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Landscape Assessment of the Sustainable Limits of Solar Irrigation Development in Attapeu Province, Laos

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Front cover photo: A portrait view of watermelon growing with the solar-powered groundwater site in Inthee village, Sanamxay District, Attapeu Province, Lao PDR, where a group of farmers utilize groundwater for an integrated and rotational agricultural system - rainfed rice, vegetables, watermelon, and a rice-fish pond (*photo:* Somphasith Douangsavanh/IWMI).

Back cover photo: A portrait view of watermelon growing in Inthee village, Sanamxay District, Attapeu Province, Lao PDR, (*photo:* Somphasith Douangsavanh/IWMI)

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Executive Summary

This study assesses the sustainable potential for expanding solar-powered groundwater irrigation (SGI) in Attapeu Province, Southern Laos. The lowland plains of Attapeu face high poverty, limited irrigation access, and increasing climate variability, making reliable water and energy access critically important for strengthening food and livelihood security.

The assessment focused on a 517 km² landscape across Samakkhixay and Sanamxay districts, an area representative of the wider challenges and opportunities facing the province. Farming remains dominated by wet-season rice, while only a small proportion of households cultivate irrigated crops during the dry season months. Well-replenished sedimentary aquifers sustain the majority of household water supplies but remain scarcely used for irrigation. This highlights both the importance of groundwater for daily life and its untapped potential to support agricultural growth.

A stepwise analytical framework was applied to estimate groundwater recharge, abstraction, and the biophysical limits of SGI expansion. Based on long-term rainfall and groundwater monitoring data, mean annual recharge was found to be high, ranging from 228–743 mm per year across sites. Current groundwater abstraction remains low at less than 4% of average annual recharge. After reserving 50% of recharge for environmental needs, the utilizable groundwater volume was estimated at 75–178 million m³ per year.

Scenario analysis indicates strong potential for SGI development. Even under conservative assumptions, the dry-season area irrigated with groundwater could expand from roughly 120 ha at present to between 11,000 ha and 27,000 ha, supporting up to 5,600 smallholder households. Expansion potential is greatest along the central corridor of the study area, where land, groundwater, and solar conditions are most suitable.

While the groundwater resources appear to be sufficient, localized risks remain—particularly if the aquifers targeted for development are thin, discontinuous, or subject to concentrated pumping. The low operating cost of solar pumps may also encourage excessive abstraction if not properly managed.

Institutional, financial, and knowledge barriers are the major constraints to adoption. High upfront investment costs, limited awareness of groundwater as a finite resource, and weak coordination among sectors all impede scaling.

To enable responsible expansion, the study recommends strengthening groundwater monitoring, developing and implementing a provincial groundwater management plan, integrating SGI into irrigation and land-use planning, improving farmer training, and creating accessible financing mechanisms. With coordinated policy, governance, and investment support, SGI can become a pathway for climate-resilient agricultural transformation in Attapeu Province and potentially beyond.

Introduction

The lowland plains of Attapeu in southeastern Laos are characterized by high poverty and acute climate vulnerability (Government of Lao PDR, 2009). Rural livelihoods that are largely reliant on subsistence agriculture, face growing risks from recurrent floods, droughts, and the intensifying impacts of climate change. These extremes put increasing pressure on water resources and food production systems.

Water availability is highly seasonal, with over 90% of annual rainfall falling between May and October. The protracted dry season, combined with increasingly erratic and shifting monsoonal seasonality (Edirisinghe et al., 2023), is exacerbating water stress.

Most smallholder farmers lack access to reliable irrigation systems, limiting opportunities for crop diversification and intensification, and reducing the capacity of their farming systems to cope with climate shocks and stresses (Lao Statistics Bureau, 2021). Many rural areas also experience seasonal drying-out of small rivers and springs, which are critical sources of community water supply. This directly undermines household water security and health, with disproportionate impacts on women and children, who bear the primary responsibility for water collection (Asian Development Bank and the World Bank, 2012).

Food security in the province is closely linked to these water challenges. Most households rely on paddy rice cultivation, which under rainfed conditions, is highly sensitive to fluctuations in water availability. Water shortages during critical growing periods contribute to crop failure, yield reduction, and heightened risk of food insecurity. Limited access to dietary diversity further exacerbates nutritional deficiencies, particularly among the more vulnerable ethnic groups. Energy constraints compound these challenges, as many areas remain reliant on expensive and unreliable electricity, limiting the use of pumps for irrigation and other essential needs (Pavelic et al., 2025).

In response to these challenges, the CGIAR together with numerous partners, are harnessing a 'Multifunctional Landscapes' (MFL) approach that integrates agroecological, nature-positive, and complementary strategies to enhance livelihoods, food security, biodiversity, and ecosystem services, while supporting climate adaptation and poverty reduction (Smith et al., 2024). One of the pillars of this MFL approach is solar-powered groundwater irrigation (SGI), which provides a reliable and renewable water source for agriculture and domestic use during the dry season at minimal marginal cost. Pilot initiatives in Attapeu demonstrate SGI's potential to improve crop productivity, diversify production, and strengthen household resilience to climate variability (Douangsavanh et al., 2025; Pavelic et al., 2025). Lessons from challenging SGI interventions help highlight the importance of context-appropriate design and community engagement in scaling (Pavelic et al., 2024). As SGI systems can reduce dependence on costly diesel and electricity while offering a cleaner energy alternative, its potential role in Attapeu merits further exploration.

This report builds on these experiences by assessing the biophysical limits of sustainable SGI expansion within an MFL context, whilst ensuring that high-value human and ecological services are preserved. The findings are intended to inform policymakers, implementing agencies, development partners, the emerging solar industry, and researchers on the potential of SGI to strengthen water security, support climate adaptation, and enhance livelihoods.

Site Description

This study was conducted within a 517.3 km^2 area of Samakkhixay and Sanamxay districts in Attapeu, taking in the10 focal villages of the MFL program and surrounding areas (Figure 1). The total population of the study area is 34,700 [1]; equivalent to 67 persons per square kilometer. The ethnic communities known to reside in the area include the Oy, Jeng, Yui, Brao, Khamu, and Talieng, and Lao (Douangsavanh et al., 2025).

The study area is bounded by the Bolaven Plateau to the north and by part of the Annamite Ranges (Phu Luang) to the south. The Sekong river, a major transboundary tributary of the Mekong River, cuts across the area. The Nonglom wetland, a 20-hectare natural lake situated adjacent to the river, is an important ecological asset and the subject on an emerging management plan being developed by participatory planning processes by local community to address threats like climate change and unsustainable resource use (Mam and Xaydala, 2024).

Land use/land cover data at 10-meter resolution for 2020 were obtained from the Mekong River Commission, (2023). The study area is dominated by evergreen and deciduous forest (44.3%), followed by paddy rice (23.4%), annual cropland (21.8%), orchards (2.3%), water bodies and marsh/swamps (2.9%), shrubland (1.2%), bare soil (1.2%), urban areas (0.7%), and grassland (0.3%).

