Diagnosis of Gravity fed Water Supply systems in the Mountainous Regions of Northern Laos.

A study case in Nyot Ou district, Phongsaly Province, Lao P.D.R

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Diagnosis of Gravity fed Water Supply systems in the Mountainous Regions of Northern Laos. A study case in Nyot Ou district, Phongsaly Province, Lao P.D.R

Tazio Siegmann[a], Erwin Poligne[b],
Anthony Guéguen[c], Touleelor Sotoukee[d]

[a] Transfers, Interfaces and Processes (TIPs), Université Libre de Bruxelles (ULB)
[b c d] Comité de Coopération avec le Laos (CCL)

Abstract

This study investigates the performance and sustainability of rural water supply systems in upland villages of northern Laos, where access to safe drinking water remains uneven despite recent improvements. Focusing on four villages in Nyot Ou district, Phongsaly Province, the research applies a socio-ecological systems (SES) framework to analyze the interactions between water resources, technical infrastructure, governance structures, and local communities dynamics. Data were collected through focus group discussions, household surveys, field observations of water systems, and remote sensing analysis of land-use change using NDVI.

The results reveal that water supply systems are affected by multiple interconnected disturbances, including population growth, governance weaknesses, land-use changes, and climate-related hazards such as droughts and landslides. Governance challenges—particularly limited participation, unclear management rules, and low trust—emerge as key constraints to effective system maintenance. Technical issues, including inadequate system design, improper sizing, and suboptimal spring selection, further reduce system reliability. In addition, land-use dynamics in watershed areas significantly influence water availability and quality, thereby affecting overall system resilience.

The findings highlight the limitations of standardized technical approaches and emphasize the need to account for local socio-ecological complexity. The study recommends integrating watershed management, context-specific infrastructure design, and strengthened community governance to enhance the long-term sustainability of rural water supply systems.

With the financial support of

Introduction

Ensuring freshwater access is one of the primary human needs and one of the 17 Sustainable Development Goals adopted by all United Nations Member States in 2015. Despite being a tropical humid zone, Southeast Asia has faced significant issues regarding freshwater availability in recent years. This challenge is notably driven by population growth and the depletion of water catchment areas (Chuan, 2003). Furthermore, the region's monsoonal weather patterns have been modified over time, leading to more extreme events such as floods and droughts (Loo et al., 2015).

Inadequate water sources are a major reason for the transmission of diseases such as cholera and diarrhea ("Lao Social Indicator Survey II 2017," n.d.). The lack of easy access to drinking water also increases the hardship of the conditions of the population, particularly women. The proportion of households accessing a basic water supply has increased from 69% in 2011 to 78% in 2017. However, disparities and water quality issues persist, with 6 out of every 7 households drinking water contaminated with faeces and the poorest households seeing almost no progress in access to basic water supplies from 2011 (56%) to 2017 (57%) (UNICEF, 2019).

In Laos, more than two-thirds of the population lives in rural areas. However, the part of the agricultural sector remains limited. Wealth is still concentrated in natural resource extraction and driven by large scale foreign investments in hydropower, mining and infrastructure (ADB, 2018). Having remained relatively on the margins of economic markets, the rural communities are facing with structural poverty which limits their investment and constitutes an overall obstacle to the sustainable development of the territory. The government's priority remains to reduce poverty in a desire to contribute to sustained and inclusive economic growth (GoL, 2021).

Since 2008, through its rural development projects, the CCL has supported eighteen mountain villages in the Nyot Ou district of Phongsaly province in improving their access to drinking water. This study is motivated by the need to assess the relevance and impact of the infrastructure that has been built, identify potential gaps and weaknesses in water resource management activities, enhance the effectiveness of future development projects, and encourage deeper reflection on the local challenges related to water access.

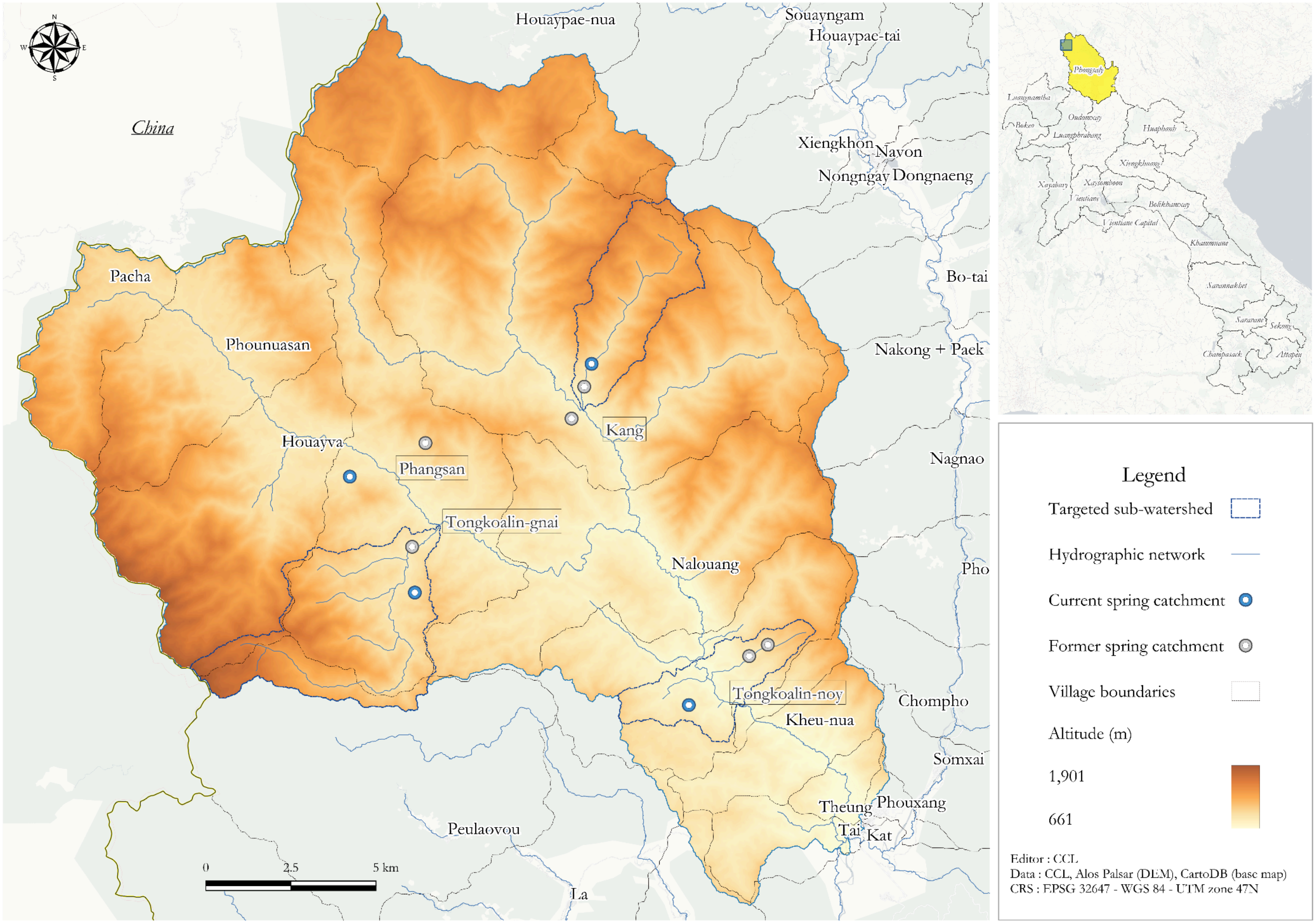
To address these interconnected challenges, this study employs a socioecological approach to analyze and establish a methodology for understanding the dysfunctions in water supply systems in upland villages. Water supply installations are complex socioecological systems composed of various subsystems with internal variability at different levels. These resource systems can be divided into components such as resource systems, resource units, governance, and actors (Ostrom, 2009).

This study explores how water supply systems are designed and implemented in upland villages of northern Laos by NGOs and relevant government institutions. By framing these systems, we aim to better understand the interconnections among their various components and characteristics, extending beyond technical elements to include social and ecological contexts. This approach also supports discussions on community strategies and levels of trust in local institutions. Furthermore, such an understanding can reveal specific circumstances that give rise to particular challenges, ensuring these dimensions receive greater attention during implementation.

Study area and national water management structure

The study takes place in the northernmost district of Laos, Nyot Ou district, located in Phongsaly province. This region experiences a monsoonal climate, which induces a binary climate pattern. The mean annual rainfall is 1,100 mm, with 80% of this precipitation falling during the rainy season from July to the end of October. The mean temperature is 22°C.

Four villages within the village cluster of Naluang have been chosen for this case study: Tungkualin Noy, Tungkualin Nyay, Pangsan, and Kang (illustration 1). All the springs are situated in the sub-watershed of the Nam Deng River, which is part of the Nam Ou River watershed and itself part of the Mekong watershed. This configuration makes all the spring located on the top of their watershed. It has two main consequences: the quantity of water is limited by the upstream area of the springs, but it significantly reduces pollutant levels since the upstream area is relatively small.



Houaypae-nua
Souayngam
Houaypae-tai
China
Xiengkhon
Navon
Nongngay
Dongnaeng
Pacha
Bo-tai
Phounuasan
Nakong + Paek
Kang
Houayva
Phangsan
Nagnao
Tongkoalin-gnai
Nalouang
Pho
Tongkoalin-noy
Chompho
Kheu-nua
Somxai
Theung
Phouxang
Tai
Kat
Peulaovou
La
0
2.5
5 km
Legend
Targeted sub-watershed
Hydrographic network
Current spring catchment
Former spring catchment
Village boundaries
Altitude (m)
1,901
661
Editor : CCL
Data : CCL, Alos Palsar (DEM), CartoDB (base map)
CRS : EPSG 32647 - WGS 84 - UTM zone 47N

The households in the four villages are predominantly Yao (Pangsan, Tungkualin Nyay, and half of Tungkualin Noy) and Kheu (Ban Kang and the other half of Tungkualin Noy). The current positions of these villages are quite recent and reflect the considerable mobility of their inhabitants over the last few decades across a territory stretching from Menghai in Yunnan, China, to the upper part of the Nam Ou River. The movements of clans and families were shaped by various factors, including political and social changes, issues occurring during the Indochina War, the search for available land for shifting cultivation, natural resources, and trade opportunities. All of the target villages have been in their present locations since 2005, date where the national poverty eradication program and its resettlement component have played an important role in reallocating some of these villages. The stated aim was to move villages from ridge areas to valleys to facilitate access to education and health services. For example, both the Yao and Kheu households that now make up Ban Tungkualin Noy had to move from the uplands to the lowlands to improve, according to the government their access to services and expedite their transition from shifting agriculture to fixed agriculture.

