A GIS-Based Integrated Multi-Stage Screening Framework for Preliminary Small-Scale Hydropower Site Selection

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ABSTRACT

Small-scale hydropower plants (PLTM, Pembangkit Listrik Tenaga Minihidro) play an important role in decentralizing the renewable energy systems, particularly in the river-rich regions. However, the site selection for PLTM remains a complex problem due to the hydrological reliability, technical feasibility, spatial planning constraints, and local energy demand. This study develops a Geographic Information System (GIS)-based multi-stage screening approach for preliminary identification and prioritization of potential PLTM sites at the watershed scale. The approach integrates the hydrological modeling derived from calibrated SWAT simulations, technical feasibility indicators, including gross head and potential power output, energy contribution assessment, and spatial conformity analysis, into a sequential screening workflow. The method was applied to the Lesti River Basin, Indonesia, where the 17 preliminary candidate locations were initially identified. After integrating the hydrological technical feasibility, energy contribution assessment, and land-use conformity analysis, seven sites were classified as technically feasible, while two locations were identified as the high-priority candidates. The results indicate that integrating multiple feasibility constraints substantially reduces the overestimation of potential sites compared with the conventional resource-based screening approaches. The proposed workflow provides a practical tool for the preliminary watershed-scale PLTM screening in data-limited environments; however, the approach is intended for the preliminary assessment and does not replace the detailed feasibility studies involving the hydraulic loss modeling, economic evaluation, and grid integration analysis.

Keywords-Geographic Information System (GIS)-based assessment; mini hydropower; multi-criteria analysis; mini hydropower planning

I. INTRODUCTION

Small-scale hydropower plants (PLTM, Pembangkit Listrik Tenaga Minihidro) are a significant component of decentralized renewable energy systems, particularly in the mountainous and river-rich regions where large-scale hydropower development is technically, economically, or environmentally constrained. By enabling the localized energy generation, the PLTM contributes to the energy access, grid stability, and rural economic development, while having lower environmental impacts compared to the large hydropower schemes [1]. Despite its considerable potential, the sustainable deployment of PLTM remains challenging due to the complex interplay between the hydrological variability, engineering feasibility, spatial planning constraints, and the socio-economic considerations [2]. The accurate site selection represents one of the most critical and uncertain stages in PLTM planning. Inappropriate site selection frequently leads to technical under-performance, cost overruns, social conflicts, and project abandonment. However, previous studies have predominantly emphasized hydrological and topographical criteria, such as dependable discharge and available head, as primary determinants of PLTM feasibility [3]. While these parameters are essential, exclusive reliance on the technical indicators often neglects the spatial compatibility, land-use constraints, infrastructure accessibility, electricity demand distribution, and community acceptance, which are equally decisive for long-term project success [4].

Advances in Geographic Information Systems (GIS), hydrological modeling, and Spatial Decision-Support Systems (SDSS) have enabled more systematic and spatially explicit assessment of the renewable energy potential. GIS-based Multi-Criteria Decision-Making (MCDM) approaches have been applied for hydropower site selection by integrating hydrological, topographical, environmental, and socio-economic indicators [5]. However, the existing frameworks are either highly case-specific or methodologically fragmented. These approaches often lack unified analytical structures capable of producing transferable, objective, and reproducible decision-support tools. In addition, many studies adopt the qualitative weighting schemes or ad-hoc scoring procedures, which limit transparency, robustness, and cross-regional applicability [6].

II. MATERIALS AND METHODS

A. Study Location

This study was conducted in the Lesti River Basin, a major sub-watershed of the upper Brantas River system, located in Malang Regency, East Java Province, Indonesia. The Lesti Basin plays a strategic hydrological role in regulating inflows to two major downstream hydropower reservoirs, namely Sengguruh and Sutami. These reservoirs together constitute a crucial component of regional electricity supply and flood control infrastructure. The watershed covers an area of approximately 58,000–65,000 ha, with elevation ranging from 235 to 3,676 m above sea level, representing highly heterogeneous physio-graphic conditions. The basin is characterized by steep mountainous terrain in the upstream zone, volcanic landforms, and complex drainage networks, with slope gradients varying from 8% to over 45%. These geomorphological features generate substantial hydraulic head potential while simultaneously imposing significant engineering and accessibility constraints. These factors make the basin particularly suitable for evaluating the spatial decision frameworks for small-scale hydropower planning.

B. Materials

This study integrates the hydro-meteorological, spatial, and socio-economic datasets obtained from multiple reliable sources. Both primary and secondary data were employed to ensure robust hydrological modeling, technical feasibility assessment, and spatial Multi-Criteria Analysis (MCA).

a) Hydro-Meteorological Data

Daily rainfall data were collected from rainfall gauging stations distributed across the Lesti River Basin, covering a continuous observation period from 2015 to 2025. Discharge records were obtained from the Sengguruh Automatic Water Level Recorder (AWLR) station, which serves as the primary hydrological control point of the basin. In addition, daily climatology variables, including temperature, relative humidity, wind speed, and solar radiation, were acquired from the nearest meteorological stations operated by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). These datasets were used to drive, calibrate, and validate the SWAT hydrological model.

The Digital Elevation Model (DEM) with a spatial resolution of 0.27 arc second, approximately 8 m per pixel, was used for topographic analysis, drainage network extraction, and head estimation. Soil type maps were derived from Food and Agriculture Organization (FAO) Soil World Database, providing spatial distribution of the soil physical properties required for hydrological simulation; Land Use and Land Cover (LULC) maps derived from the Ministry of Environment and Forestry Indonesia, were used for runoff modeling, spatial planning analysis, and socialist-environment constraints; River network and watershed boundary shape files derived from Water Resources Department of the Public Works Office, East Java Province, Indonesia, were used for spatial referencing and hydrological segmentation.

b) Socio-Spatial and Infrastructure Data

Population distribution data at the village and sub-district levels were obtained from the Central Bureau of Statistics of Indonesia (BPS) and used to estimate spatial electricity demand and service coverage. Spatial planning maps (RTRW) and protected area boundaries were acquired from local government agencies and incorporated to evaluate the land-use compatibility and regulatory constraints.

C. Methodology

This study develops an integrated GIS-based MCD framework to objectively identify and prioritize potential locations for small-scale hydropower plants (PLTM). The proposed methodology combines hydrological modeling, engineering feasibility analysis, socio-spatial assessment, and spatial MCA within a unified analytical workflow. The methodological framework consists of five sequential stages:

1) Selection of Potential Point for PLTM

The selection of the initial potential points for PLTM was carried out based on the topography and river morphology of the Lesti watershed. The initial point of PLTM is selected in the area that surrounds the outlet or downstream of the affluent in the Lesti watershed. Specifically, the watershed is delineated using DEM. During delineation, the river network was classified based on flow hierarchy. The selected initial design points were based on LULC and prioritized areas with land availability.

