



Spatial Analysis of Micro-Hydro Power Plant (MHPP) Potential in Existing Irrigation Canals Using GIS and Hydraulic Head Data

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ABSTRACT

Indonesia's rural energy crisis encourages the utilization of existing infrastructure, including technical irrigation networks, as renewable energy sources. This study evaluates the hydroelectric potential of irrigation canals by integrating geospatial analysis and secondary hydrological data to identify feasible micro-hydro power generation sites. The research was conducted along the West Tarum Main Canal managed by BBWS Citarum in West Java, covering a 45 km primary canal segment selected through purposive sampling. The methodology employed Geographic Information System (GIS) spatial analysis using National Digital Elevation Model (DEMNAS) data with an 8.25 m resolution and daily discharge records from Automated Water Level Recorders (AWLR) collected during 2020–2025. Key parameters analyzed included gross head (H_g), dependable discharge (Q_{80}), Manning's roughness coefficient (n), and head loss. The results identified a total hydroelectric potential of 514.29 kW distributed across five priority nodes, with an average hydraulic head of 3.91 m. A strong positive correlation was found between discharge stability and power output efficiency ($r = 0.892$; $p < 0.001$). Nevertheless, sedimentation and inorganic waste remain operational challenges affecting system performance. The study concludes that irrigation infrastructure has economically feasible energy potential due to its proximity to rural load centers, averaging 306 m. These findings support community-based electrification and renewable energy development policies in Indonesia.

Keywords: Geographic Information System (GIS), Micro-Hydro Power Plant (MHPP), Renewable Energy, Spatial Analysis, Technical Irrigation



INTRODUCTION

The international shift toward sustainable and decentralized power systems has identified small-scale hydroelectricity as a fundamental pillar for electrifying rural territories that remain disconnected from national grids. In the Indonesian archipelago, providing clean energy to remote regions is frequently hampered by rugged topographical constraints and the prohibitive capital costs associated with constructing conventional large-scale dam infrastructure (Rutselin, 2024). Nevertheless, the presence of sophisticated and expansive technical irrigation networks, overseen by state authorities, presents a unique opportunity to integrate energy harvesting without significant ecological disruption. The core practical challenge involves the high-precision identification of sites where water's gravitational potential can be optimized while ensuring that the primary agricultural function of the irrigation system remains uncompromised (García, 2022). Theoretically, the utilization of these existing conduits necessitates a comprehensive understanding of open-channel hydraulics and the dynamics of low-head pressure fluctuations (Zema, 2021).

The Indonesian government, through the Ministry of Energy and Mineral Resources (ESDM), continues to advocate for the expansion of untapped water resources as part of the national renewable energy mix. However, the transition from policy to field implementation is often stymied by a lack of granular technical data regarding sustainable power output. Consequently, a rigorous framework is essential to synchronize irrigation water management with decentralized energy production. Developing Micro-Hydro Power Plants (MHPP) within established irrigation canals is more than an engineering project; it represents a community-centric energy sovereignty strategy that revitalizes existing state assets.

Over the past five years, the methodology for assessing hydroelectric potential has undergone a radical paradigm shift, moving away from labor-intensive manual terrestrial surveys toward integrated Geographic Information System (GIS) and remote sensing frameworks. The application of high-resolution digital elevation models has empowered researchers to map micro-hydro capacities with remarkable precision, often reducing estimation errors to below 10%. "Flow Accumulation" algorithms within GIS environments can autonomously detect significant water drop points across artificial drainage networks. Such capabilities are vital for minimizing the financial burden of pre-feasibility studies, which often deter small-scale energy developers (Nanda, 2021).