However, the landscape remains dominated by a mosaic of fallow land for rainfed rice cultivation on the slopes. The rotation period can vary from ten to twelve years in villages such as Ban Kang, where land resources are significant, to five to six years for the Kheu community of Tungkualin Noy. Beyond the slopes adjacent to the valley, the mountainous areas are covered with secondary forests, where farmers have developed tea gardens from wild tea plants. In contrast, Ban Kang uses the forest areas for extensive cattle and buffalo breeding. A rubber plantation is encroaching on part of the slopes in Tungkualin Noy. The valley floor is developed into irrigated rice fields along the watercourse.

Laos' administrative structure is composed of ministries at the national level. The country is divided into provinces, each with its own administration, and within the provinces, there are districts. The water management structure is divided into two parts: the urban and peri-urban zones, and the rural zones. The urban part is called *Nampapa* and is under the Ministry of Public Work and Transport. The rural part is called *Namsaat* and is under the Ministry of Health.

Methodology

In this study, we conducted an assessment of the implementation of water supply systems in the four upland villages of Nyot Ou district mentioned above. To structure this assessment, we applied a slightly adapted version of the Socio-Ecological Systems (SES) framework developed by McGinnis and Ostrom (2014). The adaptation emphasizes the integration of the technical dimension of water supply systems, recognizing it as a cornerstone of the broader socio-ecological system.

Diagnosis traditionally means asserting the nature or cause of something, usually an unwanted condition. Tied to a diagnosis is the idea that different types of causes have implications for treatments. The possible amelioration of a condition by successfully applying a particular treatment is the motivation for the process. Our interest in the process of diagnosis here is to explore its potential use in overcoming the ‘panacea problem’.

Panacea problems occur when a single presumed solution is applied to a wide range of problems. This issue has two distinct dimensions. The first dimension arises when the theory is too precise to be adapted to the range of cases to which it is applied. This dimension is sometimes referred to as the "blueprint," leading to a lack of fit between programs, technical installations, and their supposed socio-ecological targets. The second dimension of the panacea problem involves theories that are excessively vague instead of excessively precise (Ostrom and Cox, 2010).

To overcome these problems, we will use the SES framework as a diagnostic tool. This approach may allow us to predict potential problems in a given configuration or at least provide hints on the dimensions we should focus on for implementing durable gravity fed water supply systems. SES are composed of subsystems and exhibit internal variation at multiple levels. SES subsystems are relatively separable but interact to produce outcomes. Understanding a complex whole requires knowledge about specific variables and how their component parts are related. Thus, we must dissect and harness complexity rather than eliminate it (Ostrom, 2009). The dynamics of an SES are structured by the interdependency between biophysical and social systems. Neither can be understood separately to grasp the systemic dynamics (Folke, 2006). The subsystems are (i) the resource systems, (ii) the resource units, (iii) the governance systems, and (iv) the actors and (v) interactions. Each of these subsystems is made up of second-Tiers variables, which will be detailed further in the development.

SES has already been used in a broad range Topic. It is employed for management practice (Stern and Baird, 2015), climate change adaptation (Frantzeskaki et al., 2019), irrigation systems (Cox, 2014), forestry (Fleischman et al., 2010). However the framework has been extend as in our case beyond the resource adding a technical dimension as energies systems (Ye, 2014) .

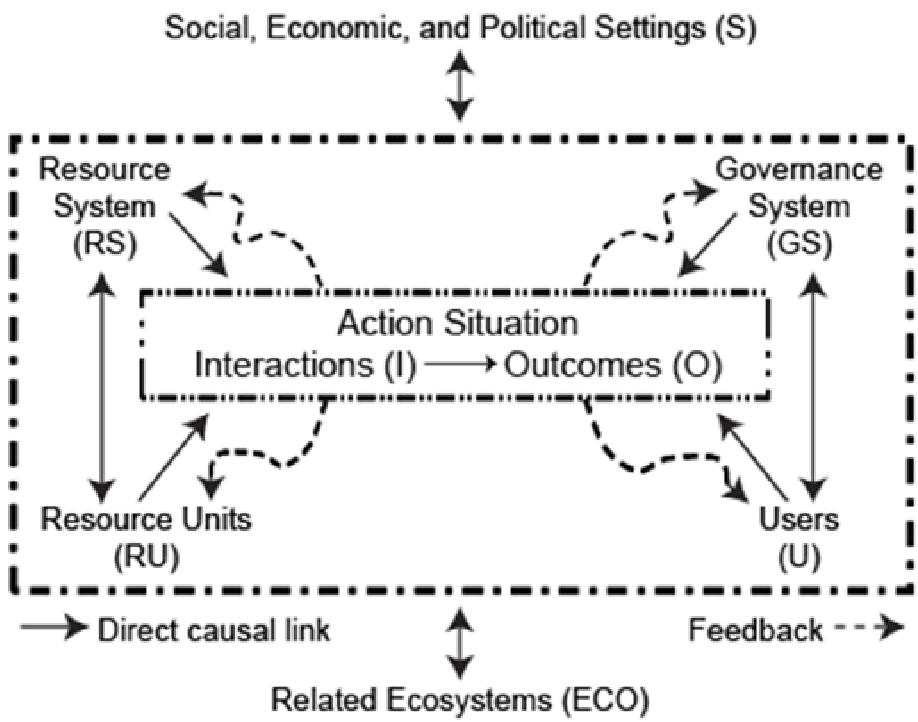


Figure 2 The first tier of a framework for analyzing an SES. Source: Adapted from Ostrom (2007:15182).

Data collection

For data collection, we selected four villages that have been supported by CCL since 2008, each representing different social and physical configurations—such as mixed ethnic groups, enclaved territories, and isolated locations. The data consist of three main components.

Firstly, we organized focus groups in the four target villages. In each village, one group included the village chief and several elders, primarily men. The second group was exclusively composed of women.

During these focus groups, we discussed the evolution of the water supply systems in the village, the governance surrounding them, the maintenance dynamics of the technical facilities, the quality of the water, and any potential problems linked to the spring itself, including the choice of the spring and the rules protecting it.

Based on the information gathered in these focus group discussions, we selected fifteen households in each village, considering a good spatial distribution to accommodate potential variability in water quantity and maintain gender parity. All these questions aimed to cover the SES framework through the perceptions of the actors and a dynamic of cross-checking the information.

The second part was based on observing the technical installation of the WS system and evaluating its relevance and evolution. This observation can provide insights into the reasons for the dysfunctions, the appropriateness of the construction choices concerning the spatial disposition of the spring, and their relevance to the village layout and population.

The third part of the analysis focuses on the evolution of land use in the small water catchment areas. Indeed, land cover and land practices have a significant influence on the water cycle (Chuan, 2003; Gallart and Llorens, 2003; Ribolzi et al., 2018). In our studies, we could not establish a definitive hydrological conclusion on the impact of land use as the cause of the spring's drying up. However, we sought to identify tendencies or presumed causes of poor management in the watershed area linked to the spring, as land use and land cover impact infiltration dynamics and groundwater residence time (Lacombe et al., 2016).

To gain an overview of land use dynamics around the spring, we decided to use a visual interpretation tool to evaluate forest cover density. The tool employed is the Normalized Difference Vegetation Index (NDVI) (Erinjery et al., 2018a; Phompila et al., 2014a), which is based on the comparison of spectral wavebands. This comparison allows us to create an index ranging from -1 to 1, where -1 indicates no vegetation and 1 indicates very high-density vegetation. The spectral bands compared are red and near-infrared: the greater the infrared component, the higher the vegetation density.

This tool uses satellite imagery, and we chose data from the Sentinel-2 program. The imagery has a resolution of 10 meters and a revisit time of 5 days. For our study, we decided to compare images from February 2018 and February 2024. This choice of month was made for meteorological reasons, as low cloud cover is typical during this period, and the impact of the dry season on vegetation is minimal.

Since the NDVI provides a continuous density index based on the resolution of the area, we needed to define categories for computing surface changes between the chosen years. The K-means clustering algorithm (Lemenkova and Debeir, 2022) was used for unsupervised categorization based on the calculation of Euclidean distances between previously determined centroid clusters. For our case, the statistical method yielded 13 classes, which we grouped into 5 classes.

- Very high vegetation density (NDVI mean 0.9)
- High vegetation density (NDVI mean 0.86)
- Medium vegetation density (NDVI mean 0.77-0.8)
- Low vegetation density (NDVI mean 0.57 - 0.6)
- Absence of vegetation (NDVI mean 0.33-0.36)

In our study, even though we have information on the key dynamics necessary for conducting a diagnosis, we do not have enough data to establish variable correlations. However, our data allows us to develop theories on the main dynamics contributing to the resilience and robustness of the WS systems. These studies are useful for developing theoretical arguments and understanding complexity but may be insufficient for testing causal claims using techniques drawn from mainstream quantitative science (Fleischman et al., 2010).

SES case study navigation

The SES structure guides our understanding of the problem and allows us to define the boundaries of the systems, and the outcomes linked to them. The actors influence the biophysical environment by making management decisions. Factors that influence resource extraction present governance challenges and shape the interactions between the SES and neighboring SES. In this table, we will navigate through all the tiers, allowing us to have a good view of the overall systems and enabling us to identify the main causes of robustness and resilience.