2) Hydrological Modeling by SWAT

After the site selection, the SWAT model was employed to calculate the river flow rate in terms of simulated daily discharge data. For each site (identified by a point), a Flow Duration Curve (FDC) was created to determine the flow rate, which would be considered as input for the calculation of the hydropower potential based on the required percentage of dependability. To ensure predictive reliability, the SWAT outputs were calibrated and validated against the observed discharge data that were recorded at the AWLR station, which represents the primary hydrological control point of the basin. However, authors in [7] expressed that a statistical approach, such as Nash–Sutcliffe Efficiency (NSE), should be used to analyze model performance. The model simulations achieving NSE > 0.65 were considered satisfactory and consistent with the established hydrological modeling standards.

3) Flow-Duration Curve

With the daily river flow obtained using the SWAT model, FDC for each potential point was used to extract the reference flow (Q). The FDC plots the percentage of time specific flow rates in a river or stream are equaled or exceeded over a given period, typically one year. It is crucial for hydropower potential assessments because it provides insights into flow characteristics that can be used to estimate power generation potential over time [8]. The shape of the FDC is used to estimate the base flows and peak flows, which are useful for sizing turbines and assessing the feasibility of hydropower plants. It is used to determine dependable flows such as Q_{90}, which represent flows exceeded 90% of the time, and ensure that hydropower projects meet their design and operational needs, even during low-flow periods. The 90% dependable discharge (Q_{90}) was computed using the Weibull probability distribution, expressed as:

$$P = \frac{m}{n+1}\, x\, 100\% \tag{1}$$

where P is the probability, m is the rank of the ordered discharge series, and n is the total number of observations.

4) Penstock Length Estimation and Gross Head Extraction

For each candidate site, the potential penstock alignment was delineated along the terrain profile derived from DEM analysis. The gross head was then estimated as the elevation difference between the initial intake location and the downstream endpoint of the penstock alignment within the defined maximum distance. In cases where extending the penstock length did not produce additional elevation drop, the shorter effective penstock length was retained to avoid unnecessary conveyance extension. This approach ensures that the estimated gross head reflects the realistic hydraulic potential achievable within practical conveyance constraints.

5) Energy Estimation

The hydropower potential (P) is typically calculated using:

$$P = 9.81 \times \rho \times Q \times H \times \eta \tag{2}$$

where Q is the water available measured in m³/s, and H is the hydraulic head in m.

In this framework, the hydraulic losses associated with friction, bends, and minor losses were not explicitly modeled, as the primary objective of this study is a comparative spatial prioritization at the watershed scale, rather than a detailed engineering design. At this planning stage, the detailed penstock configurations and hydraulic layouts are not available, which introduces substantial uncertainty in loss estimation. Consequently, the gross head is adopted as a robust and spatially consistent indicator of potential energy, in line with previous regional-scale hydropower planning studies. This assumption is consistent with the primary objective of this work, which is regional-scale spatial screening and comparative prioritization of PLTM sites, rather than the detailed hydraulic or electromechanical design. By maintaining the uniform modeling assumptions across all candidate locations, the approach ensures an objective and consistent relative comparison of the site performance. It also minimizes the uncertainties introduced by the site-specific engineering parameters that are typically addressed during the detailed feasibility and design stages.

6) Spatial Assessment Based on Regional Land Use Planning

Spatial assessment is conducted by overlaying the PLTM candidate locations with the legally adopted spatial plan of Malang Regency, as stipulated in Peraturan Daerah Kabupaten Malang Nomor 1 Tahun 2025. The spatial assessment was performed using GIS overlay analysis between candidate PLTM coordinates (17 plan points) and the official spatial pattern map (RTRW 2024–2044).

Each point was classified according to its designated land allocation category, including agricultural cultivation areas, plantation zones, horticultural areas, tourism development zones, residential areas, protected forest areas, conservation zones, and green open space areas. Special attention is given to areas designated as Protected forests, Conservation zones, and Sustainable agricultural land (LP2B). Under Undang-Undang Nomor 41 Tahun 2009, the conversion of designated sustainable agricultural land is strictly limited to safeguarding the national food security. Land-use change is only permitted under specific conditions for strategic public interest infrastructure, subject to strict procedural, licensing, and compensation mechanisms. However, since this study operates at a preliminary screening level, a detailed permitting analysis is beyond the scope of this stage.

For early-stage screening, spatial conformity is categorized as follows:

- Eligible (Spatially Compatible): areas located within cultivation zones, plantation areas, horticultural zones, tourism zones, settlement areas, and other non-protected land allocations.
- Conditionally Eligible: areas located within LP2B or strategic agricultural zones requiring regulatory clearance.
- Not Eligible: located within protected forest areas, conservation areas, and legally restricted environmental protection zones.

This simplified classification enables the identification of sites with minimal spatial conflict risk without conducting a full regulatory feasibility assessment. The overlay analysis indicates that the majority of candidate PLTM points are situated within cultivation and community-use zones. No candidate site is located within strictly protected conservation core zones. Therefore, from a spatial planning perspective, most screened locations are mainly compatible with the regional land-use designation, subject to subsequent permitting procedures.

7) Capacity Compatibility Ratio

Following the estimation of theoretical energy potential at each candidate PLTM site, this stage evaluates the spatial distribution of electricity demand and the service coverage capacity of each site. The objective is to assess whether the estimated hydropower generation can support the local electricity needs within the Lesti watershed. Given that the objective of this study is to develop a preliminary screening framework, demand estimation is conducted at the level of installed power rather than detailed energy consumption modeling. Electricity demand is estimated based on the number of households within each sub-watershed area. Each household is assumed to have a standard residential electricity connection capacity of 900 VA. To ensure consistency with hydropower installed capacity (MW), apparent power is converted into real power use. To assess adequacy, a simplified Energy Compatibility Ratio (ECR) is defined:

$$CCR = \frac{E_{generation}}{E_{demand}} \qquad (3)$$

where $E_{generation}$ is derived from Stage 2 (based on Q_{90} and head), E_{demand} is the estimated annual residential demand, $CCR > 1$ indicates a high energy contribution, while $CCR < 1$ represents a limited energy contribution.

III. RESULTS

A. PLTM Potential Point Selection

The initial filtering process spatially produces 17 points of the potential candidates of PLTM in the study area. All locations are further evaluated for the discharge availability (Q_{90}), penstock length, energy potency, suitability between water availability and demand, and land use suitability.