[1] Taken from the Laos: High Resolution Population Density Maps + Demographic Estimates dataset (Data for Good / Meta & CIESIN) in which population distribution is estimated for 2020. Although a national census was not conducted in 2020, these estimates are generated by combining recent census / survey data, remote sensing of building structures and demographic statistics, and are adjusted to match UN population totals. Thus, while the output is labeled "2020", it represents a modeled projection for that year.

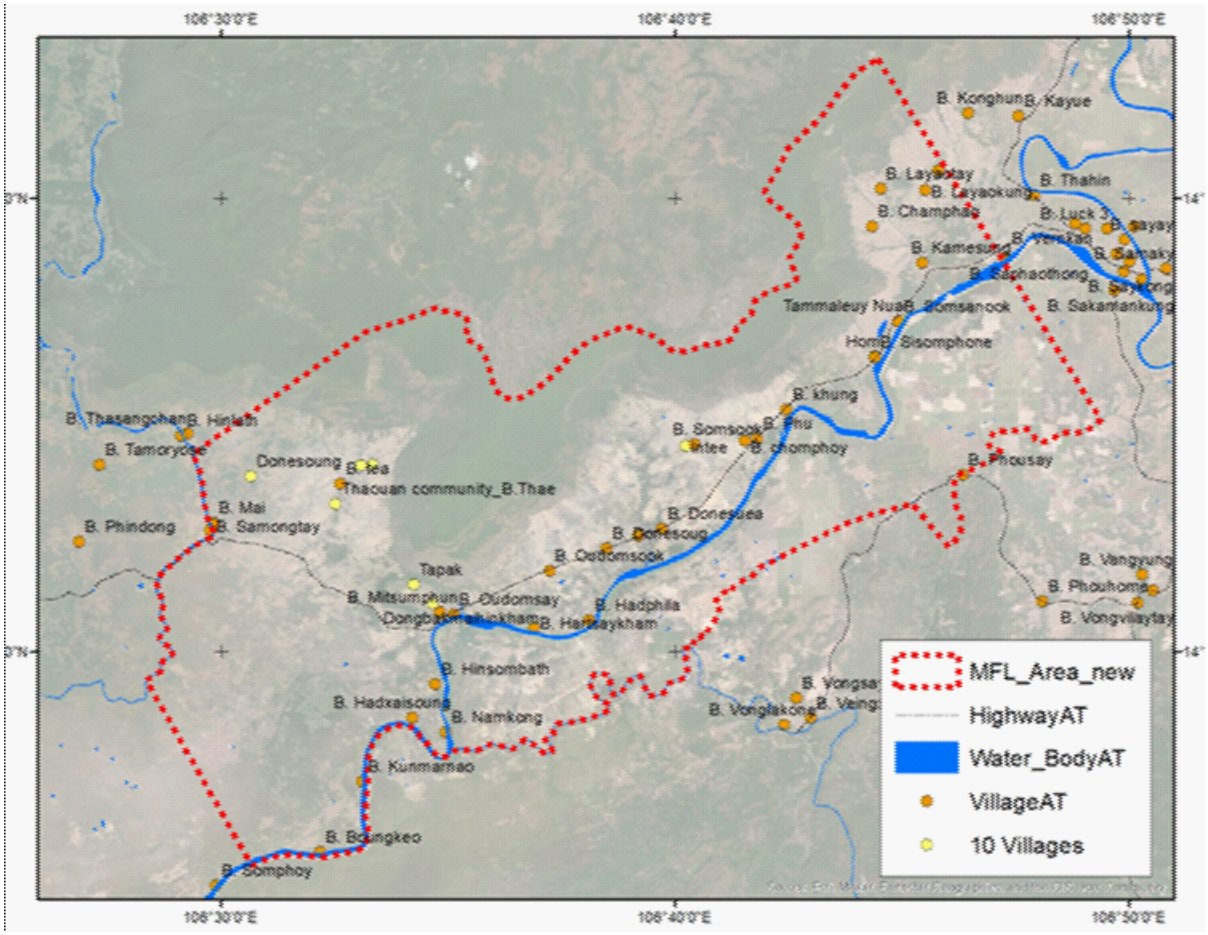

Figure 1. Location map of the MFL study area in Attapeu

Climate

The climate of the area is tropical monsoon with an average annual rainfall of around 2,200 mm/yr [2]. Average annual mean temperature is 27°C with minimum temperature observed in January with a mean of 16°C and the maximum temperature observed in March with a mean of 36°C [3].

Attapeu province receives consistently high solar radiation, making it well suited for solar irrigation (Pavelic *et al.,* 2024). Average daily global horizontal irradiance (GHI) in the study area is about 5 kWh/m²/day (ESMAP, 2019). Seasonal variation in solar irradiation is relatively subdued, say compared to rainfall, making it a reliable year-round energy resource, particularly during the dry season when irrigation demand is greatest. Cloud cover can be problematic during the monsoon months, but overall availability of solar energy offers tangible benefits for expanding sustainable groundwater irrigation in the province.

Agriculture and Irrigation

Most farmers in the region practice wet season rice cultivation in the low-lying floodplains along the Sekong river, producing both for home consumption and for market. Often, rice farming is integrated with fish trap ponds. During the dry season, households often cultivate cassava on nearby forested lands or undertake wage labor on sugarcane and banana plantations (Smith *et al.,* 2024).

Only 9% of households in Attapeu have access to irrigation infrastructure (Lao Statistics Bureau, 2021).

[2] Taken from the Integrated Multi-satellitE Retrievals for GPM (IMERG) satellite data to compile a 25-year rainfall time series covering the period 2000 to 2024. The IMERG estimates were validated against 8 years of observed rainfall data from the Attapeu climate station, provided by the Lao Department of Meteorology and Hydrology.
[3] Taken from: https://weatherandclimate.com/laos/attapu

Hydrogeology and Water Supply

The hydrogeology of the area is dominated by consolidated sedimentary rocks of Mesozoic age, predominantly sandstones and siltstones (Viossanges et al., 2018). Local drilling to depths of around 40 m reveals aquifer formations comprising conglomerate, medium-bedded sandstone, dark-red sandstone, and siltstone. Subsequent borehole testing indicates productive aquifers, with airlift yields ranging from 1.8 to 4.6 L/s (Douangsavanh et al., 2025). Laboratory testing shows that the groundwater quality is generally suitable for drinking, meeting the standards set by the Department of Environmental Health and Rural Water Supply of Attapeu province.

Census data indicates that over 80% of the population of Attapeu are dependent on groundwater, primarily from wells, but also from mountain springs to a lesser extent, for water supply (Lao Statistics Bureau, 2015).

Methods and Data

To assess the potential for sustainable expansion of solar-powered groundwater irrigation (SGI) in terms of both scale and extent, we developed a structured, step-wise framework. The framework integrates climatic, hydrological, agricultural, environmental and energy-related factors to ensure that irrigation development remains within the renewable groundwater limits while maximizing the support to local livelihoods.