First-Tier Variables	Second-Tiers Variables	Situation of the case studies
	Economic Development (S1)	Before 2005, the villages primarily engaged in subsistence agricultural practices. These consisted of rice cultivation, livestock breeding, collection of non-timber forest products, and hunting and fishing, which provided a small monetary income from livestock and opium sales. In the early 2000s, the villages began to harvest forest tea due to increased interest from Chinese traders. This period was also marked by the planting of rubber trees promoted by the government and the growing market for contract farming, utilizing off-season paddy rice areas in a 3+2 model and monoculture of bananas in a 4+1 model.
	Demographic tendencies (S2)	In all the targeted villages, the population has increased over the last two decades (+13% from 2019 to 2024 in Ban Kang and Tungkualin Nyay and 4% in Tungkualin Noy and Phangsan).
Social, economic and political context	Political Stability (S3)	The politics of the Lao People's Democratic Republic (Lao PDR) takes place within a framework of a one-party parliamentary socialist republic. The only legal political party is the Lao People's Revolutionary Party

		(LPRP), which has held power since December 1975. Administratively, the country is divided into provinces, which are further divided into districts. Each district contains several villages (79 in the concerned district). In each village, a village chief is elected for a four-year term. Candidates must be validated by the government and meet various criteria, including the ability to read and write in Lao. The village chief is assisted by at least two deputies. Villages may also have voluntary representatives from the party's decentralized services, such as a representative of the Lao Women's Union or a youth representative. Regarding customs, the committee of elders plays an important governance role. It is consulted on decisions related to land management, village relocation, and the management of potential intra-village conflicts.
	Government politic of resources (S4)	The Government of Laos adopts a state-centric approach to natural resource management, reflecting its socialist governance structure. Natural resources—including land, forests, minerals, and water—are constitutionally recognized as national property under the ownership of the Lao people, with the state acting as the administrator and regulator. Over the past two decades, the Lao government has promoted the exploitation of natural resources as a central pillar of its economic development strategy, particularly through hydropower, mining, and large-scale agriculture. These sectors attract significant foreign investment, especially from neighboring countries such as China, Vietnam, and Thailand.
	Market Trends (S5)	Linking to Section 4, exports are primarily driven by the natural resource extraction industry. In the primary

		sector, there is also the emergence of a contract farming model led by Chinese SMEs in the target area, manifested through rubber plantations (such as in Tungkualin Noy), as well as maize, job's tear plantations, and off-season vegetable farming in paddy areas.

First-Tier Variables	Second-Tier Variables	Situation of the case studies
	Sector (RS1)	Gravity-fed water supply system
Resource system	Clarity of the boundary system (RS2)	The boundary of the system has three dimensions. Firstly, we can compute the surface hydrological watershed boundary, but the hydrogeological boundary can vary slightly depending on geological configuration. In this study, we will assume that these two boundaries are the same and based on the surface watershed. Another boundary is the one that the villagers designate as a protected zone around the spring.
	Size (a) and Volume(b) (RS3)	(a) Area: Small water shed surrounding the spring ranging from 429.25 ha to 2269 ha (b) Volume: Our studies were conducted in a too short time to have a quantitative evaluation of the available volume. Even though there is a clear variability caused by the seasonal pattern of dry and wet season.
Resource System	Human constructed facilities (RS4)	The gravity fed water supply systems in Laos mainly use the same design. This technical construction brings water from a spring to the surrounding villages, passing through a tank that serves as a buffer. Two coarse filtration systems are implemented, primarily to avoid pipe obstruction. One is at the outlet of the capture, and the other is before the inlet of the tank.

	Productivity Of the System (RS5)	Productivity is the capacity of the WS system to provide enough water for the villagers' needs. These needs may change over time due to population growth and evolving habits. Productivity also encompasses the quality of the water provided.
	Equilibrium of the system (RS6)	An equilibrium is achieved when the technical dimensions of the WS align with the needs of the villagers, the actual availability of water in the spring, and the villagers' awareness of the system's limits. This awareness promotes maintenance and encourages a relatively realistic consumption level in relation to availability.
	Predictability of the system (RS7)	(a) Since water systems have complex, multifactorial dynamics of circulation in a water catchment, a sufficient analysis to predict conditions in each catchment is truly time-consuming, knowledge-intensive, and material-demanding. The circumstances we focus on do not allow us to predict the behavior of the resource. (b) In the construction of human facilities, there are no measurement tools available to detect or assess potential malfunctions. (c) Considering population growth in given villages and the presumed most logical locations for the addition of households.
	Location (RS8)	The location of the spring is essentially based on the villager's knowledge of their territory

First-tier Variables	Second-Tier Variables	Situation in the villages
	Resource units' mobility (RU1)	(a) Natural mobility exists from the rain input in the water catchment to its outlet. In a simplified view, this is a top-down displacement. This mobility is divided into a runoff component and an infiltration component. The proportion of these components depends significantly on land cover, land use, and geological/pedological configuration. (b) Human-driven mobility using the WS technical installation brings a portion of the water from one or multiple spring points upstream of the village, utilizing gravity as the driving force.
	Replacement Rates (RU2)	In the dry season, the only source of water is groundwater. The replacement rate is influenced by the amount of rain falling on the catchment, as well as the saturation rate of the soil and its permeability, which lead to the recharge of the aquifer. All WS systems should be designed based on the low flow occurring during the later stages of the dry season.
	Interactions among resource units (RU3)	Land gestures have a great influence on the water resource and its cycle.
Resource Units	Economic Value (RU4)	Since human construction is financed by external funding, the economic value is based on the eventual maintenance costs and the payments for the individuals performing this maintenance. The amount is variable among the villages and sometimes is nonexistent.
	Number of units (RU5)	1
	Distinctive markings (RU6)	There are no merchandising possibilities for this resource, as the main problem is the lack of accessibility to it.
	Spatiotemporal distribution (RU7)	The distribution is mainly driven by the monsoonal climate patterns.
First-tiers	Second-tiers	Situation in the village

	Government Organization (GS1)	The Namsaat is a program under the Ministry of Public Health. It is responsible for water supply and sanitation in rural areas. It plays two main roles in WS implementation: providing technical assistance and facilitating financing.
	Non-government Organization (GS2)	NGOs are the main funding suppliers for WS system financing in rural areas. Although in certain cases, they also provide technical assistance and help in implementing an administrative structure.
	Network Structure (GS3)	The villagers are the users of the WS and participate in decision-making through a committee council. They are responsible for the maintenance of the network and the collection of maintenance fees. In general, the same structure is applied, consisting of three members: one is the technician who makes repairs, one is responsible for accountancy, and the last is the village chief. All decisions are made in meetings that are convened when a problem arises. The taxing system has two main forms. One is a periodic fee that can vary in frequency and price, depending on the village's willingness and ability to pay. The second method is to request money only when a problem arises, specifically for repairs. There is also a hybrid model, which includes a fee to finance the person who oversees and maintains the system, with additional funds requested when materials must be purchased for repairs.
Gouvernance System	Property right-System (GS4)	When Laos PDR was established, land was transferred from royal ownership to the people, represented by the state (Ducourtieux et al., 2005). As a result, the state grants land use rights to individuals, which include the right to protect the land, the right to utilize the land, the right to benefit from the land, the right to transfer land use rights, and the right to inherit these rights. At the village level, a customary land tenure system prevails, featuring a mix of collective and individual land management.

		The first person to clear a plot for rice cultivation acquires usage rights. If another family wishes to use that fallow land later, they must seek permission from the original user. Rice fields and plots of perennial crops, such as tea, carry exclusive usage rights. Forests are utilized without formal access rights, and their management is the responsibility of the village along with district and provincial authorities.
	Operational Rules (GS5)	The guidelines for management rules are generally provided by the Namsaat, but in practice, it is primarily the village committee that decides on the structure used and the protected zone surrounding the spring.
	Collective choice rules (GS6)	The decision-making process is conducted by the committee council. The committee represents the community and is elected by its members.
	Monitoring and sanctioning process (GS7)	In certain cases, a sanctioning process exists when territorial rules are not followed. The sanction applied is decided by the village comity.

First-tier Variable	Second-tiers Variable	Villages situation
	Number of Actors (A1)	The actors are the villagers, the Namsaat technician and authority and the NGOs.
	Socio economic attribute of Users (A2)	The users are primarily smallholder farmer, with varying main income sources depending on the village.
Actors	Location (A3)	All inhabitants and users are part of the community.
	Leadership (A4)	The committee ensures the main management duties and maintenance of the WS. When major decisions need to be made, a village consultation meeting is held, and the decision is voted on.
	Knowledge of the SES (A5)	The villagers are aware of the impact of land use on water quantity. This, therefore, links

		social impacts on the environment to the resource.
	Norms and Social capital (A6)	It manifests through social networks and trust in the village chief and the committee in charge.
	Dependency of the resource (A7)	Water is one of the primary needs. Ensuring a sufficient quantity and quality helps avoid numerous problems. Providing water close to the villagers allows them to allocate the time previously spent fetching water to other activities.
	Technology used (A8)	The technique used is a simple gravity fed water supply system.

First-tier Variables	Second- tier Variables	Village situation
	Consumption level of diverse users (I1)	The theoretical consumption set by the Namsaat is between 45 and 65 L/person/day. The technical WS installations are built based on these values.
	Information sharing among users (I2)	The main share of information is through the meeting council in the villages.
	Deliberation process (I3)	When major decisions must be made, a vote is conducted.
	Conflict among users (I4)	Conflict can have two dimensions: (a) Inter-village conflict can arise from the impact of land use by another village that is adjacent to the watershed spring. (b) Intra-village conflict can occur regarding the use of the resource, as well as the location and

		use of the land surrounding the spring.
Interactions	Investment activities (I5)	Investment takes two different forms: financial and manpower. These investments have different sources: (a) Government institutions (Namsaat) (b) Non-governmental organizations (c) Contributions from the villagers themselves
	Lobbying activity (I6)	none
	Self-organization activity (I7)	In some cases, the villagers decide to build the WS themselves, without financing or technical support.
	Networking activities (I8)	No network activities have been observed.
	Sanctioning activity (I9)	In some cases, fines are imposed when the land protection zone is not respected.
	Evaluative activity (I10)	No long-term evaluations have been conducted by any actors.