B. Hydrological Modeling by SWAT

The ArcGIS SWAT model was used to generate outlets of each sub-watershed for 17 points identified as the initial locations for PLTM development. Discharges of these 17 points were calculated using the SWAT model, followed by validation and calibration using observed station data at the outlet in the downstream end of the Lesti sub-watershed. The calibration and validation of the SWAT model were carried out on a monthly scale, although the model is simulated with daily data. This approach is selected because the monthly aggregation is more stable and can decrease uncertainty due to daily discharge fluctuation, noise measurement, and limitations of hydrology data, mainly in the study of the watershed scale. In addition, the present study focuses on assessing the availability of dependable discharge (Q_{95}) for regional PLTM screening demand, not on the hydrology simulation that is based on the daily event.

The calibration process is carried out using hydrology data from 2016 to 2024 to represent the updated watershed condition, including the updated land use characteristics and hydrology response. However, the model validation uses data from 2025 to determine the robustness and the ability of the model prediction for different periods. This approach is in line with the general practice in the SWAT modeling for evaluating the long-term hydrology [9, 10]. The Calibration and validation results are presented in Figures 1 and 2.

C. FDC, Penstock Length, and Energy Estimation

After calibrating the discharge model using SWAT, it was used to calculate the discharge at 17 PLTM design points. A dependable discharge of 95% (Q_{95}) was considered the discharge value for the generation of PLTM. The results of the 95%-dependable discharge at 17 points are depicted in Figure 2. Potential hydropower was estimated using (2), with the length of the waterway pipe and gross head estimated as explained earlier. The results of the dependable discharge (Q_{95}), gross-head (m), length of waterway (m), and output power calculation are presented in Table I. The analysis revealed that multiple locations failed to satisfy the output power, dependable discharge (Q_{95}), topography, and penstock length (> 2 km) requirements.

In this research, only locations with output power estimation of more than 1 MW are selected for further evaluation. These locations generate enough energy capacity to support the regional energy demand and to increase the initial technical feasibility of the infrastructure development. Figures 3 and 4 illustrate the spatial distribution of the waterway pile length availability and electrical power generation potential, respectively.

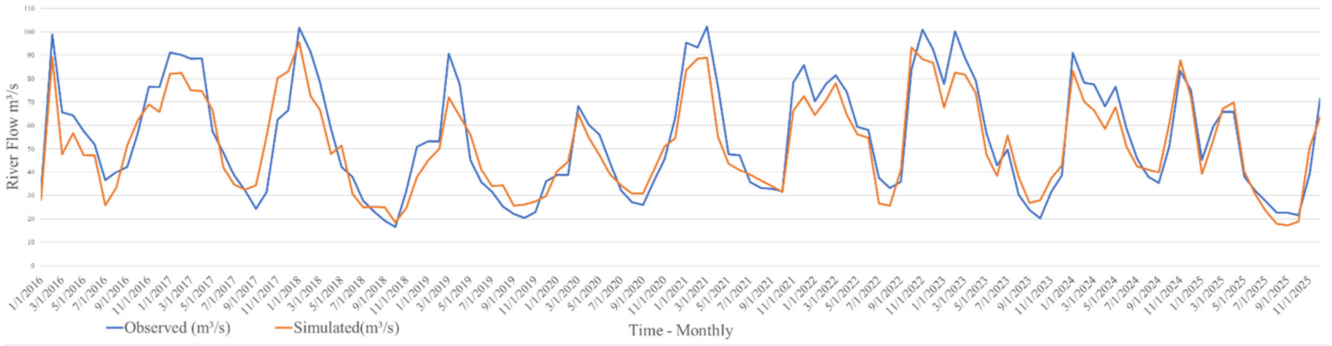


Fig. 1. Simulated and observed monthly river flow data for the calibration and validation period for the Sengguruh Gauged station.

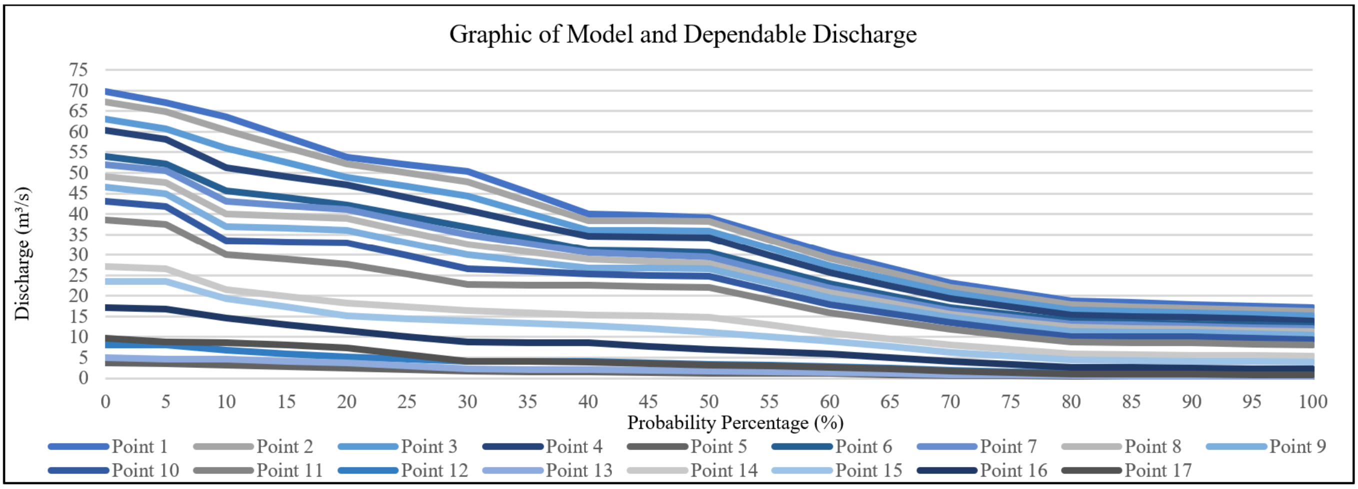


Fig. 2. Dependable discharge for 17 points.

