Surface Stream Water Management in Northern Vietnam's High-Mountain, Water-Scarce Regions: Status Evaluation and Strategic Solutions

Thuy Thanh Thi TRAN [1,], Tuyet Minh Dang[2]*

[1)] Faculty of Environment, Hanoi University of Mining and Geology, 18 Vien Street, Hanoi, Vietnam;

[2)] Thuyloi University, 175 Tay Son Street, Hanoi, Vietnam.

ORCID: https://orcid.org/0009-0000-0682-5933
ORCID: https://orcid.org/0000-0001-8379-1087

* Corresponding author: tranthithanhthuy@humg.edu.vn

http://doi.org/10.29227/IM-2025-01-44

Submission date: 20-7-2025 | Review date: 20-11-2025

Abstract

This study investigates surface stream water scarcity in high-mountain areas of Northern Vietnam, specifically Cao Bang, Tuyen Quang, and Son La - where seasonal variability, deforestation, pollution, and limited infrastructure severely affect water security. Using a multi-method approach including field surveys, secondary data analysis, and a scoring system (1÷5), the research assessed influences from natural, socioeconomic, and technological factors. Findings show that nearly 69% of surface water facilities in the Northwest region are degraded, with extraction inefficiencies heightened during dry seasons. The lack of integrated management, weak regulatory frameworks, and limited community participation further compound the instability of water sources. To address these challenges, the study introduces a cause-effect model and proposes six strategic solution groups: improving governance systems, protecting upstream forests, upgrading infrastructure, adopting climate-resilient designs, enhancing water treatment methods, and promoting community-based management. These strategies are tailored to the unique environmental and socioeconomic conditions of high-mountain regions. Unlike earlier research that focused on isolated issues, this work offers a holistic framework for sustainable water resource planning. The practical value lies in its low-cost, locally adaptable solutions that support long-term water availability and resilience in vulnerable communities. Policymakers and stakeholders are encouraged to utilize the findings to improve water access and promote sustainable development across water-stressed rural landscapes in Northern Vietnam.

Keywords: *Surface water resources, mountain stream systems, water resource management, water supply infrastructure, Sustainable water solutions.*

1. Introduction

Surface water resources are one of the essential elements for socioeconomic development, particularly in developing countries like Vietnam, where agriculture continues to play a leading role in the economic structure. Surface water not only serves agriculture, industry, and domestic needs, but also contributes significantly to ecosystem maintenance, energy security, and disaster prevention. However, in the context of global climate change, population growth, rapid urbanization, and unsustainable resource exploitation, surface water is facing severe threats in both quality and quantity.

According to the International Water Resources Association, a country is considered water-scarce if its per capita endogenous water availability is less than 4,000 m^3/year. Vietnam currently averages approximately 3,370 m^3/person/year, indicating the existing and worsening water scarcity. Especially in high-mountain regions, where terrain is fragmented, population is scattered, and water supply systems are underdeveloped, people mainly rely on stream water sources for daily use and production. However, this water source is increasingly threatened by various factors such as climate change, headwater deforestation, pollution from domestic and production activities, and deterioration of water exploitation infrastructure.

Globally, many studies have demonstrated that protecting and sustainably exploiting surface water requires interdisciplinary coordination ranging from resource planning, headwater forest management, and pollution control to enhancing community awareness. Falkenmark & Rockström (2004) emphasized the role of "green water" (moisture in soil and vegetation) in maintaining natural flow and surface water stability [1]. Gleick (1998) introduced the concept of "water security" as a pillar of sustainable development, highlighting the need to ensure both quantity and quality of water for all citizens. Meanwhile [2], UN-Water (2020) warned that more than 2 billion people globally live in areas suffering from severe water shortage, a figure expected to rise unless effective policies are implemented [3].