	Social Performances measurement	A sufficient and high-quality amount of water during both the dry and wet seasons for each villager.
Outcomes	Ecological performances measurement	The ability to supply sufficient water, even during a prolonged dry season, and to provide non-polluted water for all users while conserving the area surrounding the spring.
	Externality to other SES	

Results

Common Disturbances

The four villages experience five different types of disturbances. Three of them are internal to the village communities: disturbances in leadership and governance structure, disturbances in membership transition, and disturbances in land use and land practices. A fourth disturbance is external to the villages, namely disturbances caused by natural disasters and climate change. The fifth type can have both origins, as it includes disturbances related to the sizing of the WS system and the choice of the spring. This bivalent origin is linked to the fact that some aspects of the process are more dependent on the villagers' input, while others come from external sources. Although natural disasters in our cases have a non-measurable provenance and impact, we will attempt to discuss the social implications of the weaknesses in the SES to withstand these disturbances. The duration of disturbances can range from a punctual event such as a flood to longer-term membership disturbances such as population growth.

In these villages, the disturbances have different time scales and significance in terms of impact. Some of these disturbances have a greater irreversibility component compared to others. Each community will react and may respond, and in some cases, they may implement adaptive responses with varying degrees of effectiveness and durability. Moreover, each village has its own land characteristics, surface area, and relationship with surrounding villages. These characteristics contribute to the relative ability to maintain a robust WS SES, or they may indicate points that are intrinsically more sensitive.

Leadership and Governance structure				
Village	**Event**	**Factors leading to disturbances**	**Eventual response**	**Adaptiveness of the response**
Ban Kang	Water consumption abuse, maintenance issue	Network Structure (GS3), Operational Rules (GS5), Collective Choice Rules (GS6), Monitoring/Sanctioning Process (GS7), Location [of Users] (A3), Leadership (A4), Consumption Level (I1), Information Sharing (I2).	Sanctioning Activity (I9)	No information

Ban Pangsan	none	Number of Actors (A1), Knowledge of SES (A5), Norms/Social Capital (A6), Dependency on Resource (A7), Operational Rules (GS5).	none	No information
Ban Tungkualin noy	Conflict between two ethnic group within the village, garden watering, maintenance issues.	Network Structure (GS3), Operational Rules (GS5), Collective Choice Rules (GS6), Knowledge of SES (A5), Norms/Social Capital (A6), Information Sharing (I2), Deliberation Process (I3), Conflict Among Users (I4).	none	No information
Ban Tungkualin nai	Maintenance issue and water use abuse	Network Structure (GS3), Operational Rules (GS5), Norms/Social Capital (A6)	none	No information

Membership transition				
Village	**Event**	**Factors leading to disturbances**	**Eventual response**	**Adaptiveness of the response**
Ban Kang	Increase of population	Demographic Tendencies (S2), Predictability of System (RS7), Number of Actors (A1), Leadership (A4).	none	No information
Ban Pagsan	Increase of population and upstream village displacement	Demographic Tendencies (S2), Predictability of System (RS7), Number of Actors (A1), Leadership (A4).	Human-Constructed Facilities (RS4), Government Organizations (GS1), Non-Government Organizations (GS2),	Adaptative

			Investment Activities (I5)	
Ban Tungkualin noy	Multiethnic village population	Demographic Tendencies (S2), Location [of Spring] (RS9), Network Structure (GS3), Collective Choice Rules (GS6), Location [of Users] (A3), Knowledge of SES (A5), Norms/Social Capital (A6).	none	No information
Ban Tungkualin nai	Increase of population and upstream village growth	Demographic Tendencies (S2), Predictability of System (RS7), Number of Actors (A1), Socio-Economic Attributes (A2), Leadership (A4).	Human-Constructed Facilities (RS4), Non-Government Organizations (GS2), Investment Activities (I5)	Maladaptative

Land use and land practice				
Villages	**Events**	**Factors leading to disturbances**	**Eventual response**	**Adaptiveness of the response**
Ban Kang	Use of the land surrounding the spring	Size of Resource System (RS3), Operational Rules (GS5).	none	No information
Ban Pagsan	none	/	none	No information

Ban Tungkualin noy	Use of the land surroundin g the spring	Size of Resource System (RS3), Operational Rules (GS5).	none	No information
Ban Tungkualin nai	Use of the land surroundin g the spring	Size of Resource System (RS3), Operational Rules (GS5).	none	No information

Natural disasters and climate hazards				
Village	**Events**	**Factors leading to disturbance s**	**Eventual response**	**Adaptiveness of the response**
Ban Kang	Land slide due to heavy rain	Stochastic event	Investment Activities (I5), Self-Organiza tion Activities (I7).	Maladaptive
Ban Pangsan	none	none	-	-
Ban Tungkualin noy	Drought	Stochastic event	Operational Rules (GS5).	Maladaptive
Ban Tungkualin nai	Drought	Stochastic event	Knowledge of SES (A5), Non-Govern ment Organizations (GS2).	Maladaptive

Sizing, design of the WS system				

and spring choice				
Village	**Events**	**Factors leading to disturbances**	**Eventual response**	**Adaptiveness of the response**
Ban Kang	Quantitative issues, Turbidity, pesticides contamination, poor construction	Size of Resource System (RS3), Human-Constructed Facilities (RS4), Equilibrium of System (RS6), Spatiotemporal Distribution (RU7), Technology Used (A8), Evaluative Activity (I10).	Human-Constructed Facilities (RS4), Government Organizations (GS1), Investment Activities (I5)	Maladaptive
Ban Pagsan	Quantitative issues, Turbidity, pressure drops	Size of Resource System (RS3), Human-Constructed Facilities (RS4), Equilibrium of System (RS6), Location [of Spring] (RS8), Productivity of System (RS9), Spatiotemporal Distribution (RU7), Technology Used (A8).	Human-Constructed Facilities (RS4), Government Organizations (GS1), Non-Government Organizations (GS2), Investment Activities (I5)	Adaptative
Ban Tungkualin noy	Quantitative issues, Turbidity, Poor construction	Human-Constructed Facilities (RS4), Equilibrium of System (RS6),	Human-Constructed Facilities (RS4), Government Organizations (GS1),	Adaptative

		Productivity of System (RS9), Spatiotemporal Distribution (RU7), Technology Used (A8).	Non-Government Organizations (GS2), Investment Activities (I5)	
Ban Tungkualin nai	Sizing issues	Human-Constructed Facilities (RS4), Equilibrium of System (RS6), Location [of Spring] (RS8), Government Organizations (GS1), Non-Government Organizations (GS2), Technology Used (A8).	Human-Constructed Facilities (RS4), Non-Government Organizations (GS2), Investment Activities (I5).	Maladaptive

Leadership and Governance Structure

The governance structure of the WS system encompasses various elements, including water usage, fees and payments, maintenance responsibilities, and the management of the land surrounding the spring. Namsaat and the non-governmental institutions (GS1, GS2) consistently suggest a similar structure for water governance (GS3, A5). This structure consists of a committee composed of villagers (I9). The committee is made up of three members: firstly, the head of the village, who should possess the greatest authority as they have been elected (GS6, A5). The second member is responsible for accountability and collecting funds for various purposes. These funds serve two main objectives: compensating committee members for their work and providing materials for any necessary repairs. The exact purpose and amount of money collected depend on the village (GS5, GS6). The third member is tasked with maintaining the capture system, the tank, and the network of pipes (RS4).

Three villages are experiencing leadership disturbances: Ban Kang, Ban Tungkualin Noy, and Ban Tungkualin Nai. A failure to develop and adhere to collective choice rules in Ban Kang has contributed to these disturbances (GS6). No responsibilities were distributed, and individuals responsible for repairs were not clearly designated (GS3). As a result, no one acted when technical issues arose, and no fees were regularly collected to facilitate repairs. The entire system relies heavily on trust and individual willingness to contribute both time and resources (A6). With population growth (A1), an increasing number of people are using the same taps, which is straining this informal organization. Due to the lack of regulation, instances of water abuse—such as watering gardens and leaving taps open when not in use—have been observed (A6, A7). The situation has worsened (A8), prompting the community to decide, through a village meeting, to build a new capture system themselves (GS3, I5, I7) with very limited resources and technical expertise. Unfortunately, this solution proved not to be sustainable.

Tungkualin Nyay is facing similar issues but with less dramatic outcomes compared to Ban Kang (A2). This village has encountered problems related to water consumption abuses (A6) and maintenance issues, with no one stepping up to make repairs, despite the existence of a fee and a water committee (GS3, GS5). The fee and its objectives were clearly stated but did not appear to be consistently operational.

In Tungkualin Noy, the village is made up of two distinct ethnic communities, each of them been relocated by the government from ridge area to the valley (A4). This has created a multiethnic population complicating the leadership and governance system (GS3, A2, A5, A6). There are two chiefs, one representing each ethnic group (I4). In the previous WS system, a committee existed for a few years but did not function perhaps because of the coexistence of the two communities in the same administrative entity. Each ethnic group has issues of trust. Regarding the selection of a new capture system. Two proposals were presented, but each seemed to correspond to the territory of one ethnic group. The chosen site appeared to be private land belonging to an ethnic group member who is no longer a resident of the village (RS9, GS5). The second ethnic group has been observed to water gardens, thereby limiting the use of water from the old capture system during the dry season (GS5). A clear dual system exists with no real consensus or agreement within or between the ethnic groups (GS3, GS6, A2).