The process begins by quantifying groundwater recharge and current levels of groundwater abstraction to derive estimates of the available groundwater after reserving environmental requirements, and finally projects the scale of irrigation expansion feasible for different crop type and recharge scenarios in geographic locations where conditions for solar suitability are most favorable. An overview of the steps and associated data inputs is provided in Table 1, with detailed descriptions of each step given in the following subsections.

Table 1. Step-wise approach taken to establish scale of sustainable SGI expansion

Step	Task	Input Data
Step 1	Estimate mean annual groundwater recharge	Groundwater hydrographs, long-term rainfall records, aquifer storage properties
Step 2	Estimate groundwater abstraction for domestic and irrigation demand for reference crops	Population statistics, daily per capital water use, irrigated areas, crop water requirements, rainfall, potential evapotranspiration, crop coefficients
Step 3	Derive utilizable groundwater availability	Environmental groundwater allocation
Step 4	Project SGI expansion in areas of high site suitability	Solar suitability maps

Step 1. Estimate groundwater recharge

Accurate estimation of mean annual groundwater recharge is an essential first step as it directly determines groundwater availability and the sustainable use of these resources. Recharge during the 2024 monsoon season was estimated using the Water Table Fluctuation (WTF) method, which relates seasonal groundwater level rises to recharge through the aquifer's specific yield (Sy) (Healy and Cook, 2002). The method has been widely applied across diverse climatic settings.

For this study, the WTF method was applied at three groundwater monitoring sites located at Donephay, Intee and Tamaleuy villages (Figure 2), using continuous water level data collected during the 2024–2025 hydrologic year by Douangsavanh et al., (2025). To account for short-duration dry spells that bring about intra-monsoon declines in water levels, all positive rises were cumulatively summed, assuming these are attributable to recharge events. This avoids underestimation of recharge caused by non-recharge-related declines (i.e. due to lateral groundwater flow, evapotranspiration or abstraction). Recharge (R) was calculated as:

$$R = Sy \times \Sigma(\Delta h) \quad (1)$$

where Sy is the aquifer's drainable porosity used to convert water-level changes into recharge volumes, and $\Sigma(\Delta h)$ is the sum of all groundwater level rises during the monsoon.

As site-specific Sy values were unavailable, estimates based on typical Sy values from Viossanges et al., (2018) identified from the location-specific aquifer types identified from the well drilling logs from Douangsavanh et al., (2025).

To refine 2024 recharge estimates to long-term averages, rainfall data were used. Daily rainfall for 2000–2024 was obtained from the IMERG Version 6 Final Run Daily Product (Huffman et al., 2019), accessed via NASA's GES DISC (https://disc.gsfc.nasa.gov/). Since rainfall in 2024 (2054 mm) was slightly below the long-term average (2211 mm), annual recharge was scaled proportionally for each year over the 25-year period, and the results averaged to give the mean annual recharge.

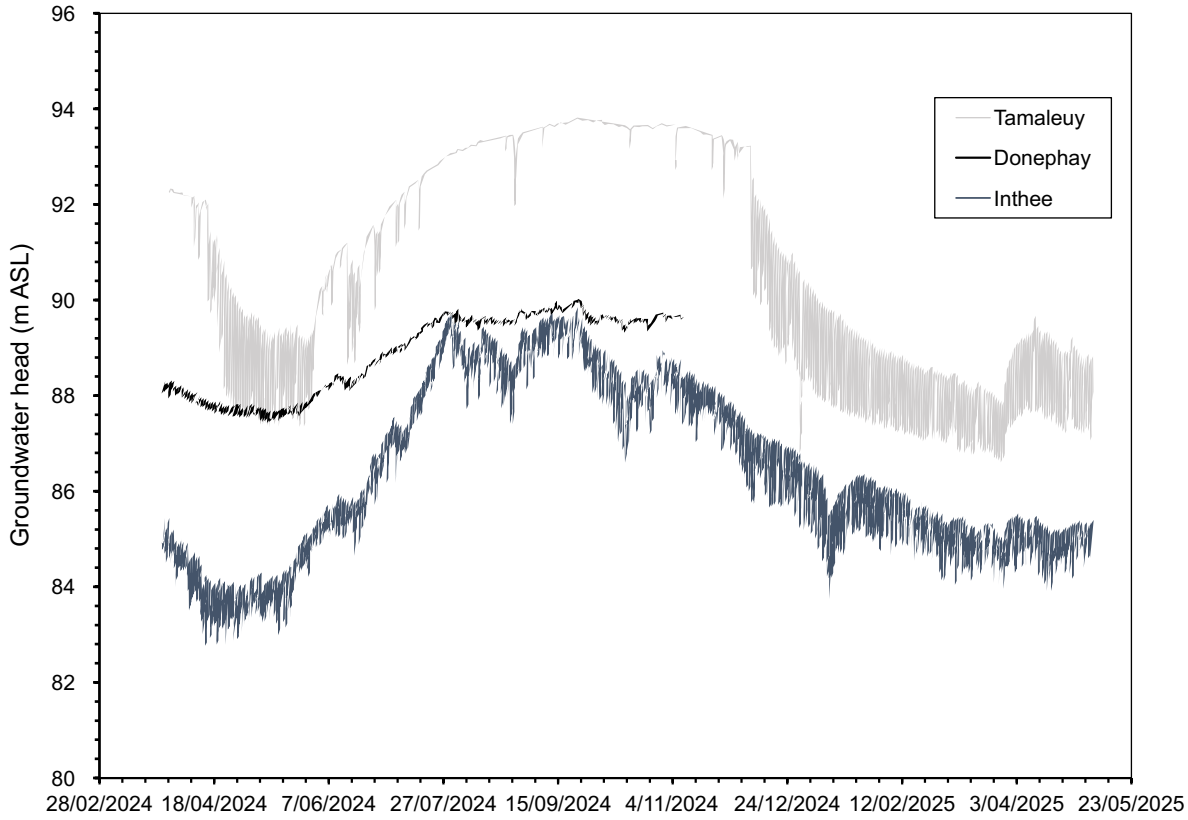

Figure 2. Groundwater hydrographs from March 2024 to April/May 2025 at the three SGI sites

Step 2. Estimate groundwater abstraction

Within the study area the total groundwater abstraction (Q_a) can be assumed to be the combined demand from domestic (Q_d) and irrigation (Q_i) use.

Domestic

For domestic demand, it was assumed that groundwater supplies all household requirements, likely ensuring a conservative overestimation of current use.

$$Q_d = Q_{pc} \times N \quad (2)$$

where Q_{pc} is the per capita groundwater use and N is the total population (in 2020 and 2030).