In Vietnam, numerous studies have addressed surface water exploitation and protection, especially in water-scarce areas. Do Ngoc Anh (2019) proposed models for karst water extraction to supply drinking water in high-mountain areas, emphasizing the importance of protecting headwater forests [4]. Nguyen Thanh Cong (2018) explored the exploitation of freshwater lenses in coastal sandy zones, demonstrating the potential for surface water use in arid coastal areas [5]. Ha Hai Duong (2019) analyzed the challenges in water resource management in the Central Highlands [6], a region characterized by complex terrain and uneven water distribution. Reports from the Ministry of Natural Resources and Environment (2012, 2020) have pointed out the degradation of surface water due to pollution, overexploitation, and the lack of comprehensive planning [7, 8].

However, most existing research focuses only on individual aspects such as extraction technologies, water treatment, or forest management without adopting a comprehensive approach integrating natural, socioeconomic, and technological factors to evaluate surface stream water stability. Moreover, proposed solutions in such studies often lack feasibility when applied to high-mountain areas, where terrain, economic conditions, and community awareness remain major obstacles.

Therefore, this study was conducted to synthesize the status of surface stream water exploitation and use in the provinces of Cao Bang, Tuyen Quang, and Son La; to analyze the factors affecting water source stability; and to propose comprehensive, feasible solutions tailored to local conditions. The ultimate goal is to protect and sustainably exploit surface stream water, contributing to water security and socioeconomic development in high-mountain, water-scarce regions of Vietnam.

2. Study Area

The study area encompasses three mountainous provinces in northern Vietnam: Cao Bang, Tuyen Quang, and Son La, characterized by complex terrain with high mountains and dense networks of small rivers and streams. These water systems play a vital role in supplying water for domestic use and local production activities.

The surface water system in these provinces primarily consists of major rivers (Da, Lo, Bang, Gam, etc.) and hundreds of smaller, local streams. Due to the fragmented topography, mountain streams often serve as the main water source for highland communities, especially during dry seasons. However, significant seasonal variability, degraded water quality, and unstable volume pose serious challenges. Water reserves depend heavily on rainfall, vegetation cover in recharge zones, and the impact of human activities such as deforestation, livestock raising, and mineral exploitation.

As a representative region of water-scarce mountainous areas, this study site demands detailed assessments of stream sources to propose sustainable water extraction strategies that ensure community wellbeing and promote socio-economic development.

3. Methodology

This study was carried out using a comprehensive approach that combines field investigations, secondary data analysis, and both qualitative and quantitative assessments to identify factors influencing the stability of surface stream water sources in high-mountain, water-scarce regions. The scope of the research was focused on three provinces representative of the Northern region - Cao Bang, Tuyen Quang, and Son La - characterized by complex terrain, dispersed population, and a reliance on natural surface water.

First, the research team conducted field surveys in communes and districts where stream water exploitation infrastructure is currently in operation. Collected information included: the type of facilities, extraction capacity, number of households served, operational conditions, water quality, seasonal dependency, and any problems encountered during usage. The survey also documented topography, vegetation, current status of headwater forests, and local production and domestic activities with potential impacts on water sources.

Concurrently, the research team gathered and synthesized secondary documents, including sectoral reports, previously published studies, statistical data from the Ministry of Natural Resources and Environment (MONRE), provincial People's Committees, and international organizations. These materials provided insights into hydrological characteristics, climate conditions, stream flow data, water quality parameters, current exploitation status, and existing water resource management policies at the local level.

Next, the team developed a set of evaluation criteria to assess the degree of influence exerted by natural conditions, socioeconomic factors, and water exploitation technologies on stream water source stability. Each criterion was scored on a scale from 1 to 5, corresponding to impact levels from low to very high. Evaluation was based on comprehensive analysis, expert consultations, and validation against local realities.

Finally, the survey and analytical results were synthesized to construct a cause-and-effect model, which served as the foundation for proposing appropriate solution groups aimed at stabilizing surface stream water sources. These solutions were categorized according to their goals: maintaining water flow, improving water quality, enhancing extraction infrastructure, and reinforcing integrated management frameworks.

4. Results and Discussion

4.1. Current status of surface stream water exploitation and use

In Vietnam's high-mountain regions, especially in the Northeast and Northwest, surface stream water serves as a vital source of domestic supply. The most common exploitation method involves gravity-fed conduits from mountain streams to holding tanks via pipe networks, or pump stations that deliver water to residential areas. These systems are generally simple and utilize steep terrain and available water flows, which helps reduce initial investment costs and aligns with the local economic context [4].