TABLE I. RESULTS OF HYDROLOGICAL AND TOPOGRAPHICAL SCREENING FOR CANDIDATE PLTM SITES IN THE LESTI RIVER BASIN

Point	**Coordinate**		**Model discharge (m^3/s)**	**Q_{95} % (m^3/s)**	**Type of PLTM**	**Gross head (m)**	**Length of waterway (m)**	**Output power (MW)**	**Screening results**
	X	**Y**							
1	-8.18693	112.5543	40.929	17.083	Runoff	16	569	4.81	Selected
2	-8.20864	112.5755	39.285	16.181	Runoff	1	1,914	0.29	Excluded
3	-8.22228	112.5997	36.747	15.092	Runoff	3	1,090	0.81	Excluded
4	-8.22391	112.6011	34.627	13.983	Runoff	4	181	1.02	Selected
5	-8.19176	112.6575	1.706	0.330	Runoff	12	1,960	0.15	Excluded
6	-8.22571	112.6011	31.036	12.629	Runoff	1	174	0.23	Excluded
7	-8.2285	112.6051	29.833	12.021	Runoff	4	256	0.88	Excluded
8	-8.24017	112.6259	28.085	11.312	Runoff	6	232	1.24	Selected
9	-8.23758	112.6404	26.273	10.500	Runoff	6	1,399	1.16	Selected
10	-8.23445	112.6551	24.095	9.407	Runoff	15	2,000	2.65	Selected
11	-8.21545	112.7004	21.204	8.035	Runoff	5	1,529	0.78	Excluded
12	-8.20734	112.7378	4.027	1.086	Runoff	15	1,342	0.44	Excluded
13	-8.2052	112.7506	2.329	0.433	Runoff	15	716	0.26	Excluded
14	-8.19734	112.7063	14.689	5.296	Runoff	12	2,000	1.29	Selected
15	-8.17107	112.7189	12.266	3.862	Runoff	15	1,954	1.35	Selected
16	-8.14878	112.7302	8.460	2.214	Runoff	15	1,100	0.93	Excluded
17	-8.12407	112.7369	4.434	0.821	Runoff	15	713	0.49	Excluded

D. Spatial Assessment Based on Regional Land Use Planning

The results of the spatial overlay to the RTRW of Malang Regency 2024-2044 show that all PLTM candidate points are on the plantation and the other usage (APL). These categories allow the development of energy infrastructure. Some candidate locations are situated in village residential areas, horticulture, plantation, and tourism areas. There are no candidate points in the protected forest area, core conservation zone, or the environment protected area with strict utilization restrictions. As all candidate locations have good initial compatibility with regional spatial planning, there is no potential conflict for development. However, the spatial suitability in this research is for the preliminary screening and does not include licensing details, land ownership, and environmental impact analysis (AMDAL).

The detailed spatial classification for each candidate site is presented in Tables II and III, while the spatial overlay distribution is illustrated in Figure 5.

E. Energy Demand and Compatibility Coverage Ratio (CCR)

The results of the CCR analysis show variation in the level of energy contribution provided by each PLTM candidate point to the domestic electrical demand in the service area. Two locations, Point-1 and Point-8, have CCR > 1, indicating that these locations have the potential to fulfill the domestic electrical demand in each service area. In contrast, the remaining PLTM candidate points have CCR < 1, indicating that these points are unable to fulfil the electrical demand in the surrounding area. Some locations show significant energy contribution potential; however, they cannot achieve the full coverage demand. These results indicate that the CCR is a much better indicator of contribution potential compared to other parameters, such as the length of the waterway pipe and energy generation potential. Therefore, this study prioritizes this CCR requirement for the realistic screening of the PLTM candidate point.

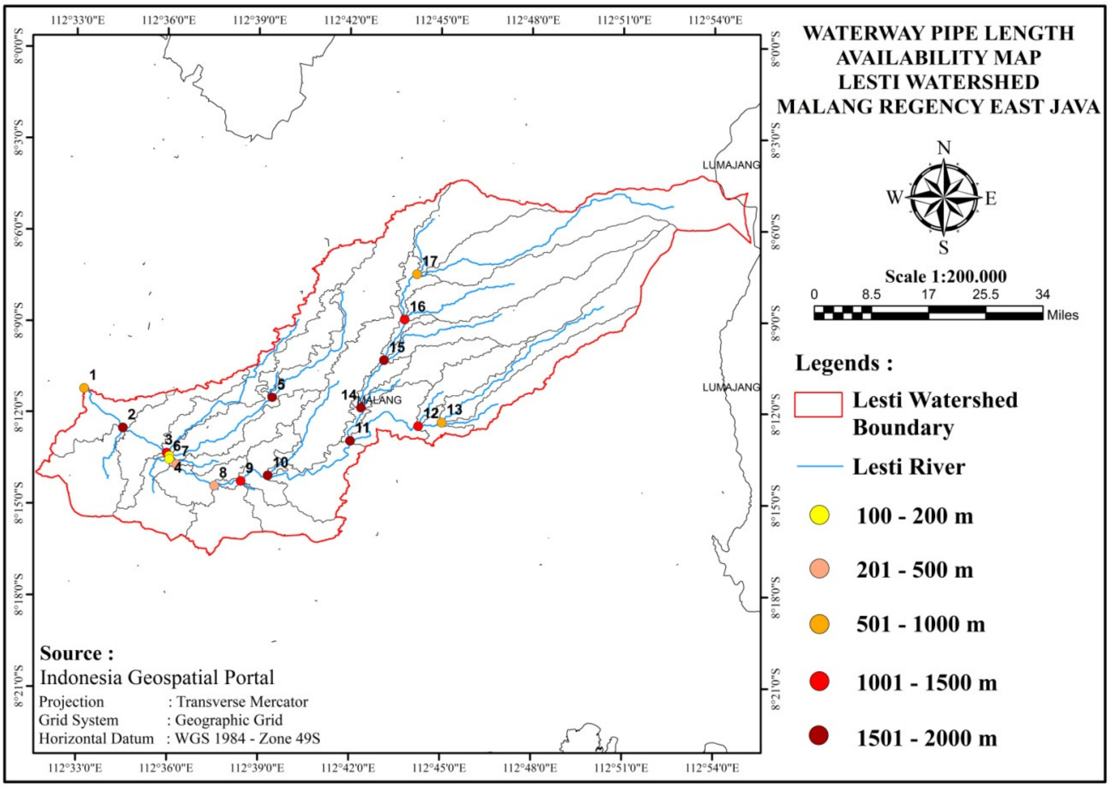


Fig. 3. Spatial distribution of waterway pipe length availability map.