Population data were taken from Laos: High Resolution Population Density Maps + Demographic Estimates dataset (Data for Good / Meta & CIESIN) which provides gridded population estimates for 2020 based on census/survey data, remote sensing of buildings, and UN demographic statistics. Although labelled "2020," the data provides modelled projections rather than observed counts. Each population node represents a modelled estimate of people living within a grid 30 m cell, which may not always align perfectly with visible settlements due to the way census data and building structures are spatially distributed in the dataset [4]. Population figures from

[4] Gridded population values are modelled estimates and not direct counts, therefore they may misrepresent actual settlement patterns at the village scale

2020 were projected to 2030 assuming a continuation of the population growth rate trend over the past decade of 1.5 percent (ILO, 2022).

Daily per capita use was set at 130 L/person/day, based on field studies in Soukhouma district, Champassak province (Vongphachanh, 2019). This is the highest measured value across the year and takes account of use for home gardening and watering small livestock.

Irrigation

While domestic withdrawals account for part of the overall groundwater demand, irrigated agriculture represents another potentially important and relatively dynamic component. Estimating crop-specific water requirements enables a more precise quantification of groundwater abstraction, linking estimated withdrawals to actual consumptive use, particularly during the dry season when irrigation demand is highest

Irrigation abstraction was estimated using the most reliable irrigation mapping datasets available (Chandrasekharan and McCartney, 2019). Areas of dry season irrigation were identified. This was supplemented by field survey data collected as part of Intervention Package 7 of the ASEAN-CGIAR Innovate for Food and Nutritional Security program to captures smallholder and farmer-led systems that the maps do not fully represent. Surveys included farmers using groundwater via solar, diesel, or electric pumps, as well as rainfed farming.

With irrigated areas defined, seasonal crop water demand was then estimated to derive abstraction for irrigation (Q_i) for two reference crops.

Irrigation water demand during the dry season (Q_i) was calculated using the FAO method at daily time steps, then aggregated to seasonal totals. Demand can be defined as:

$$Qi = f \times [(ET_o \times K_c \times L_f) - P_{dry}] \quad (3)$$

where ET_o is the potential evapotranspiration (mm/day), Kc is the crop coefficient, L_f is the leaching fraction, P_{dry} is the dry season rainfall and '*f*' is the fraction of additional irrigated area added by SGI.

ET_o was estimated on a monthly basis using the well-established Blaney–Criddle method:

$$ET_o = p \times (0.46 \times Tm + 8) \quad (4)$$

where p is the day length (fraction of annual daylight hours), and Tm is the mean monthly air temperature (°C). The Blaney–Criddle method was applied due to limited climate data, as the more accurate Penman–Monteith approach requires radiation, humidity, and wind speed inputs that were unavailable.

Two reference crops (tomato and rice) were selected for analysis because of their contrasting irrigation requirements and scope for widespread cultivation. Crop coefficients and growth-stage curves for these reference crops were taken from Allen et al., (1998). A leaching fraction of 20% was included in all cases.

Step 3. Derive utilizable groundwater availability

The utilizable groundwater (Qu) is the portion of recharge (R) available for irrigation after reserving an environmental allocation (e) and subtracting total abstraction (Q_a). It is defined as:

$$Q_u = [(1-e) \times R] - Q_a \quad (5)$$

where $Q_a = Q_d + Q_i$

Whilst estimation of *e* is methodologically challenging, there is general consensus that groundwater systems often play a vital role in supporting ecosystem functions in both terrestrial and riparian landscapes. These may include environmental flows to rivers, wetlands, estuaries, and coastal systems as well as groundwater uptake by deep rooted vegetation (WLE, 2015).

Although knowledge of groundwater-dependent riparian ecosystems in Laos is limited, studies in Central and Southern Laos indicate river systems receiving important groundwater inputs (Douangsavanh, 2022; Vongphachanh, 2019). Here we assume that 50% of mean annual recharge was allocated to environmental needs, consistent with earlier research in Africa (Pavelic et al., 2013) and higher than the global average estimate of 30% (Sood et al., 2017). The conservative figure used here provides a buffer for future irrigation expansion, increased demands due to population growth, and potential climate change impacts.

To remain conservative, only low and median estimates of recharge were used to establish irrigation demand, with the highest estimate of recharge excluded.

Step 4. Project SGI expansion

To map the spatial distribution of SGI suitable areas, we built upon a farmer-led irrigation (FLI) suitability mapping framework developed for the ASEAN-CGIAR Innovate for Food and Nutritional Security program (Wickramasinghe et al., 2024). This framework uses multi-criteria analysis and open geospatial data to identify areas with suitable biophysical (hydrology, climate, terrain) and socio-economic (demographics, infrastructure, intensification potential) conditions. Suitability is into five uniform classes: highly suitable, suitable, moderately suitable, marginally suitable and unsuitable. Testing of the framework in Cambodia by Wickramasinghe et al., (2024) indicates high predictive accuracy.

SGI suitability is expected to overlap substantially with general farmer-led irrigation (FLI) potential but includes an additional requirement for energy feasibility (e.g. solar radiation and solar pump performance).

A hierarchical allocation approach was applied using ArcGIS 10.8.2 to spatially assign utilizable groundwater availability to locations according to SGI suitability. To do this, the average annual utilizable recharge was converted into the equivalent expanded irrigated area (IA_e) for low- and medium-recharge scenarios, using:

$$IA_e = Q_u / Q_i \quad (6)$$

where Q_u is the annual utilizable recharge (million cubic meters, MCM) and Q_i is the irrigation water demand per unit area (m). Their ratio yields an area, representing the potential expansion of irrigated land. For Q_i the average water demand from rice and tomato was used, reflecting that dry season irrigation would support both rice and non-rice crops.

The allocation was applied to the FLI suitability map (raster format) with five classes. Based on IA_e, the target area was sequentially assigned hierarchically, beginning with the highest suitability class and proceeding stepwise to lower classes. All available area in the highest class was fully allocated before moving to the next class, and so forth, until the entire IA_e was distributed. For the lowest suitability class, where the remaining irrigated area was smaller than the total available area, randomized pixel-level selection was used. This ensured that allocation consistently favored the most suitable areas while achieving the target area requirement.

Results

Groundwater recharge

Mean annual recharge over the period from 2000-2024 varied markedly across the three study sites, ranging from 228 ± 37 mm/yr at Donephay to 571 ± 92 mm/yr at Tamaleuy, a difference of nearly threefold (Table 2). Intee showed intermediate values (743 ± 120 mm/yr). Across all sites, inter-annual variability was calculated at around 20%, emphasizing the need for long-term monitoring to obtain reliable mean estimates.

Recharge differences across the sites reflect contrasts in the seasonal rise in groundwater level, given the uniformity in aquifer storage characteristics. The largest water level rise was recorded at Intee (8.6 m), followed by Tamaleuy (6.6 m), then Donephay (2.7 m).