Since Ban Pangsan has not faced major leadership disturbances, all four villages are encountering problems related to a lack of transparency and participation between the leadership core and the village members (I2, A5), particularly concerning the women in this community. Despite this, Ban Pangsan's leadership has maintained a good maintenance process and tax system, with a clear record of payments made.

Membership Transition

The four villages are facing a population growth disturbance (A1) which intrinsically increases the demand on the resource (S2, RU3). Thereby, new house constructions are sometimes higher than the existing water tank (RS4). Gravity being the driving force of the pressure becomes impossible to provide water to these houses (A4, A9).

Ban Pangsan has been limited by the space availability on the original village emplacement. So that a big part of the villages had to move to a higher place (A4).

As discussed previously Ban Tungkualin noy is composed of two ethnic groups leading to several consequences in the area used by each ethnic groups and leadership outcomes.

In villages where the incomes are low (S1, A2), the adaptation ability is weak because the accessibility to resources is low and the number of users is still increasing (A1, RU2). Being poor do not allow the villagers to invest time and money in their infrastructure (I5, I7). This situation is well represented by Ban Kang. In an opposite situation Ban Tungkualin Nyay has a wealthier situation (S1) allowing them to buy filtering devices, repairing materials or, for some families, by purchasing 20-liter bottles of water from the district capital.

Interpreting NDVI Dynamics

The NDVI (Normalized Difference Vegetation Index) remote sensing technique allows us to have an overview of the land use and practices surrounding the water supply springs (RS2, RS4, RS6). In **Tungkualin Nyay**, a clear trend of increasing vegetation density is observed. The proportion of the watershed classified as high-density vegetation rose substantially from 54.3% to 66.4%, while areas of medium and low-density cover decreased. This shift indicates a process of vegetation regrowth and increasing biomass, likely due to natural forest regeneration on fallow lands or the establishment of perennial crops like tea. For the water supply system, this trend is promising; increased high-density vegetation enhances soil infiltration, reduces surface runoff and erosion, and promotes more stable groundwater recharge. This ecological improvement likely contributes to greater resilience of the spring's flow, buffering against seasonal droughts and protecting water quality by minimizing sediment load.

Conversely, **Tungkualin Noy** exhibits a pattern of vegetation degradation or fragmentation. The area of high-density vegetation decreased from 49.3% to 43.2%, while medium-density vegetation expanded markedly from 30.6% to 48.1%. This transition signals a reduction in mature forest canopy and a shift towards younger, sparser, or more disturbed vegetation. This pattern is consistent with active forest clearing, the shortening of agricultural fallow cycles, or the lasting impact of the 2019 fire described by the villagers. For water resources, this trend is concerning. The loss of dense canopy reduces the watershed's water retention capacity, potentially leading to more extreme flow variations—higher peaks during rains and swifter declines during dry periods. It also increases susceptibility to soil erosion and landslides, which directly threaten water quality and infrastructure, aligning with the village's reported experiences of water shortage and system vulnerability.

Tungkualin Nyay		*Surfaces (Ha)*		*%*	
Classes	*Clusters (NDVI mean values)*	*2018*	*2024*	*2018*	*2024*

Barren land	*0.12-0.42*	*/*	*/*	*/*	*/*
Low vegetation density	*0.42-0.68*	*68*	*18.5*	*3.0%*	*0.8%*
Medium vegetation density	*0.68-0.83*	*898*	*743*	*39.6%*	*32.8%*
High vegetation density	*0.83-0.9*	*1233*	*1507*	*54.3%*	*66.4%*
Very high vegetation density	*>0.9*	*70*	*/*	*3.1%*	*/*

Tungkualin Noy		Surfaces (Ha)		%	
Classes	Clusters (NDVI mean values)	2018	2024	2018	2024
Barren land	0.12-0.42	11	5	1.3%	0.6%
Low vegetation density	0.42-0.68	161	70	18.8%	8.1%
Medium vegetation density	0.68-0.83	263	413	30.6%	48.1%
High vegetation density	0.83-0.9	423.5	371	49.3%	43.2%
Very high vegetation density	>0.9	/	/	/	/

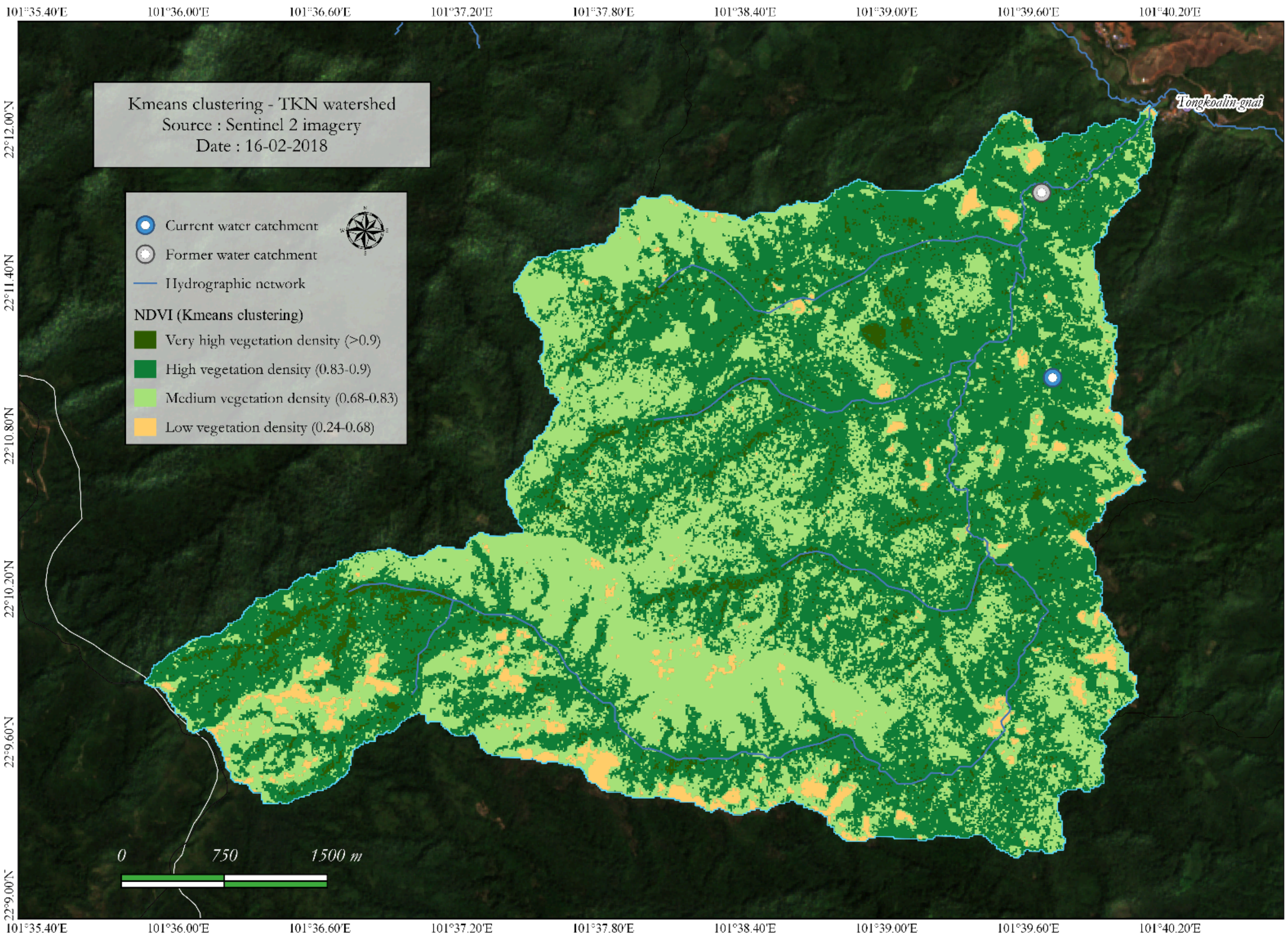


Figure 3: NDVI map of Tungkualin Nyay watershed -16-02-2018 sentinel 2A imagery.