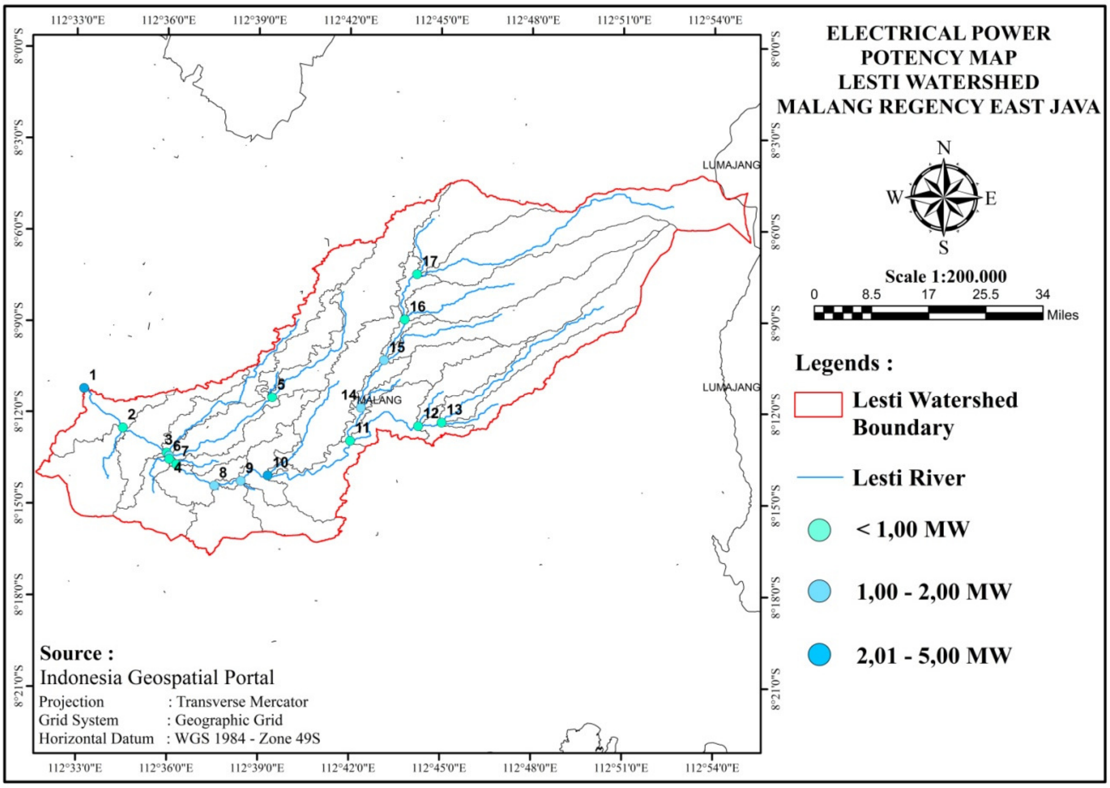


Fig. 4. Spatial distribution of electrical power generation potential.

Based on this analysis, the candidate locations are classified into 4 categories:

- a) High priority for the location with CCR is > 1, with high energy contribution potential that can fulfill or surpass the local electrical demand.
- b) Moderate priority for the location with $0.4 \leq \text{CCR} \leq 1$, with moderate energy contribution potential.
- c) Low priority for the location with $0.1 \leq \text{CCR} < 0.4$, which has limited energy contribution.
- d) Not feasible for the location with CCR < 0.1.

Based on this classification, Site 1 and Site 8 were categorized as of High Priority since they have CCR values of 2.64 and 1.48, respectively. Some locations, including Site 4, Site 9, and Site 14, were categorized as of Moderate Priority because they still show a significant enough energy contribution, although they cannot fully meet the local electrical demands. This approach provides a more realistic assessment for considering the relevance of energy contribution to the local electrical demand condition.

TABLE II. LAND USE COMPATIBILITY ASSESSMENT OF CANDIDATE PLTM SITES

Point	Coordinate		Spatial pattern	Allocation	Spatial compatibility
	X	Y			
1	-8.18693	112.5543	Village residence area	APL – fulfil	Compatible
2	-8.20864	112.5755	Smallholder plantation area	APL – fulfil	Compatible
3	-8.22228	112.5997	Crops area	APL – Fulfil	Compatible
4	-8.22391	112.6011	Crops area	APL – Fulfil	Compatible
5	-8.19176	112.6575	Crops area	APL – Fulfill	Compatible
6	-8.22571	112.6011	Smallholder plantation area	APL – Fulfil	Compatible
7	-8.2285	112.6051	Horticulture area	APL – Fulfil	Compatible
8	-8.24017	112.6259	Plantation area	APL – Fulfil	Compatible
9	-8.23758	112.6404	Crops area	APL – Fulfil	Compatible
10	-8.23445	112.6551	Plantation area	APL – Fulfil	Compatible
11	-8.21545	112.7004	Village residence area	APL – Fulfil	Compatible
12	-8.20734	112.7378	Horticulture area	APL – Fulfil	Compatible
13	-8.2052	112.7506	Horticulture area	APL – Fulfil	Compatible
14	-8.19734	112.7063	Horticulture area	APL – Fulfil	Compatible
15	-8.17107	112.7189	Horticulture area	APL – Fulfil	Compatible
16	-8.14878	112.7302	Tourism area	APL – Fulfil	Compatible
17	-8.12407	112.7369	Plantation area	APL - Fulfil	Compatible

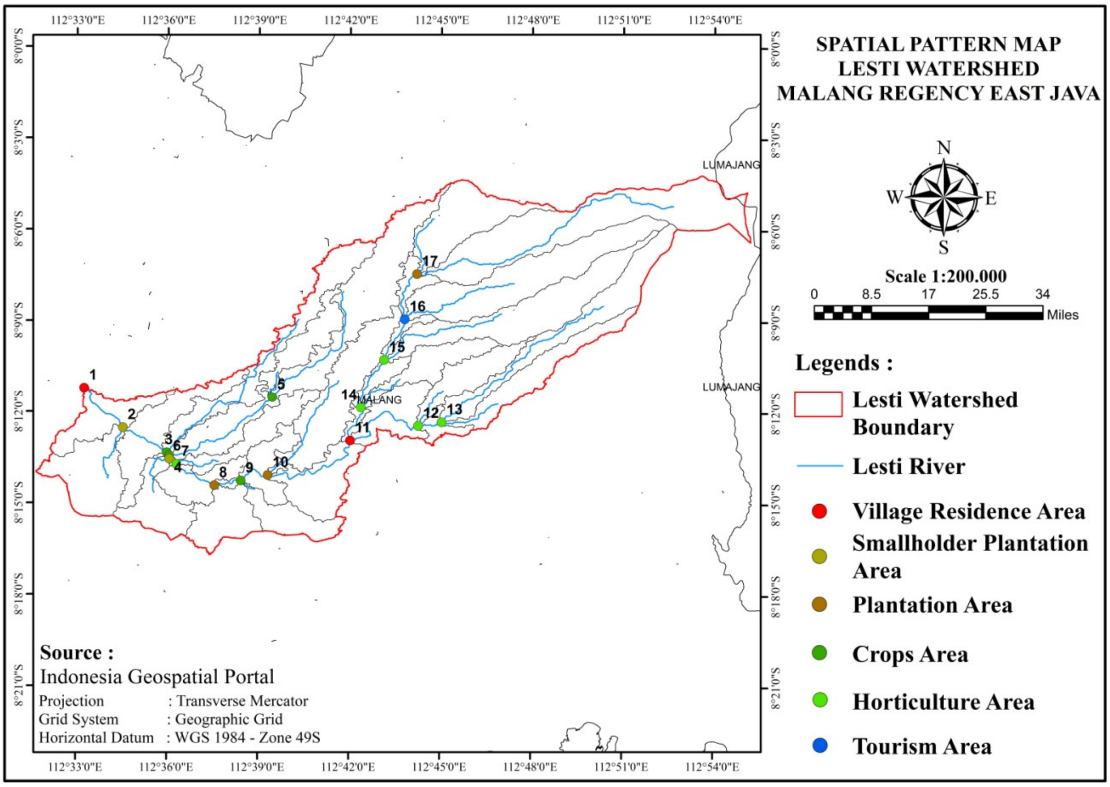


Fig. 5. Plan map of spatial pattern.