Across the study area, variability in groundwater recharge likely reflects spatial variations in biophysical conditions. Given the similar elevation, land use, and climate across the sites, soil type was explored as a possible explanatory factor for recharge variations. According to the Land Resources Information Management System (LRIMS) of DALaM (https://lrims-dalam.net/?thematic=aez), Donephay is underlain by moderately draining loam soils, while Intee and Tamaleuy are characterized by poorly drained loamy sands. Counter to expectation, recharge was lowest where soils are mapped as better drained, suggesting that the available soil data provide limited insights into the recharge processes in this setting.

Because recharge cannot be directly measured at landscape scale and must be inferred indirectly, estimates are subject to a degree of uncertainty. To check consistency, local values were compared with independent regional estimates from Lacombe *et al.,* (2017), which suggest mean annual recharge of 540–815 mm/yr for grid cells overlapping with the study area. These regional estimates align well with our results.

For assessing the potential for solar groundwater irrigation (SGI), we adopt 300 mm/yr as a conservative lower threshold for recharge and 700 mm/yr to represent more typical mean conditions. The upper end of our local estimates (~900 mm/yr) was not considered further to remain conservative.

Table 2. Mean annual estimates of groundwater recharge at the three sites. Key input and explanatory variables are also given.

	Tamaleuy	Intee	Donephay
Mean annual recharge (mm/yr)	571 ± 92	743 ±120	228 ± 37
Mean annual recharge (MCM/yr)	295 ± 48	384 ± 62	118 ± 19
Maximum groundwater level rise in 2024 (m)	6.63	8.63	2.65
Aquifer type [1]	Sandstone	Sandstone	Mudstone
Specific Yield (Sy)	0.08	0.08	0.08
Soil type	Loamy sand	Loamy sand	Loam
Mean annual recharge (mm/yr)	571 ± 92	743 ±120	228 ± 37

[1] Derived from well drilling logs. Note the 1:200,000 Geological Map of Attapeu (D-48-XI) identifies the surface geology of Tamaleuy and Donephay villages to be Quaternary Terrace sediments, that are not continuous to the aquifer zone.

Groundwater abstraction

Groundwater use in the study area reflects both the distribution of village settlements and agricultural practices. Communities are dispersed throughout the low-lying areas, with the highest concentrations located along Road no. 18 and the Sekong river corridor (Figure 3). Groundwater withdrawals are generally modest, with most population nodes drawing less than 300 m³ annually. However, higher demand is evident in certain locations, particularly around Oudomsook and Layaokung villages, where nodal withdrawals exceed 1,000 m³. Overall, total groundwater use in the study area was estimated at 1.65 MCM in 2020, with demand projected to rise slightly to 1.91 MCM by 2030.

Agriculture represents the primary user of groundwater, particularly for irrigation. In the dry season, irrigation is limited to small pockets amounting to 159 ha around Thae village in the northwest of the study area (Figure 3). This represents only 1.7% of the total agricultural area (0.3% of the study area). By contrast, wet season irrigation is far more extensive, covering 7,650 ha, or 81% of the agricultural area. Wet season irrigated land exceeds rainfed areas by nearly a factor of five, highlighting the central role of irrigation in sustaining agricultural production during the monsoon period.

Farmer-led irrigation (FLI) surveys provide further insight into local irrigation practices. Seventeen farmers were identified as undertaking dry season irrigation within the study area; nine using electric pumps and eight using diesel pumps (Figure 4). An additional two farmers practiced only rainfed agriculture. No farmers reported using solar irrigation, although such technologies are more common a few kilometers to the east in neighboring Xaysetha district, a contrast that requires further investigation. All irrigating farmers cultivated plots smaller than 2 ha to primarily grow various types of vegetables. Interestingly, none were located in areas currently shown as irrigated on official maps. This suggests that smallholder irrigation is underrepresented in existing datasets, particularly where new or informal irrigation activities are taking place.

According to the most recent (2019/20) agricultural census, groundwater supports approximately 38% of dry season irrigation is drawn from groundwater in Attapeu, the highest of any province in the country (Lao Statistics Bureau, 2021).

Within the mapped irrigated areas this is equivalent to 61 ha. A comparable share is likely under FLI activities with areas that are unmapped due to the recent or small-scale nature of this development. Taken together, the total dry season irrigated area is estimated at around 120 ha. This includes formal dry season paddy cultivation within established irrigation schemes, as well as FLI smallholder production of vegetables and other crops outside these schemes.

To better understand the implications for groundwater demand, irrigation water requirements were estimated for key crops. For the dry season growing cycle, water demand was 862 mm for rice and 542 mm for tomato (Table 3), with rice requiring about 60% more water than tomato. Effective rainfall reduces irrigation demand by an average of 13% for rice and 17% for tomato. Based on the estimated dry season irrigated area, groundwater irrigation volumes are calculated at approximately 1.0 MCM for rice and 0.65 MCM for tomato. The actual situation is likely to fall between these ranges, with 0.8 MCM per year representing a practical working estimate.

Table 3. Irrigation water demand for reference crops and estimated groundwater abstracted for irrigation

	Rice	Tomato
Total growing period 1 (days)	150	135
Growing months	November - March	November - March
Crop coefficients	1 – 1.1	0.45 – 1.15
Leaching fraction (%)	20	20
Mean effective rainfall during dry season (mm)	133	111
Total irrigation water demand for crop cycle (mm)	862	542
Current groundwater irrigation (MCM/yr)	1.0	0.65
Total growing period 1 (days)	150	135

[1] Neglects duration and water use in plant nursery prior to transplanting seedlings