However, reality shows that most surface stream water facilities are seriously degraded. According to surveys from Project Code DTDL.CN-61/15 (Ministry of Natural Resources and Environment) [9], the proportion of ineffective or damaged facilities in the Northeast reaches 55%, while in the Northwest it is as high as 69%. Main causes include insufficient funding for maintenance, a lack of capacity for management and operation at commune and village levels, and aging infrastructure built decades ago with little to no upgrading, resulting in leakage, rupture, water loss, and contamination.

Notably, during the dry season, typically from November to May, stream flows drop significantly, even to zero in many areas, making it impossible for water facilities to meet domestic needs. This is particularly severe in mountainous communes with no groundwater sources or centralized water supply systems. According to [7], dry season natural stream flow accounts for only 20 ÷ 30% of the annual total volume, posing immense challenges to maintaining water access for residents. Water shortages not only affect daily life but also interrupt agricultural production, increasing risks of local food insecurity.

4.2. Factors affecting the stability of surface stream water sources

The stability of surface stream water in terms of both flow rate and quality is subject to a complex interplay of natural conditions, socioeconomic pressures, and technological capacity. In mountainous terrain, stream flows are typically small and reliant on rainfall and forest cover. According to MONRE (2012), dry seasons in Northern Vietnam last for 6 to 9 months, during which natural stream flow volumes drop to only 20 ÷ 30% of the annual average. This leads to water scarcity, especially in highland communes like Ha Quang (Cao Bang) or Muong La (Son La). The impact level of natural conditions on the stability of surface water sources in the three surveyed provinces is assessed as shown in Table 1.

Table 1. Evaluation of the influence of natural conditions on surface water source stability in the surveyed provinces [10]

Tab 1. Ocena wpływu warunków naturalnych na stabilność źródeł wód powierzchniowych w badanych prowincjach [10]

No.	Criteria	Level		
		Cao Bang Province	Tuyen Quang Province	Son La Province
1	Impact of geographical location	2	2	2
2	Impact of topographic features	4	3	4
3	Impact of meteorological and climatic conditions	4	3	4
4	Impact of hydrological characteristics	5	5	4
5	Overall impact assessment score	3.2	2.8	3.0

Where, impact Levels on Water Source Stability is described through levels as follows: Level 1: Stability remains unaffected; Level 2: Minor influence detected; Level 3: Noticeable changes begin to occur; Level 4: Significant disruptions observed; Level 5: Severe destabilization present.

Climate change is a major destabilizing factor. Rising temperatures, decreasing rainfall, and irregular seasonal patterns reduce recharge rates for surface water. Moreover, extreme weather events such as prolonged droughts and unusual floods cause severe damage to water infrastructure, interrupting supply chains and degrading water quality. UN-Water (2020) warns that highland and coastal areas will be among the hardest hit by climate change-related water shortages.

Socioeconomic conditions also play a pivotal role. Population growth and agricultural expansion increase water demand while generating more domestic and industrial waste. In many rural areas, water-use practices are inefficient, with little awareness of conservation. Practices like free-range livestock grazing, dumping waste directly into streams, and burying the dead near headwater zones are common yet detrimental to water quality [4].

Furthermore, activities such as mining, road construction, and infrastructure development near recharge zones alter stream flow patterns, causing erosion, sedimentation, and contamination. Many water systems operate without permits or clear protocols, leading to overexploitation and mismanagement. According to the DTDL.CN-61/15 survey, most surface stream water facilities lack protective zoning, designated safety corridors, and collaboration mechanisms between local governments and communities for water management [9].

Collectively, these factors severely compromise the stability of surface stream water sources. Without comprehensive, integrated solutions encompassing environmental protection, resource planning, and public education, the risk of water shortages and ecosystem degradation will intensify, especially in mountainous, water-stressed regions.

