation using drilled wells at a very sustainable (Very good) level has a total area of 73 km^2 (accounting for 0.07 % of the study area), sustainable (Good) has a total area of 13 561 km^2 (13.66 %), moderately sustainable (Medium) has a total area of 56 113 km^2 (56.53 %), unsustainable (Poor) has a total area of 27 160 km^2 (27.36 %), and very unsustainable (Very poor) with a total area of 2360 km^2 (2.38 %).

4 Discussion and Conclusions

The determination of area for applying suitable groundwater exploitation technologies by wells in the mountainous, water-scarce areas in Northern Vietnam using GIS technique provided an effective solution for managing the sustainable explotation of water resources. The results show that the used criteria are suitable for the mountainous, water-scarce areas and the weights of the established criteria ensure a consistent ratio (CR < 10 %) according to the hierarchical analysis method. Additionally, the areas applying groundwater explotation technologies by wells for water supply at the levels of very sustainable and sustainable are distributed across 1895 communes in 15 provinces.

Identifying and selecting appropriate criteria and determining suitable weights is crucial for determining areas to apply technological solutions for groundwater exploitation. This study demonstrates the effectiveness of using GIS to exploit drilled wells in high mountainous and water-scarce areas in Northern Vietnam. It provides a scientific and practical basis for planning the rational exploitation and use of groundwater resources in the region. However, when implementing these technological solutions, it is essential to carefully survey hydrogeological conditions and integrate management solutions to ensure sustainable project outcomes.

Four out of seven criteria were provided by State-level projects (Aquifer thickness, Water depth, Aquifer conductivity, Exploitable reserves). Due to incomplete data coverage of the study area, we used interpolation methods to estimate these criteria in similar areas. To improve the results, further studies are needed. In the near future, a groundwater monitoring network should be established to monitor groundwater levels and quality in real-time. Additionally, satellite monitoring should be used to estimate groundwater fluctuations through land subsidence/uplift using the InSAR method.

Data availability. Data are available on request from the authors.

Author contributions. TDH and PBQ planned the research; TDH, VMH and PBQ performed the measurements; PBQ, BDD, and VMH analyzed the data and modelling; VMH and BDD wrote the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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