TABLE III. ENERGY DEMAND AND COMPATIBILITY ASSESSMENT FOR CANDIDATE PLTM SITES

Point	Coordinate		Number of houses	Electrical demand at every point (MW)	Output power (MW)	CCR	Interpretation	Priority ranking
	X	Y						
1	-8.18693	112.5543	2,529	1.82	4.81	2.64	High energy contribution	1
2	-8.20864	112.5755	6,399	4.61	0.29	0.06	Limited energy contribution	4
3	-8.22228	112.5997	7,225	5.2	0.81	0.16	Limited energy contribution	3
4	-8.22391	112.6011	3,832	2.76	1.02	0.37	Limited energy contribution	2
5	-8.19176	112.6575	13,349	9.61	0.15	0.02	Limited energy contribution	4
6	-8.22571	112.6011	4,368	3.14	0.23	0.07	Limited energy contribution	4
7	-8.2285	112.6051	5,625	4.05	0.88	0.22	Limited energy contribution	3
8	-8.24017	112.6259	1,171	0.84	1.24	1.48	High energy contribution	1
9	-8.23758	112.6404	3,438	2.48	1.16	0.47	Limited energy contribution	2
10	-8.23445	112.6551	13,191	9.5	2.65	0.28	Limited energy contribution	3
11	-8.21545	112.7004	2,827	2.04	0.78	0.38	Limited energy contribution	2
12	-8.20734	112.7378	2,764	1.99	0.44	0.22	Limited energy contribution	3
13	-8.2052	112.7506	4,151	2.99	0.26	0.09	Limited energy contribution	4
14	-8.19734	112.7063	3,085	2.22	1.29	0.58	Limited energy contribution	2
15	-8.17107	112.7189	7,756	5.58	1.35	0.24	Limited energy contribution	3
16	-8.14878	112.7302	7,225	5.2	0.93	0.18	Limited energy contribution	3
17	-8.12407	112.7369	7,844	5.65	0.49	0.09	Limited energy contribution	4

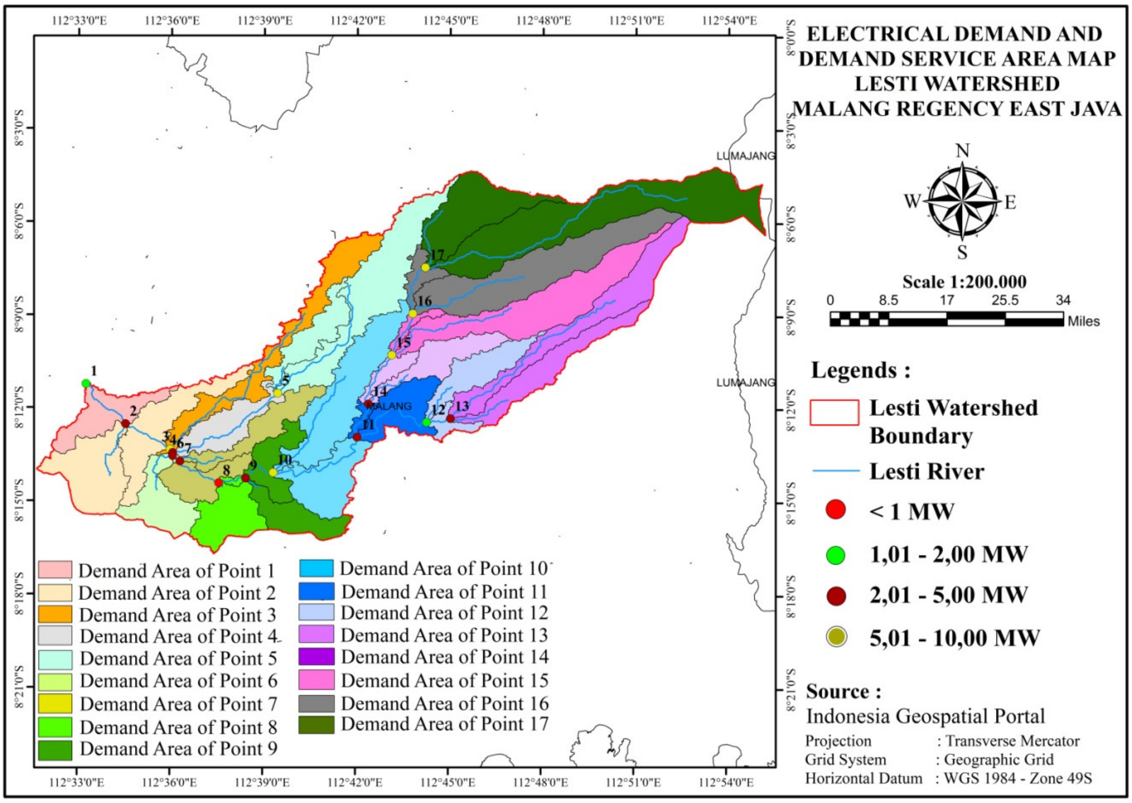


Fig. 6. Map of electrical demand.

F. Integrated Screening Results and Site Prioritization

The integrated screening results demonstrate the distinct analytical role of each assessment layer within the proposed framework. The hydrological–technical assessment acted as the primary feasibility filter by evaluating dependable discharge (Q_{95}), gross head, waterway length, and estimated power output. Based on these criteria, seven candidate sites were classified as technically feasible, while the remaining locations were categorized as not feasible due to insufficient hydraulic head, low discharge reliability, or limited power generation potential.

The spatial conformity assessment indicated that all candidate sites were located within compatible land-use zones according to the regional spatial plan (RTRW) of Malang Regency, including plantation areas, agricultural cultivation zones, horticultural areas, tourism zones, and village residential areas. Consequently, no additional candidate sites were eliminated during this stage, suggesting that the preliminary hydrological–technical screening had already concentrated potential PLTM locations within spatially compatible development areas.