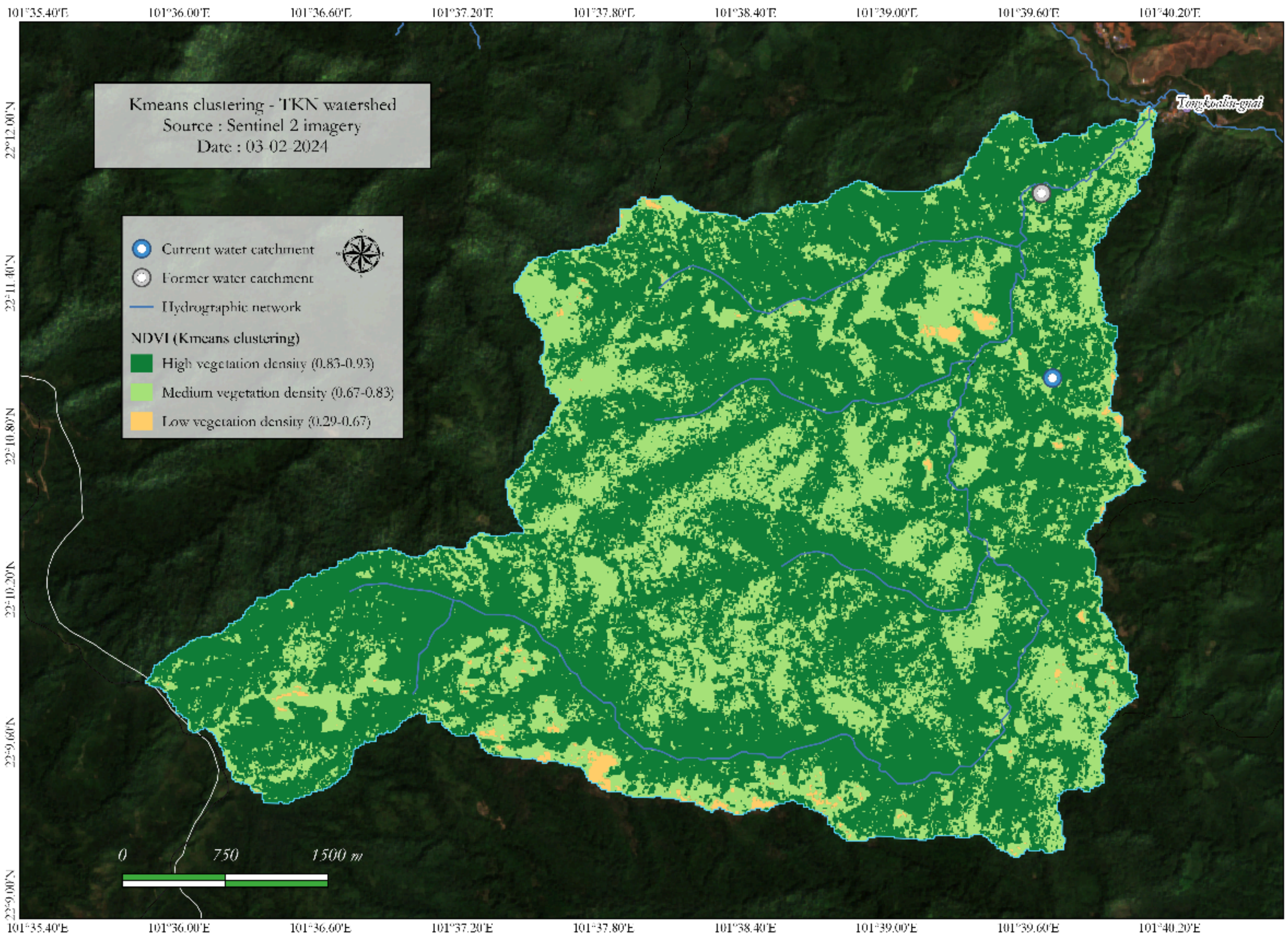


Figure 4: NDVI map of Tungkualin Nyay watershed - 03-02-20 sentinel 2A imagery.

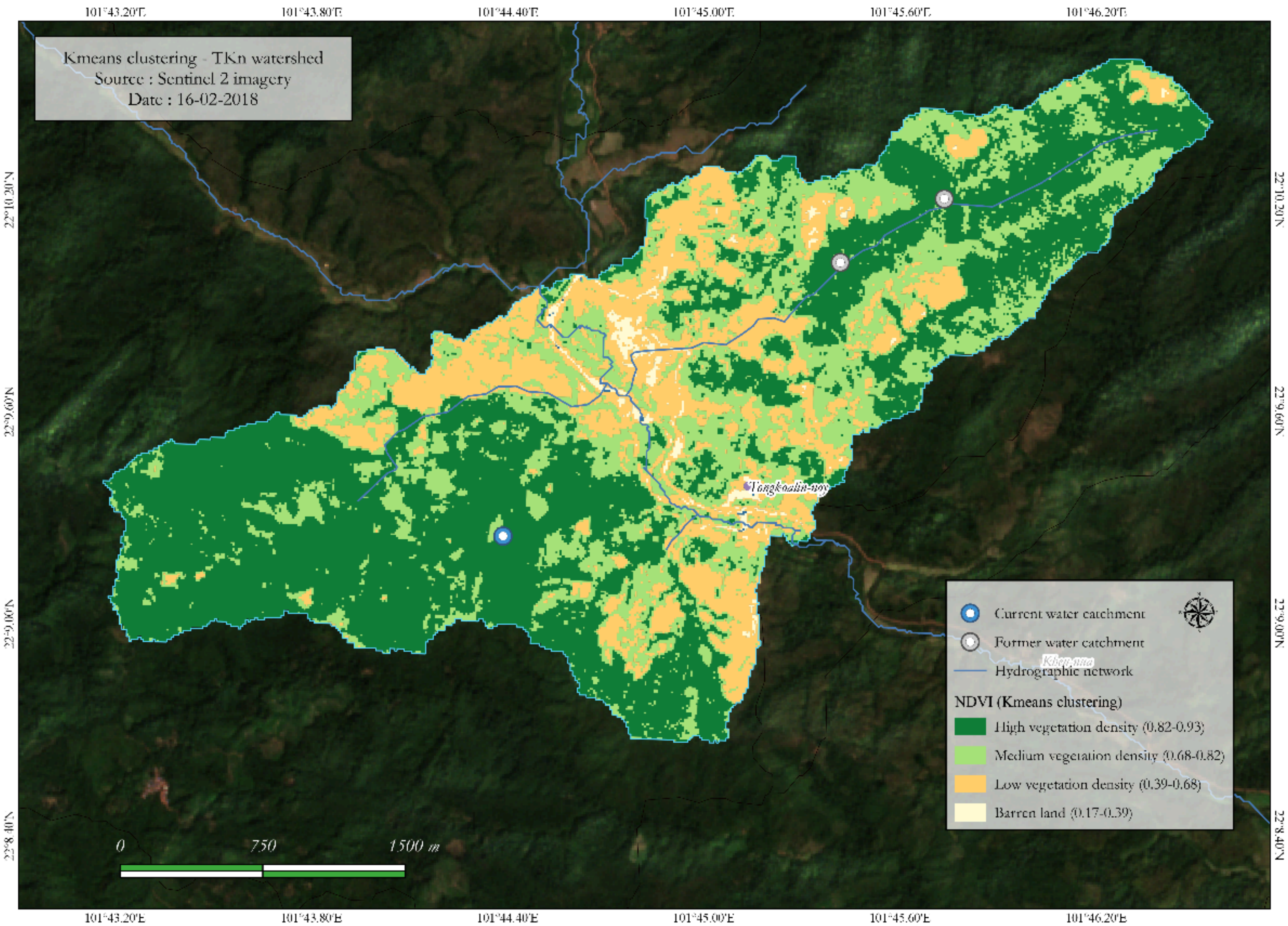


Figure 5: NDVI map of Tongkualin Noy watershed - 16-02-2018 sentinel 2A imagery.

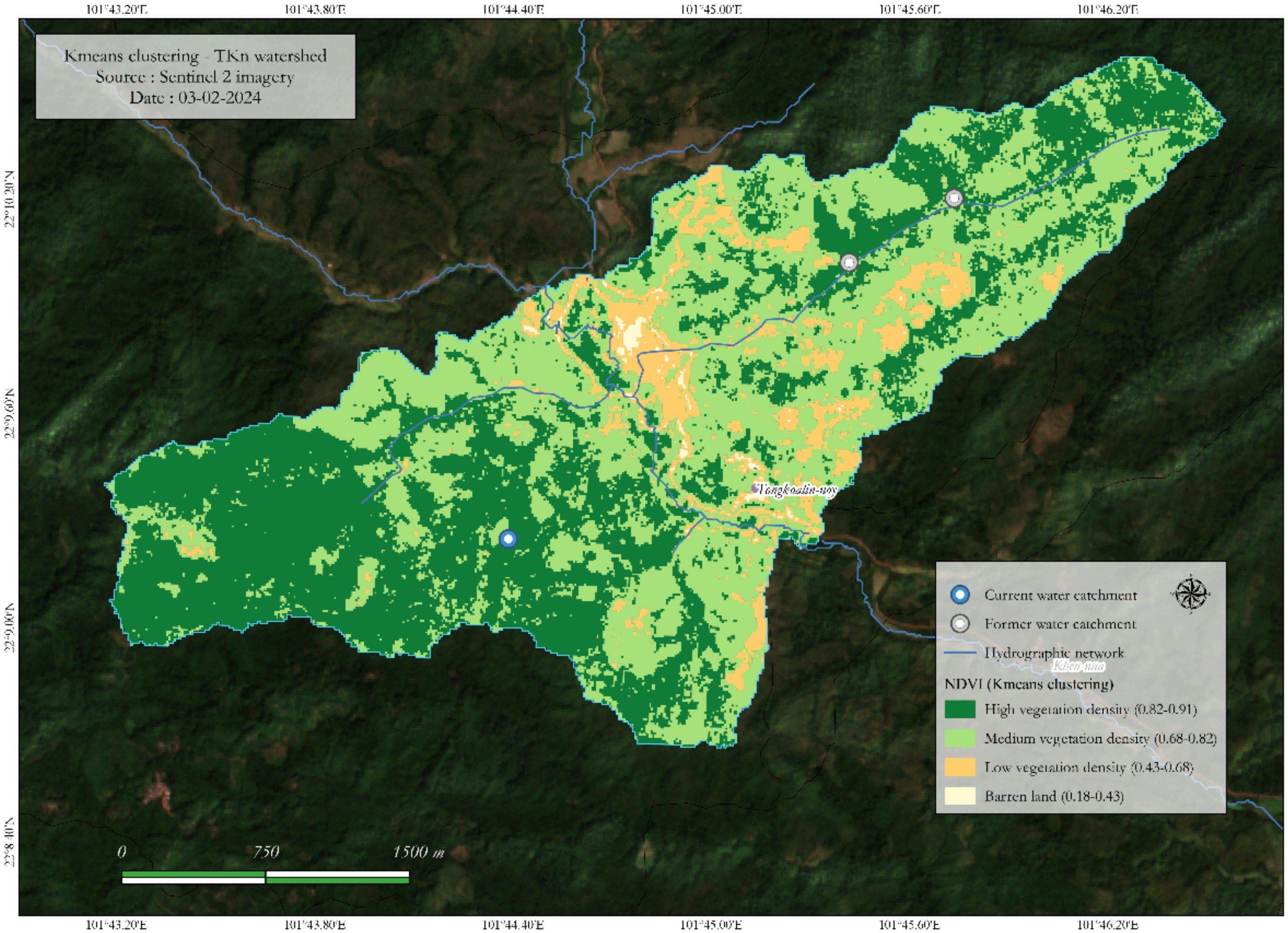


Figure 6: NDVI map of Tongkualin Noy watershed - 03-02-2024 sentinel 2A imagery.