4.3. Challenges in water management

Water management in high-mountain areas presents a complex web of challenges shaped by geography, climate variability, and socio-economic constraints. These regions, often characterized by steep terrain, fragile ecosystems, and limited infrastructure, are particularly vulnerable to water scarcity and seasonal fluctuations. One of the most pressing issues is the high variability in precipitation and runoff patterns, which are increasingly influenced by climate change. Snowmelt and glacial retreat have altered the timing and volume of streamflow, leading to unpredictable water availability during critical agricultural and domestic periods.

Another major challenge is the lack of reliable hydrological data. Many mountainous regions suffer from sparse monitoring networks, making it difficult to model water systems accurately or plan for future demand. This data scarcity hampers the development of robust water management strategies and limits the effectiveness of early warning systems for floods or droughts. In addition, the topographical complexity of high-altitude areas makes infrastructure development both technically demanding and financially burdensome. Constructing reservoirs, pipelines, or treatment facilities in these terrains often requires specialized engineering solutions and significant investment, which may be beyond the reach of local governments or communities.

Socio-economic factors further complicate water governance. Many mountain communities rely on traditional water-sharing practices that may not align with modern regulatory frameworks. Fragmented institutional arrangements and weak enforcement mechanisms often result in inefficient water allocation and conflict among users, especially during dry seasons. Moreover, transboundary water issues arise when rivers and streams cross national or provincial borders, requiring coordinated policies and diplomatic cooperation that are not always in place.

Environmental degradation also plays a role. Deforestation, overgrazing, and land-use changes reduce the natural capacity of watersheds to retain and filter water. This leads to increased sedimentation, reduced water quality, and heightened risk of landslides and flash floods. The thawing of permafrost and retreat of glaciers further destabilize slopes and threaten existing infrastructure. In some regions, tourism and urban expansion have placed additional pressure on limited water resources, often without adequate planning or regulation.

To address these challenges, a shift toward integrated water resource management is essential. This includes investing in nature-based solutions like reforestation and wetland restoration, improving data collection through remote sensing, and fostering inclusive governance that empowers local stakeholders. Without such coordinated efforts, high mountain areas will continue to face mounting risks to water security, livelihoods, and ecological integrity.

4.4. Proposed solutions for stabilizing surface stream water sources

Based on an analysis of factors affecting the stability of surface stream water sources, the study proposes a comprehensive, interdisciplinary, and highly feasible system of solutions to protect, sustain, and ensure the sustainable use of water resources in mountainous and water-scarce regions. These solutions are divided into six main groups aligned with management, technical, and community goals.

a. Forest cover and vegetation preservation

Preserving forest cover and vegetative ecosystems plays a pivotal role in stabilizing surface stream water sources, especially in mountainous terrains where hydrological cycles are highly sensitive to land-use changes. Headwater forests, particularly natural and watershed forests, act as ecological buffers that regulate runoff, reduce sedimentation, and maintain perennial stream flows. Their root systems enhance soil retention and groundwater recharge, mitigating the impacts of seasonal droughts and flash floods.

To incentivize forest conservation, consistent implementation of forest ecosystem service payments is recommended. These payments should be coupled with livelihood support programs for forest-dependent communities, ensuring that conservation efforts align with socio-economic development goals [4]. Moreover, population growth control in vulnerable areas and the promotion of water-saving practices such as greywater recycling, rainwater reuse, and low-flow irrigation are essential for reducing pressure on natural water sources. Integrating agroforestry and reforestation into local land-use planning can further enhance vegetative resilience and water retention capacity.

b. Climate change adaptation

Climate change poses escalating risks to water availability in high-mountain regions, necessitating proactive adaptation strategies tailored to local topography and climatic conditions. One effective approach is the construction of decentralized, climate-resilient water storage systems. These include tanks (cisterns), subsurface dams that trap underground flow, and rainwater harvesting structures designed to capture and store seasonal precipitation (Figure 1).