The CCR analysis further classified the feasible sites based on their relative contribution to local electricity demand. Sites with CCR values greater than 1 were classified as High Priority due to their strong potential contribution to the local energy supply, whereas sites with moderate CCR values were categorized as Moderate Priority, and sites with lower CCR values were classified as Low Priority. As a result, Site 1 and Site 8 emerged as the highest-priority candidates, demonstrating both strong hydropower potential and high relative contribution to the surrounding electricity demand. Overall, the integrated framework enables a more realistic and structured prioritization process by distinguishing physical feasibility, spatial compatibility, and relative energy contribution within a unified watershed-scale assessment workflow. Table IV presents the integrated hydrological-technical, spatial, and energy contribution assessment for PLTM site prioritization, while Figure 7 displays the classification of the PLTM design points.

TABLE IV. INTEGRATED HYDROLOGICAL–TECHNICAL, SPATIAL, AND ENERGY CONTRIBUTION ASSESSMENT FOR PLTM SITE PRIORITIZATION

Site ID	Hydological-technical analysis					Spatial conformity assessment		Energy contribution assessment			
	Q_{95} (m³/s)	Gross head (m)	Length of waterway (m)	Power output (MW)	Preliminary technical feasibility	Spatial status	Spatial compatibility	Estimated demand (MW)	CCR	Site priority	Final classification
1	17.083	16	569	4.81	Feasible	Village residence area	compatible	1.82	2.64	1	High Priority
2	16.181	1	1,914	0.29	Not Feasible	Smallholder plantation area	compatible	4.61	0.06	4	Not Feasible
3	15.092	3	1,090	0.81	Not Feasible	Crops area	compatible	5.2	0.16	3	Not Feasible
4	13.983	4	181	1.02	Feasible	Crops area	compatible	2.76	0.37	2	Moderate Priority
5	0.33	12	1,960	0.15	Not Feasible	Crops area	compatible	9.61	0.02	4	Not Feasible
6	12.629	1	174	0.23	Not Feasible	Smallholder plantation area	compatible	3.14	0.07	4	Not Feasible
7	12.021	4	256	0.88	Not Feasible	Horticulture area	compatible	4.05	0.22	3	Not Feasible
8	11.312	6	232	1.24	Feasible	Plantation area	compatible	0.84	1.48	1	High Priority
9	10.5	6	1,399	1.16	Feasible	Crops area	compatible	2.48	0.47	2	Moderate Priority
10	9.407	15	2,000	2.65	Feasible	Plantation area	compatible	9.5	0.28	3	Low Priority
11	8.035	5	1,529	0.78	Not Feasible	Village residence area	compatible	2.04	0.38	2	Not Feasible
12	1.086	15	1,342	0.44	Not Feasible	Horticulture area	compatible	1.99	0.22	3	Not Feasible
13	0.433	15	716	0.26	Not Feasible	Horticulture area	compatible	2.99	0.09	4	Not Feasible
14	5.296	12	2,000	1.29	Feasible	Horticulture area	compatible	2.22	0.58	2	Moderate Priority
15	3.862	15	1,954	1.35	Feasible	Horticulture area	compatible	5.58	0.24	3	Low Priority
16	2.214	15	1,100	0.93	Not Feasible	Tourism area	compatible	5.2	0.18	3	Not Feasible
17	0.821	15	713	0.49	Not Feasible	Plantation area	compatible	5.65	0.09	4	Not Feasible