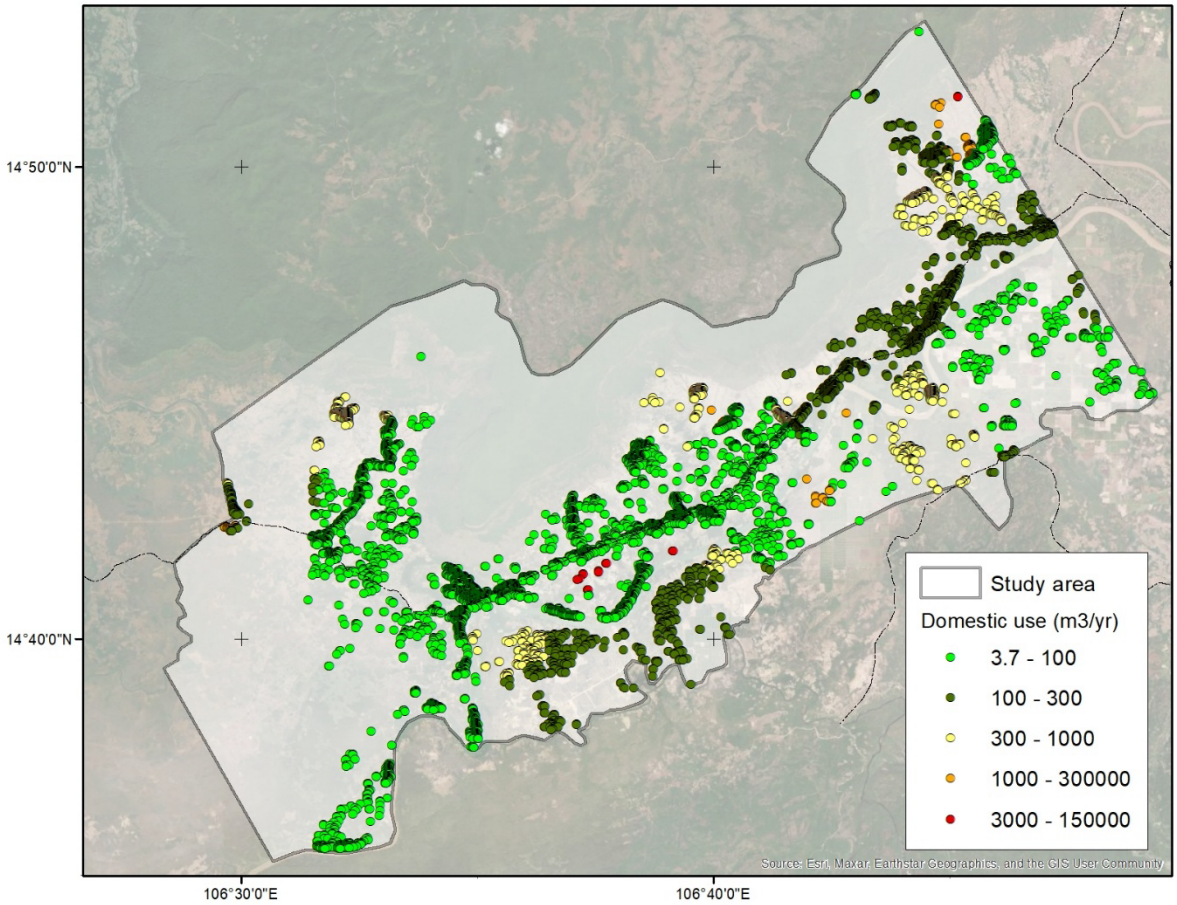

Figure 3. Domestic water demand distribution based on population and per capita water use data

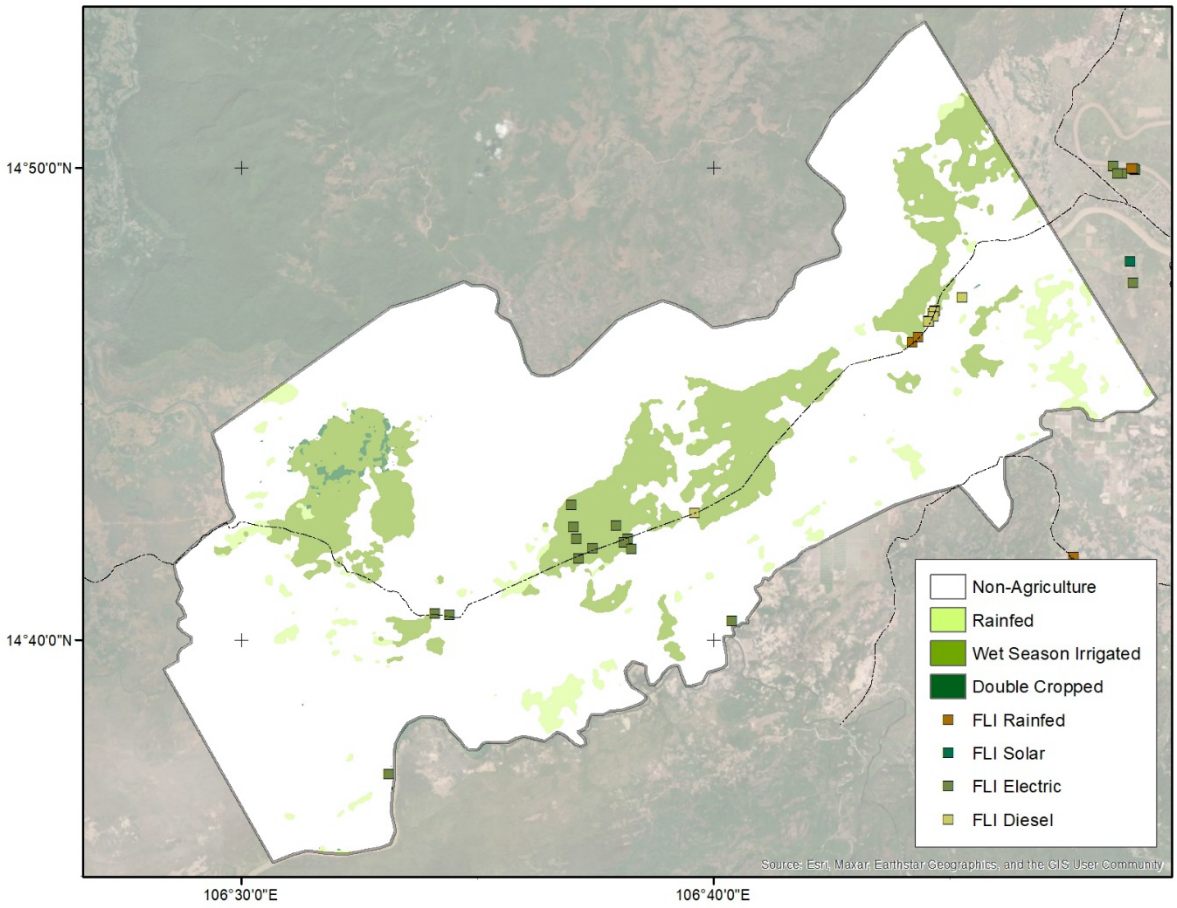

Figure 4. Current (2017/18) irrigated area map together with FLI survey sites overlaid

Utilizable groundwater availability

Groundwater availability was assessed as the portion of recharge that can be sustainably abstracted for irrigation after accounting for environmental requirements and existing abstraction (Equation 5). In this study, environmental allocation (*e*) was assumed to be 50% of mean annual recharge, reflecting a conservative approach consistent with international experience (Pavelic et al., 2013). This allocation provides a generous safeguard for ecosystem functions and allows flexibility for future increases in water demand or potential climate change impacts.

Recharge estimates varied across the study area. Using conservative assumptions, the low and median estimates of recharge were 155 MCM and 362 MCM per year, respectively (Table 4). After accounting for a 50% environmental allocation and subtracting current abstraction, the utilizable groundwater (Q_u) for irrigation was calculated as 74.9 MCM per year for the low recharge scenario and 178.3 MCM per year for the median scenario.

Groundwater abstraction is currently dominated by domestic use, while withdrawals for smallholder irrigation remain modest. Domestic withdrawals are estimated at 1.9 MCM per year, while dry season irrigation accounts for approximately 0.8 MCM per year. These values represent only a small proportion of the calculated utilizable groundwater (between 2 and 4 percent), suggesting that significant additional abstraction could be feasible for irrigation expansion.