This spatial analysis validates key socio-ecological dynamics identified in the diagnosis. The divergent paths of the two villages underscore that land use in the catchment is a decisive factor for water system sustainability, often overshadowed by technical or governance focus. The degradation in Tungkualin Noy visually confirms the "Land use and land practice" disturbance and its exacerbation by natural hazards, creating a vicious cycle that undermines system resilience. In contrast, the regrowth in Tungkualin Nyay may provide an ecological buffer that contributes to its relative socio-economic capacity to cope with water challenges. This clear evidence reinforces that integrated watershed management—including spring protection zones, sustainable land-use planning, and community-led reforestation—must be a foundational component of any strategy aimed at achieving durable water supply systems.

Design, sizing of the WS system and the choice of the spring

This factor has two inputs. One part is from the villagers (I9) which is to suggest the position of the capture on their territory (RS9). A second role of the villagers is to provide manpower for the construction of the technical equipment (I5). The other part is from two external actors supporting the villagers on the technical point of view and material point of view. These actors are the Namsaat and NGOs (GS1, GS2). The NGOs provide the financial support for material (RS4) and support financially Namsaat technician (I5) for the supervision of the built and follow-up activities. Sometime NGOs provides technician to supervise the construction. The Namsaat has a first step to do a feasibility study. Which is the theorical sizing of the WS tacking in accordance with the water availability at the spring (RS5), the needs of the villages (A1, A8), and then the needed material for the construction. On a second time they are supervising and leading the construction of the WS system (A5, A7).

The choice of the spring (RS9) and location of the water catchment is based on the empirical knowledge of the villagers of their territory (A7). The first criterion is to find a source that provides water during the dry season. The second condition is to choose a source not too far from the village to limit the costs of investments, both human and material. Since the main expense for the construction is the pipes, going further to get a spring is a big factor increasing the price of the system (RU4). The village territory configuration is one of the main factors guiding the choice of the spring (RS9). For instance, Tungkualin Noy is land locked between several villages in the same main water catchment. This configuration is a major limiting factor for having several choices (RS7). In this case, they were two main catchment that were relatively isolated to any agricultural practice from intra and extra origin. As the choice of one or another is an ‘empirical’ choice (A2, A3). They were disagreements on the reliability of the springs and their potential quality (RS5). Another example of landscape constraints are the villages located on the ridge so that the water catch area is small, limiting then the amount of water. In an opposite way villages like Ban Kang are situated of the top of the catchment with no upstream villages with a big village territory. The limiting factor will be the available resources to reach a reliable spring without being too far from the village.

The choice of spring has also a great influence on the water quality (RS5, RS9). The quality of the water can have three main issues. Firstly, it is the turbidity of the water during the rainy season caused by the rain runoff and the subsequent erosion who touches all the villages. Since turbidity has no direct impact on health. It is accepted that there is a link between water quality and turbidity (Mann et al., 2007) even if the cases we discuss by the upstream position on the overall watershed reduce pollution possible sources. A dimension of comfort and taste can also be considered.

Another source of pollution can be the upstream agricultural practices, especially in the case of farmers using pesticides (RU3). In Ban Kang after the landslide episode that covered the water supply carried out in 2009, the village built a capture really close to the village, being limited by the pipe’s length on the main river of the village territory. This capture is situated just under agricultural areas. Some of the villagers have mentioned a possible pesticides contamination while others said that the capture was cursed. In this case, a clear fecal matter contamination could also be the origin of the contamination since livestock is circulating in the area.

In Ban Pangsan, at first a spring location has been used considered being the best option to implement a WS (A7). The villages having moved and the population growing, they had to make a demand for a new WS system and then choose another spring location. The new location has been discovered several years after the choice of the old location by coincidence, thanks to the new cardamom plantation activities created later. The new spring seems to provide more water with better quality.

The second aspect of the disturbance is the design and sizing of the water supply (WS) system. The design can be divided into two parts (A9). The first part is always the same; it consists of a dam structure around the spring with a volume of coarse filtration. After this filtration step, the water is piped into a tank that has three basins at the top. One basin is for charging, the second is a finer filter containing small rocks and sometimes charcoal, and the third allows water to enter the main tank. After the tank, the distribution to the villagers occurs in two forms. The first is public fountains, which should provide for a certain number of households. The second is the installation of water points in each household, with or without a water meter. The choice between one system or the other influences the potential for structuring the payment systems (GS5). New WS systems tend to favor individual systems with water meters.

Sizing is done by the Namsaat (GS1). Their method is based on the lowest flow rate occurring at the end of the dry season (RU7). The flow measurement technique involves using a bucket in a hole of known volume, filled in a specified time. In the feasibility document, all the flow rates were the same (0.2 L/s). The rest of the sizing is based on this value and the number of users in each village, with an estimated consumption of 65 liters per person per day. Given the low flow from the spring and its productivity, they calculate the daily production and needs. To approximate future needs, they apply a population growth rate of 2.9% (RS7). With the population forecast, consumption estimates, and the spring's productivity, one can calculate the storage requirements for the system.

In practice, all tanks are built in the same way, with identical storage capacity and filtering systems. The capture method is slightly adapted to the spring's situation but always follows the same principle of a dam structure blocking incoming water. The dam is located downstream of the sources, which can consist of several resurgences and/or a river or small creek configuration.

For all the villages, the old tanks became unusable for a significant portion of the villagers due to new households established at higher altitudes, making water supply impossible (RS9). In Ban Tungkualin Nyay and Ban Pangsan, there have been storage issues following peak morning consumption (RS8). There is no more water at the taps during the dry season in Ban Pangsan and permanently in Tungkualin Nyay.

In response to these disturbances, which rendered the WS system ineffective, Ban Tungkualin Nyay and Ban Kang established their own installations with relative effectiveness. Ban Tungkualin Nyay received external support for materials but no technical assistance (GS2). This led to a tank that was far too small for the demand. After just a few hours, the tank would overflow, wasting a significant amount of water overnight. Another issue was that the pipes they received were not long enough to reach the targeted spring, so they had to use the pipes from their old WS system. The new pipes were also too small to supply sufficient water. In Ban Kang, no support was provided. A fundraising effort was made to construct a capture system located on the main river next to the village, where health issues had been previously reported. A decision was made to move to several upstream small creeks, where the pipes were simply blocked in the riverbed with rocks.

Natural disaster and “climate change”

Whereas all the previous disturbances link human action to the WS SES, natural disasters (RS9, RU1, RU2, RU7) demonstrate how the resource system influences governance (GS3) and the permanence of the entire system. They also underline how human actions affect the ability of ecological systems to provide services. Moreover, this illustrates the irreversible nature of actions that have a direct impact on the community, since water is an indispensable resource (A8).

Two natural disasters were identified in the survey. The first is a severe drought that occurred in 2019, which affected all four villages. Two villages were particularly impacted by this natural occurrence. Ban Tungkualin Nyay was using two springs located next to each other that stopped providing enough water for the village. As villagers explained, an abrupt change arose after this drought. In Tungkualin Noy, a fire provoked by a neighboring village burned a significant portion of the forest. The neighbors were engaged in a traditional slash-and-burn practice during the dry season. Since 2019 was a dry year, they lost control of the fire, which affected a considerable part of the watershed surrounding the spring. This fire, combined with the drought, led to an insufficient water supply for the village.

In Ban Kang, a significant rain event occurred in 2017 that resulted in a landslide burying the capture of the WS and thus cutting off the water supply to the village.

Discussion

Observing four similar mountainous communities allows us to gain insight into the impact of disturbances on the robustness of a gravity fed WS SES. This diagnosis illustrates the clear multifactorial nature of the system and the importance of understanding and considering these linkages when implementing a system in a village.

Firstly, we noted that two of these disturbances can be considered non-controllable. The membership transition due to population growth is surely limiting the system over time. As the villages grow, they will occupy higher land to build houses. A consideration of the land-limiting space due to membership transition and the consequent displacement could be considered when deciding on the tank's position. This consideration could allow the actors to make adaptive constructions on the previous system as an updating dynamic rather than restarting the system from the beginning. Another dimension of the membership transition is the socioeconomic shift in some of the villages, particularly Ban Tungkualin Nyay. This village has transitioned from traditional agricultural practices to tea cultivation as a main source of income. Tea has significant market value, resulting in increased average incomes. However, this rising income has led to a focus on commercialization and individualism at the expense of collective interests and labor (Suhardiman et al., 2023). This capitalization of the community could impact users' ability to form a cohesive community and trust each other. Changes in socioeconomic status could necessitate modifications to the governance structure or rules regarding monitoring and sanctioning. On the other hand, increased income also allows the community to invest in their systems and ensure maintenance operations are not constrained by finances.

The last observation is linked to the relocation of two or more communities in the same village, as is the case in Ban Tungkualin Noy. This multi-ethnic configuration can lead to significant constraints in terms of leadership and governance.

The second non-controllable disturbance is natural disasters and “climate change”. Since these disturbances occur stochastically, the goal is to prevent and enhance the system's ability to accommodate such disturbances. The ability to withstand natural disasters is closely linked to land use and land habits. The natural disasters affecting the villages include droughts and landslides. Landslides occur naturally in Southeast Asia, but land cover and deforestation significantly influence erosion dynamics and soil structure (Douglas, 1999). In Ban Kang, which experienced a landslide affecting the capture of the WS system after a heavy rain event, the village had previously made no significant modifications to the land cover in the water catchment area which highlights the impact of climate hazards even in a context of low human disturbance.

The second type of natural disaster is drought. These events have caused the spring supplying the capture to dry up. Our study identified two villages facing such events. Firstly, Ban Tungkualin Noy has made significant modifications and endured a fire affecting the lands surrounding the spring. The change in proportion from low cover vegetation density to medium suggests that the significance of the modifications is regrowing through the years. Even if a reprieve period of change seems to have occurred, the weakened ability to support a drought event is suggested by the previous changes, consequently decreasing the recharge capacity of the aquifers through infiltration.