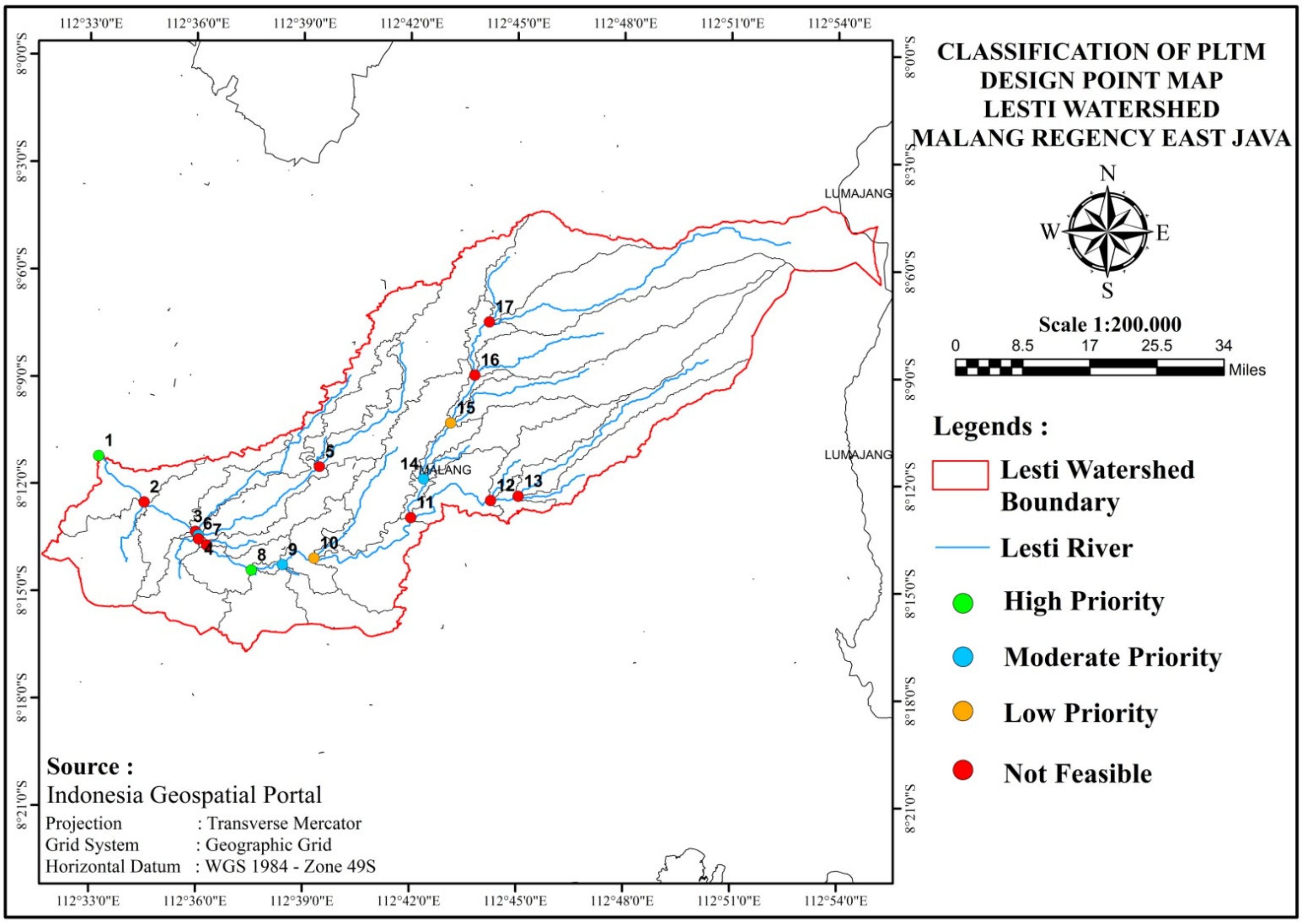
IV. DISCUSSION

A. *Methodological Contribution of the Multi-Stage Screening Framework*

The proposed framework demonstrates how sequential integration of hydrological reliability, technical feasibility, energy contribution assessment, and spatial conformity analysis can improve preliminary PLTM site screening at the watershed scale, as expressed in [11]. From 17 initially identified candidate locations, only seven sites satisfied the minimum hydrological–technical feasibility criteria based on the dependable discharge (Q_{95}), gross head, waterway length limitation, and minimum power output requirements [12]. This result indicates that the early integration of firm flow reliability and technical constraints substantially reduces the overestimation risk commonly associated with theoretical hydropower mapping approaches based solely on DEM and average discharge analysis.

The CCR assessment further differentiated the technically feasible sites according to their relative contribution to the local electricity demand. Two sites (Site 1 and Site 8) were classified as High Priority with CCR values greater than 1, indicating a strong potential contribution to the surrounding electricity demand. Three sites were classified as Moderate Priority, while two feasible sites were categorized as Low Priority due to lower relative energy contribution. These results demonstrate that technically feasible PLTM locations may exhibit substantially different local energy relevance, which is often overlooked in conventional hydropower potential studies. Similar approaches have been advocated in rural electrification planning, where generation potential must align with demand forecasts to ensure social and economic relevance [13].

The spatial conformity assessment showed that all candidate sites were located within compatible land-use zones under the Malang Regency spatial plan. Although this stage did not eliminate additional sites, it verified that the selected feasible locations present relatively low preliminary regulatory conflict risk. Therefore, the framework not only performs technical filtering but also integrates practical planning considerations within a single assessment workflow.



Source :
Indonesia Geospatial Portal
Projection : Transverse Mercator
Grid System : Geographic Grid
Horizontal Datum : WGS 1984 - Zone 49S

Fig. 7. Classification of PLTM design point.

B. Comparison with Existing PLTM Site Selection Approaches

Small hydropower assessments often rely on the GIS-based hydropower atlases derived from DEM analysis and mean discharge estimates, as written in [14]. However, conventional GIS-based hydropower assessments generally focus on theoretical resource identification using topography and discharge mapping, often producing a large number of technically uncertain candidate sites. In contrast, the proposed framework applies staged feasibility filtering before prioritization. In the present study, 17 preliminary candidate locations were initially identified, but only seven sites remained technically feasible after incorporating dependable flow reliability, gross head constraints, waterway limitations, and minimum power thresholds.

Furthermore, unlike conventional approaches that primarily rank sites based on resource magnitude, the proposed framework differentiates feasible sites according to their relative contribution to the local electricity demand through the CCR parameter. As a result, only two locations were ultimately categorized as High Priority sites, indicating that not all technically feasible locations provide similar planning relevance. This integrated workflow, therefore, produces a more realistic and implementation-oriented prioritization compared to conventional theoretical hydropower potential mapping.

C. Planning and Policy Implications

The integrated framework supports more practical watershed-scale energy planning by distinguishing between technical feasibility, energy contribution level, and spatial compatibility. However, early integration of spatial planning compliance minimizes conflict with agricultural protection and conservation policies, aligning with the literature on sustainable land-energy planning [15]. The hydrological–technical screening effectively reduced unsuitable candidate locations at an early planning stage, while the CCR assessment identified sites with stronger relevance to the local electricity demand conditions.

The spatial conformity analysis further verified that all technically feasible locations were situated within compatible land-use allocations, including plantation, agricultural cultivation, horticultural, tourism, and residential development zones. This indicates relatively low preliminary land-use conflict risk for future PLTM development within the study area. Overall, the framework provides a transparent and reproducible workflow for supporting preliminary PLTM planning under multiple practical constraints.

D. Uncertainty and Study Limitations

Several limitations remain within the proposed framework. First, hydraulic losses associated with friction and conveyance systems were not explicitly modeled because the study focuses on watershed-scale preliminary screening rather than detailed engineering design. Second, electricity demand estimation was simplified using installed residential capacity assumptions without dynamic load variation or future demand projections. Therefore, CCR should be interpreted as a relative energy contribution indicator rather than a strict adequacy threshold. In addition, economic feasibility indicators, such as LCOE, NPV, and IRR, were not included, and transmission infrastructure conditions were not evaluated. Consequently, the framework is intended for preliminary screening and prioritization rather than final investment decision-making.

E. Transferability and Reliability

The proposed framework is designed as a modular and transferable workflow that can be adapted to different watershed conditions, hydrological thresholds, demand characteristics, and spatial planning regulations. By integrating feasibility filtering, energy contribution assessment, and spatial conformity verification within a single GIS-based workflow, the framework provides a practical decision-support approach for preliminary PLTM planning in data-limited and developing-region contexts.

V. CONCLUSION

This study develops and applies an integrated feasibility and prioritization framework for preliminary small-scale hydropower plant (PLTM, Pembangkit Listrik Tenaga Minihidro) site assessment at the watershed scale. The proposed framework sequentially integrates hydrological reliability (Q_{95}-based dependable flow), technical feasibility assessment, energy contribution evaluation through the Compatibility Coverage Ratio (CCR), and spatial conformity analysis based on regional land use planning. Unlike conventional approaches that primarily focus on hydropower resource potential, the proposed framework differentiates the functions of each assessment layer into feasibility filtering, energy contribution prioritization, and regulatory conformity verification within a unified workflow.

The results indicate that the hydrological and topographical assessment acts as the primary constraint in reducing candidate locations by filtering physically unsuitable sites based on dependable discharge, gross head, penstock limitation, and minimum power criteria. Meanwhile, the CCR assessment provides additional insights into the relative contribution of each feasible site toward local electricity demand, while the spatial assessment verifies the compatibility of candidate locations with regional spatial planning policies. This integrated approach enables a more realistic and context-sensitive identification of potential PLTM sites by reducing overestimation risk and incorporating practical development considerations at the preliminary planning stage.

Although the framework is intended for watershed-scale preliminary screening rather than detailed engineering or investment analysis, the proposed methodology provides a transparent, structured, and transferable approach for supporting sustainable PLTM planning in data-limited regions. Future studies may further improve the framework by incorporating hydraulic loss modeling, techno-economic analysis, grid integration assessment, and climate change-adjusted hydrological scenarios to enhance long-term planning robustness.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

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Not applicable to this work.

DATA AVAILABILITY

Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

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