Table 4. Estimates of Qu for two alternative recharge scenarios (e = 0.5)

	Volume (MCM)
Q_d	1.9
Q_i	0.8
R (low)	155
R (medium)	362
Q_u (low)	74.9
Q_u (medium)	178.3

SGI expansion

Baseline dry season irrigation in the study area is limited to around 120 ha. Under the low- and medium-recharge scenarios, the potential irrigated area increases to 11,226 ha and 26,736 ha, representing approximately 90-fold and 220-fold expansions compared to current levels. Table 5 gives the allocation of potential irrigated area across the five FLI suitability classes. In the low-recharge scenario, all irrigated area is contained within the top two suitability classes. In contrast, under the medium-recharge scenario, only 46% falls within the top two classes, while 54% extends into moderate suitability class. From a spatial viewpoint, expansion is concentrated along the central corridor of the study area (Figure 5), while allocations in peripheral northern zones are mainly associated with non-agricultural land. In this medium scenario, the projected irrigated area exceeds the available cropland, resulting in instances of inappropriate allocations into grassland and forest areas.

At the household scale, and assuming a median landholding size of 2 ha in Attapeu, the low-recharge scenario could support irrigated agriculture for approximately 5,600 households (90% of households in the study area, based on an average household size of 5.5). Typical privately operated SGI units support 1–2 ha or irrigated area, indicating sufficient biophysical capacity to support irrigation expansion at the household level.

Table 5. Allocation of irrigated area (ha) across FLI suitability classes under low- and medium-recharge scenarios.

Suitability Class	Irrigated area (ha)	
	Low Recharge	Medium Recharge
Highly Suitable	119	119
Suitable	11,107	12,187
Moderately Suitable	-	14,430
Marginally Suitable	-	-
Unsuitable	-	-
Total	**11,226**	**26,736**

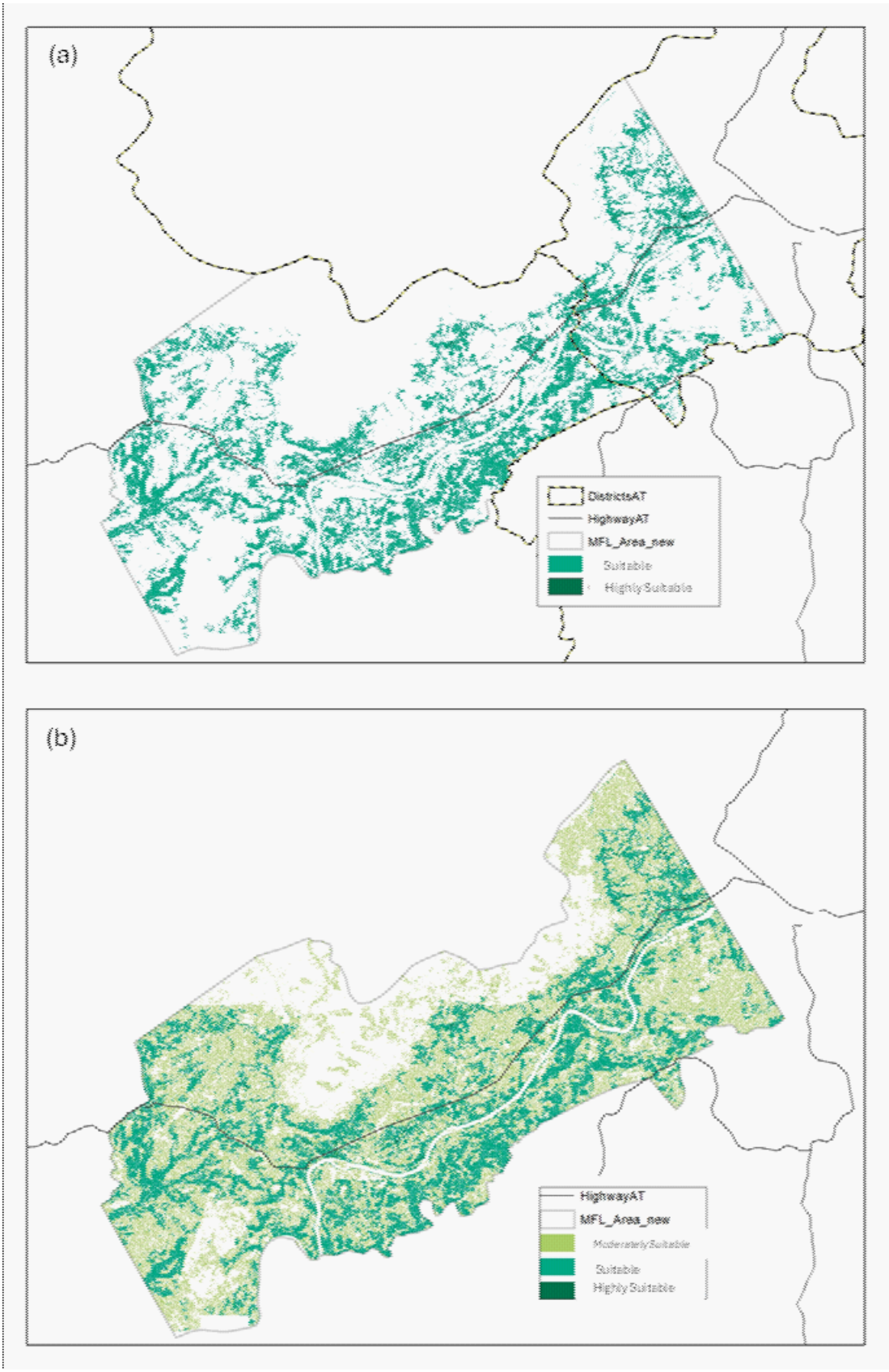

Figure 5. Spatial distribution of projected SGI expansion by suitability class for low recharge (a) and medium recharge (b) scenarios

Discussion

Risks to groundwater resources

Current levels of groundwater use for domestic and irrigation purposes in Attapeu are modest, accounting for less than 2% of the replenishable resource. This suggests considerable scope to sustainably expand groundwater development for irrigated agriculture. With high recharge potential, relatively sparse population, and low levels of abstraction, the risks of significant levels of overexploitation are likely to be lower than in many other countries (Coulon et al., 2021). Given that groundwater underpins household water security and supports existing dry season agriculture, even moderate increases in withdrawal can have marked impacts in cases where aquifers are thin or localized in extent (Bierkens et al., 2021). Localized depletion risks are therefore conceivable, particularly if clusters of SGI systems are established in vulnerable settings without appropriate coordination or monitoring.