Figure 1. Water storage system serving the local population in Son La and Cao Bang Provinces [11, 12]

Rys 1. System magazynowania wody obsługujący lokalną ludność w prowincjach Son La i Cao Bang [11, 12]

Pilot projects in Binh Thuan and Gia Lai provinces have demonstrated the viability of these systems in maintaining year-round domestic water supply, particularly during extended dry seasons [5]. Scaling up such models requires technical training, community engagement, and financial support from both national and international partners. Furthermore, climate adaptation should be mainstreamed into socio-economic development plans, with emphasis on integrating climate risk assessments, greenhouse gas mitigation technologies, and cross-border cooperation on water resource management. By aligning local adaptation efforts with global climate goals, Vietnam can enhance its resilience to hydrological stress and safeguard water access for remote communities.

c. Integrated water resource management

Integrated Water Resource Management (IWRM) is a foundational strategy for ensuring long-term water security in high-mountain, water-scarce regions. This approach emphasizes the coordinated development and management of water, land, and related resources to maximize social and economic benefits without compromising ecosystem sustainability. In Vietnam, the legal framework for IWRM is anchored in the Water Resources Law (2023) and Decree 53/2024/ND-CP, which mandates the identification of protected water sources and the establishment of water protection corridors.

Key implementation steps include delineating sanitation buffer zones, regulating wastewater discharge points, and enforcing spatial boundaries around critical water bodies. These measures are essential for preventing contamination and preserving water quality. Additionally, strengthening the licensing system for water resource exploitation, particularly for irrigation canals, reservoirs, and pumping stations, is vital. Licensing not only helps monitor extraction volumes but also prevents financial losses due to unregulated use and inefficiencies in water budgeting (MONRE, 2020). To enhance effectiveness, local authorities should integrate digital monitoring tools and community-based reporting mechanisms into their water governance systems.

d. Water quality protection

Solutions for water quality protection center on controlling pollution sources from domestic activities, agriculture, industry, and mining operations. Key interventions include constructing wastewater treatment systems, implementing waste segregation at the source, promoting biogas technology in livestock farming, and managing construction-related waste. These measures play a critical role in minimizing pollutants entering water bodies (Figure 2).

Additionally, raising community awareness is essential to shift water usage and discharge behaviors. This is especially important in ethnic minority regions, where traditional practices have a notable influence on water quality. Encouraging behavioral changes in daily water use and waste disposal will contribute significantly to safeguarding water resources in a sustainable and long-lasting way.

Figure 2. Installation of a biogas system for waste treatment purposes [13,14]

Rys 2. Instalacja systemu biogazowego do celów przetwarzania odpadów [13,14]

e. Sustainable water infrastructure

To ensure the long-term viability and functionality of surface water extraction facilities, it is critical to implement a systematic evaluation of all degraded infrastructure. Structures that have deteriorated over time due to factors such as erosion, under-maintenance, and aging materials should be prioritized for repair, modernization, or complete replacement based on current engineering standards and local environmental conditions. This approach helps extend the operational lifespan of water systems, reduce water loss, and secure a reliable supply for communities in mountainous and water-scarce regions.

Equally important is the restructuring of management frameworks to encourage greater community participation. Delegating operational authority to locally organized water management groups has shown promising results in improving responsiveness and accountability. When backed by sustained technical training and financial assistance from local governments and development agencies, community operators are better equipped to handle routine maintenance, emergency response, and data reporting. This decentralization model enhances ownership, promotes resource stewardship, and fosters greater sustainability through localized solutions.

Moreover, the application of innovative and context-appropriate technologies has proven crucial in addressing water scarcity issues. Among these, subsurface dams and hillside water collection ditches, developed and validated by the Water Resources Institute, have emerged as low-cost, high-efficiency alternatives to conventional infrastructure. Subsurface dams help retain water within streambeds by preventing underground seepage, while hillside ditches capture rainwater runoff and channel it for household or agricultural use. These solutions are particularly suited to steep terrains and fragmented landscapes where large-scale water systems are impractical. Their adaptability and scalability make them valuable assets in climate-resilient water planning strategies [15].