On the other hand, Tungkualin Nyay has not made substantial modifications near the spring, yet drought still occurred. The result even shows an increase of the vegetation density in the watershed area. However, the drought occurred in 2019, one year after the NDVI reference analysis (2018). Perhaps, the land may have been modified previously. This demonstrates that changes in land use indeed impacts the water cycle (Lacombe et al., 2016), but behaviors can vary significantly depending on the spring and geological configuration. It also shows the NDVI technique limits. Comparing and linking land use to water shortage in a spring using this technic as bias, as factors like sunlight incidence, cloud cover, and the angle of the picture of the satellite can slightly change and result in variations in perceived light. On the other hand, each year receives a specific amount of rain, which leads to a certain level of vegetation development. There is a gray area between the regrowing forest after fallow cultivation and land cover degradation because of drought. This tool allows us to obtain a preliminary approximation of land changes around the springs.

The other disturbances will be considered controllable. These include leadership and governance structures, as well as the design, sizing, and spring choice of the systems. The sizing and design of the WS system are the entry points of the SES. Despite the self-designs created by villagers, WS technical systems, especially the tanks, are standardized. This systematic sizing leads to several instances of water shortages during critical times of the day. A clear lack of precision in the feasibility study contributes to these results. The choice of the spring is difficult to evaluate despite being based on low flow periods, which offers no insight into resilience against climatic and land use disturbances. Since these two factors are the entry points of the system connecting users and resources, appropriate sizing, design, and spring selection are among the most impactful factors that can be controlled by external actors for the durability of a WS system. Indeed, as Hardin (n.d.) stated: “When will the users of a resource invest time and energy to avert the tragedy of the commons?” A theoretical answer to this question is that when the expected benefits of managing a resource exceed the perceived costs of investing in better rules and norms for most users and their leaders, the probability of users self-organizing is high (Ostrom, 2009).

Furthermore, leadership and governance also have a direct impact on the system's durability by implementing a robust maintenance system, delineating and enforcing a protected zone around the spring, avoiding water use abuse, and structuring fees and financial systems. If not well implemented, all these factors can lead to the deterioration of the system, resulting in a lack of benefits for users, thereby increasing perceived costs and reducing their willingness to invest resources. On the leadership side, another aspect that is difficult to grasp is the relative authority of the leaders among the villagers. Insights into this aspect could stem from poverty-related issues that lead to a lack of resources available for investment. Conversely, the shift toward capitalization and more individualistic communities may result in a loss of authority—or at the very least, a decline in collective, inclusive, and cross-cutting decision-making processes.

Examining the individual variables from the Ostrom (2009, 2007; Ostrom and Cox, 2010) framework, we found that human facility construction (RS4), the location of the chosen spring (RS9), the operational rules, and the collective choices (GS4, GS5), as well as leadership (A5), are key factors on which to focus to implement a durable WS system.

Conclusion

The diagnosis underscores that water supply systems in Northern Laos face interconnected threats from population pressure, land-use change, and climate change, manifesting as more unpredictable rainfall, intense droughts, and severe floods. The recommendations above form an integrated response:

- Understanding watersheds is the first defense against climate impacts, enabling communities to protect the very source of their water.
- Resilient infrastructure ensures the physical system can withstand these increasing shocks.
- Robust and adaptive governance allows the community to manage scarcity, maintain the system, and adapt rules as conditions change.

Moving beyond the "panacea" of standardized technical solutions requires embracing the socio-ecological complexity revealed by Ostrom’s framework. By investing in local knowledge, appropriate technology, and, most importantly, in the social processes that govern the resource, stakeholders can support the development of water supply systems that are not only built to last but are also managed, adapted, and sustained by the communities they serve.

We have shown that, although many factors influence the robustness of the system, a relatively small number are significant in most cases. Our empirical study suggests that the foundation of the entire system is the choice of spring and the construction of human facilities. A stable foundation allows users, and their management practices, to make mistakes while fostering a virtuous cycle of improvement.

Moreover, greater investment from villagers in what they envision as a sustainable system must be encouraged and supported before the facility is built and even as a first step of the WS implementation activity. Lastly, implementing a system must align with the rhythm of social-ecological circumstances. Rushing to meet schedules does not enhance the system's robustness and resilience.

Our findings are limited by the number and duration of the cases we analyzed, but they provide an initial perspective on the situation through the Ostrom framework and may facilitate comparisons with other case studies across Laos.

Recommendations

Improve Understanding and Management of Watershed Headwater

The study highlights the critical influence of land use and land cover on water availability and spring behavior. However, hydrological knowledge at the local level is often empirical, and the complex relationship between vegetation, soil, and subsurface flow is not fully integrated into planning.

In this matter, some solutions could be implemented such as:

- **Develop a Simple Spring Typology and Monitoring Protocol:** Create a localized classification system for springs (e.g., hillslope seep, fracture spring, riverbank infiltration) based on geological and hydrological indicators. Train district technicians and villagers in simple monitoring techniques (e.g., seasonal flow measurement, water clarity observation) to document spring behavior throughout the year. This knowledge is crucial for selecting resilient sources.
- **Integrate Local Ecological Knowledge with Science:** Combine villagers' empirical knowledge of their territory with basic scientific tools. Use participatory mapping to document perceived changes in water sources and forest cover. Supplement this with accessible remote sensing data (like NDVI trends shown in the study) to visualize and discuss land-use changes around springs.
- **Promote Watershed-Scale Awareness:** Move beyond the immediate spring protection zone to consider the entire contributing watershed. Develop and disseminate accessible educational materials on the water cycle, emphasizing concepts like infiltration, groundwater recharge, and the impact of deforestation and soil compaction on water availability. This understanding is the foundation for sustainable land-use decisions.

Optimize Water Collection Infrastructure for Resilience

The standardized design of capture systems (small dams/weirs) may not suit all spring types or geologies, leading to vulnerability (e.g., siltation, landslide damage as in Ban Kang) or water quality issues. The sizing of systems often fails to account for realistic population growth and consumption patterns.

Therefore, designs should consider the following parameters:

- **Diversify Capture Techniques Beyond Standard Weirs:** Promote context-appropriate water collection methods. For springs with low flow or quality concerns (e.g., turbidity, contamination risk), introduce alternative techniques such as **infiltration galleries** or protected spring boxes. These can provide cleaner water, have less environmental impact, and be more resilient to sedimentation.
- **Adopt Adaptive and Modular Design Principles:** Instead of one-size-fits-all tanks, encourage designs that can be expanded or adapted. This includes planning for future population growth and potential village expansion to higher altitudes by strategically placing tanks and considering booster systems. Feasibility studies must use realistic population growth rates and consumption data.
- **Incorporate Climate Resilience into Design:** Ensure new constructions consider increased climate variability. This includes reinforcing structures against more intense rainfall and landslides, designing for longer or more severe dry seasons by selecting springs with proven dry-season resilience, and considering water storage solutions for critical periods.

Strengthen Governance, Community Management, and Knowledge

Governance structures are often proposed as a master plan but fail to account for local social dynamics (e.g., multi-ethnic tensions in Tungkualin Noy, shifting socioeconomics in Tungkualin Nyay). Management rules are frequently unclear, and maintenance systems break down due to lack of trust, transparency, or resources.

This observation can be addressed by solutions such as:

- **Decouple Infrastructure Project from Governance Capacity Building:** Treat the establishment of a functional Water User Committee (WUC) and management rules as a **separate, funded activity**, not just an appendix to construction. This process requires time, facilitation, and conflict resolution support, especially in multi-ethnic villages.
- **Use Participatory Tools like Serious Games:** Implement innovative engagement methods such as the **TerriStorries** approach or other role-playing

games. These tools allow communities to safely simulate scenarios (e.g., drought, conflict over water, land-use decisions), explore consequences, and collaboratively develop their own rules for resource sharing, fee collection, maintenance, and sanctioning.

- **Develop Clear, Context-Specific Management Plans:** Facilitate the co-creation of simple, written management plans that include:
    - Clearly demarcated and legally recognized protected zones around springs.
    - Transparent and equitable water fee structures and use rules.
    - Defined maintenance responsibilities and protocols.
    - Conflict resolution mechanisms.
- **Empower Through Targeted Education:** Conduct workshops on practical topics directly linked to WS system sustainability: basic hydrology (why watershed protection matters), simple system maintenance (cleaning filters, repairing leaks), and financial management for the WUC. This builds ownership and capacity.

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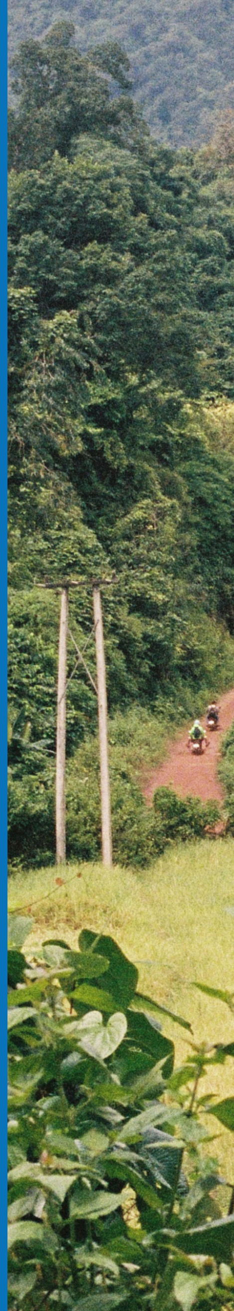

Comité de Coopération avec le Laos

ASEAN Road, House No.123, Unit 7
Sidamdouane Village, Chanthabouly District
BP 4791, Vientiane, Lao PDR
+856-21-254-039
vientiane@ccl-laos.org
www.ccl-laos.org

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