The adoption of solar pump technologies could also lead to shifts in water demand patterns that place greater pressure on water resources. Once installed, solar pumps have negligible operating costs that may encourage higher levels of abstraction, potentially exacerbating localized drawdown if not carefully managed (Balasubramanya et al., 2024). While the sedimentary aquifers in the study area offer reasonably good storage capacity and resilience to variable climate regimes, these benefits are unevenly distributed. Even from the limited observations available, recharge rates and well airlift yields vary by a factor of almost three, suggesting that the aquifers of the area are highly variable and do not have the same capacity to sustain increases in irrigation. Further research is required on the aquifer systems of Attapeu to better characterize their dimensions and properties and to define their sustainable limits. Surveys of SGI system operators in Attapeu and Vientiane reveal a low level of awareness of groundwater as a resource with finite limits (Pavelic et al., 2025), underscoring the importance of raising awareness to compliment technical studies.

Monitoring is central tool for managing the risks over overexploitation and for evidence-based, adaptive management under climate change more broadly. Effective groundwater management requires knowledge of the sustainable development potential of the resource and robust monitoring networks. In Attapeu's complex hydrogeological setting, access to reliable local information is critical for successful borehole siting and construction, particularly given the high costs associated with drilling for new SGI investments. Yet monitoring systems remain absent or inadequate, constraining the ability to track quantity and quality trends, assess ecological interactions, and evaluate the impacts of pumping.

Barriers for SGI expansion

The results indicate substantial potential for SGI expansion in the MFL area and across Attapeu more broadly. Even under the most conservative set of assumptions, the area under dry-season irrigation could increase many-fold. If realized, this expansion could transform household food security, reduce vulnerability to climate variability, and enable diversification into higher-value crops (Douangsavanh et al., 2025; Smith et al., 2024). While SGI remains limited within the study area, a greater presence in neighboring districts shows that adoption can be achieved.

Realizing this potential requires overcoming significant barriers, given that adoption of SGI appears to be constrained not by resource limits, but by institutional, financial, and awareness barriers. High initial investment costs remain a central hurdle for adoption, particularly for marginal farmers (Pavelic et al., 2024). Sustaining livelihoods through irrigated agriculture also depends on adequate household labor, access to new knowledge on solar irrigation practices, working capital for inputs, and institutional support (Clément et al., 2018). Land tenure arrangements, cultural practices, and opportunities from alternative livelihood options further influence adoption dynamics (Suhardiman et al., 2020).

SGI expansion must also include the safeguarding of sensitive ecosystems such as wetlands and traditional fish trap ponds (Inphonephong et al., 2024). For example, the Nonglom wetland is known to interact directly with local aquifers, though the precise nature of these interactions is not yet fully understood (Douangsavanh et al., 2025). Land-suitability assessments that prioritize appropriate cropland and protect critical ecosystems are essential to ensure environmentally responsible expansion.

Policy and institutional implications

This study highlights the importance of integrating SGI within local water resource planning. Groundwater underpins domestic supply and contributes to ecosystem services, both of which must be safeguarded as SGI expands. Water quality, while not currently a constraint, requires ongoing monitoring to ensure compatibility for irrigation and domestic use, particularly as crop intensification increases risks from greater use of agrochemicals.

At the national level, groundwater resources are governed by established legal and regulatory frameworks (Coulon et al., 2021). However, Attapeu has yet to implement a provincial groundwater management plan, despite such plans having been adopted in most other provinces (Australian Water Partnership, 2021). Groundwater

planning of this kind provides a practical tool for balancing groundwater development with protection, clarifying institutional responsibilities, and embedding groundwater into land-use and agricultural planning. National and provincial governments, together with development partners, have a key role in facilitating this process and ensuring that SGI expansion aligns with broader development objectives. The current National Irrigation Development Plan (2021–2025) prioritizes major plains, including the Attapeu Plain, to expand wet- and dry-season irrigation (Department of Irrigation, 2021). It aims to achieve this by rehabilitating irrigation structures, enhancing resilience to floods and droughts, and strengthening the capacity of Water User Associations (WUAs). Strengthening the coordination between irrigation planning and groundwater management will be important to ensure that future irrigation expansion remains sustainable.

Enabling policies and integration of SGI into provincial water and basin-level planning will also be vital. Without this, adoption may remain uncoordinated and inequitable, favoring wealthier or better-connected households. Embedding SGI in broader livelihood and landscape initiatives offers a pathway to align expansion with poverty reduction and climate-resilience goals. To enable responsible growth, incentives for sustainable adoption, clearer legal frameworks, decentralized monitoring, and strong public–private partnerships are essential.

Conclusions

The analysis conducted through this study highlights both the promise of, and the requirements for, solar groundwater irrigation (SGI) in Attapeu Province. Current groundwater use is modest, suggesting ample room for sustainable expansion, particularly given the high recharge potential and favorable solar conditions. Conservative recharge scenarios indicate that SGI could expand dry season irrigation far beyond present levels, potentially transforming food security and enabling greater livelihood diversification.

Expansion, however, would not be without risks. Even small increases in withdrawals may have disproportionate impacts in areas where aquifers are thin, localized, or already heavily relied upon. The low operating costs of solar pumps may encourage over-abstraction, raising the likelihood of localized depletion if development is clustered in vulnerable settings. Furthermore, aquifer yields and recharge rates vary considerably across the province, underscoring the need for site-specific information to guide investment decisions.

Effective management will require stronger groundwater monitoring and data management systems to track recharge, withdrawals, and quality. Equally important are institutional frameworks at provincial and basin levels that balance development with protection, integrate SGI into broader land and water planning, and protect groundwater-dependent ecosystems. Without these measures, SGI expansion may lead to negative externalities, including environmental degradation and inequitable social outcomes.

SGI holds clear potential to reduce vulnerability to climate change, improve nutrition, and support poverty reduction in Attapeu. Realizing this potential depends on combining the biophysical opportunities that have been the focus of this study, with a broader set of measures that include formulating enabling policies, farmer capacity building, financial mechanisms to reduce entry barriers, and inclusive governance. A coordinated approach can help position SGI as a central pillar of sustainable rural transformation in Southern Laos.

Recommendations

We propose a set of proactive measures for government agencies, NGOs, the private sector, and researchers to promote sustainable and inclusive SGI adoption among smallholder farmers in Attapeu.

1. Establish comprehensive groundwater assessments and monitoring (levels, abstraction, quality) and develop trigger points to detect emerging depletion or contamination hotspots. Communicate this new scientific knowledge to policy makers, groundwater users, and other stakeholders to support better decision making.
2. Maintain existing SGI pilot schemes and extend implementation to new villages, supported by farmer training, participatory planning, and institutional support, to demonstrate feasibility, benefits, and inclusive adoption.
3. Develop mechanisms for affordable finance (credit, subsidies, guarantees) to reduce upfront costs for smallholders and encourage investment in sustainable irrigation.
4. Integrate SGI into provincial groundwater and agricultural planning, while protecting existing beneficial uses of groundwater, including domestic supply and groundwater-dependent ecosystems.
5. Promote public–private collaboration and harness emerging technologies to support sustainable groundwater use and improve scalability of successful interventions.
6. Build long-term institutional capacity within provincial authorities and farmer groups for governance, adaptive management, and climate-resilient irrigation practices.

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