f. Household water treatment solutions

Improving household water quality in mountainous and remote areas requires investment in low-cost, decentralized treatment methods suitable for communities lacking access to centralized systems. Practical solutions include alum-based clarification to reduce turbidity, activated carbon filtration to remove chemical contaminants and unpleasant tastes, chlorine disinfection to kill harmful microbes, and the use of household-scale filter tanks composed of layered materials such as sand, gravel, and carbon. These systems can be constructed from locally available resources and tailored to treat surface, rainwater, or shallow well sources effectively. Implementation should be linked to rural development programs that provide technical training, financial support, and community education to ensure correct operation and maintenance. Promoting local manufacturing of treatment materials, along with behavior change campaigns on water hygiene and safety, helps embed these technologies in daily life. Overall, household-level water treatment enhances public health, supports climate resilience, and advances equitable access to clean water in marginalized regions.

Overall, these solutions encompass technical measures and require strong coordination among government, community stakeholders, and professional institutions. Comprehensive implementation will enhance stream water stability, secure drinking water access, and support sustainable development in challenging regions.

5. Conclusion

This study presents a comprehensive evaluation of surface stream water usage in Vietnam's high-mountain, water-scarce regions, specifically in Cao Bang, Tuyen Quang, and Son La provinces. It highlights that most water exploitation systems are seriously deteriorated and ineffective in maintaining a stable supply during dry seasons. Stream water stability is further challenged by environmental and anthropogenic factors such as deforestation, climate change, population growth, pollution, and limitations in management capacity and technology.

Through detailed analysis, the study identifies key drivers of water source degradation and introduces six integrated solution groups aimed at protecting and managing stream water sustainably. These strategies encompass technical, institutional, and social dimensions, emphasizing the need for cross-sector coordination and active community engagement to ensure effectiveness and long-term resilience.

The findings offer a foundation for enhancing water security and improving livelihoods in disadvantaged upland areas. Additionally, the research sets the stage for future directions in water resource planning, with a focus on terrain-specific and climate-adaptive approaches that align local management practices with broader sustainability goals.

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TYTUŁ: Zarządzanie wodami powierzchniowymi w górskich regionach północnego Wietnamu o ograniczonych zasobach wodnych: ocena stanu i rozwiązania strategiczne

Badanie analizuje niedobór wód powierzchniowych w północnych prowincjach górskich Wietnamu - Cao Bang, Tuyen Quang i Son La - gdzie sezonowa zmienność, wylesianie, zanieczyszczenie i słaba infrastruktura wpływają na bezpieczeństwo wodne. Zastosowano podejście wielometodowe: badania terenowe, analizę danych wtórnych i system ocen od 1 do 5, by określić wpływ czynników naturalnych, społeczno-ekonomicznych i technologicznych. Prawie 69% instalacji wodnych w regionie północno-zachodnim jest zdegradowanych, a w porze suchej problemy się nasilają. Brak zintegrowanego zarządzania, nieskuteczne regulacje i ograniczony udział społeczności pogłębiają niestabilność źródeł. W odpowiedzi przedstawiono model przyczynowo-skutkowy i sześć grup rozwiązań: ulepszenie zarządzania, ochronę lasów, modernizację infrastruktury, projekty odporne na zmiany klimatu, skuteczniejsze oczyszczanie wody oraz działania oparte na społecznościach lokalnych. Strategie są dostosowane do warunków środowiskowych i społecznych regionów górskich. W przeciwieństwie do wcześniejszych prac skupiających się na pojedynczych aspektach, niniejsze badanie prezentuje całościowe ramy zrównoważonego planowania zasobów wodnych. Wartość praktyczna polega na dostępnych cenowo, lokalnie dostosowanych rozwiązaniach wspierających trwały dostęp do wody oraz odporność społeczności zagrożonych jej niedoborem. Zachęca się decydentów i interesariuszy do wykorzystania wyników w celu poprawy dostępu do wody i rozwoju obszarów wiejskich dotkniętych stresem wodnym.

Słowa kluczowe: *Zasoby wód powierzchniowych, Systemy górskich cieków wodnych, Zarządzanie zasobami wodnymi, Infrastruktura zaopatrzenia w wodę, Zrównoważone rozwiązania wodne*