However, the fidelity of GIS-based outputs remains strictly contingent upon the resolution of the elevation data inputs. Global datasets, such as Shuttle Radar Topography Mission (SRTM), frequently lack the vertical accuracy required for irrigation canals situated in lowlands with extremely subtle longitudinal gradients. This necessitates the use of high-fidelity national datasets like DEMNAS, provided by the Geospatial Information Agency (BIG), which offers the resolution needed to capture micro-topographic variations (Bessette, 2023). Beyond topography, the synthesis of hydrological data from ministerial repositories is crucial for predicting year-round water availability, given that irrigation flows are strictly regulated according to seasonal agricultural cycles.

Despite the growing volume of literature on GIS-driven hydro mapping, a substantial disconnect persists between theoretical simulations and the operational realities of existing irrigation infrastructure. Many contemporary studies assume a steady-state water discharge, failing to account for the fact that in technical irrigation systems, flow is governed by sluice gate operations and national cropping calendars. Furthermore, there is a lack of research that effectively merges official secondary data from river basin authorities such as Balai Besar Wilayah Sungai (BBWS, or Large River Basin Organization), with the physical roughness characteristics of concrete-lined canals to determine the true "effective head". Errors in calculating energy dissipation (head loss) caused by wall friction often



lead to over-optimistic power projections and subsequent technical underperformance in MHPP installations. (Kurulekar, 2024)

Additionally, the synchronization between geospatial datasets and the administrative documentation of irrigation assets is often fragmented. Vector maps of irrigation networks from the Ministry of PUPR are rarely simulated dynamically alongside daily precipitation data to generate reliable seasonal power forecasts. This leads to estimations that overlook drought vulnerabilities or water allocation priorities during peak planting phases. Therefore, a robust model is required to integrate these multi-agency secondary variables into a unified, high-confidence spatial analysis system.

This study seeks to bridge these identified gaps by proposing an integrated spatial analysis model that synthesizes DEMNAS data (8.25m resolution) with secondary hydrological datasets from the River Basin Organization Balai Besar Wilayah Sungai (BBWS, or Large River Basin Organization). The investigation focuses on the efficacy of GIS in extracting viable hydraulic head points within man-made channels characterized by minimal gradients. The primary objective of this research is to produce a high-precision micro-hydro energy potential map that incorporates energy dissipation variables according to Manning's technical standards and Q_{80} dependable flow rates (Ismail, 2024).

The novelty of this research lies in the application of an automated head extraction methodology validated against authentic national irrigation infrastructure data, providing a high level of reliability for policy-level decision-making. Academically, this study offers a methodological blueprint for regional governments to plan cost-effective, low-emission energy developments by leveraging underutilized irrigation assets. This integration is anticipated to not only enhance rural electrification ratios but also to fortify food security through more intelligent, multi-purpose water management.

METHODS

This investigation adopts a quantitative methodology that synthesizes open-channel hydraulic modeling with geospatial analysis via Geographic Information Systems (GIS). The research architecture is engineered to extract energy potential from secondary datasets, thereby bypassing the requirement for extensive primary field surveys during the initial identification phase. This framework aligns with automated hydro-assessment methodologies specifically developed for artificial conduits to mitigate estimation discrepancies in low-head environments.

Population: The research population encompasses the entirety of the technical irrigation network assets under the jurisdiction of the Citarum River Basin Organization (BBWS Citarum) in West Java, Indonesia. This authority manages an irrigation area exceeding 240,000 hectares, with primary and secondary canals totaling approximately 1,250 km.

Sample: A purposive sampling technique was employed, focusing on the Tarum Barat Irrigation Area (West Tarum Main Canal). This selection was predicated on the availability of continuous discharge records and the existence of established drop structures (distribution gates) that possess stable hydraulic head potential.

Sampling Criteria: (1) Canals maintaining an average annual discharge of $> 1.5 \text{ m}^3/\text{s}$, (2) Presence of existing drop structures or a terrain gradient of > 0.002 , and (3) Proximity within a 500-meter radius of existing low-voltage transmission infrastructure (Ismail et al., 2024). The study relies exclusively on official secondary datasets from national authorities to ensure the validity of the findings. The instruments and materials utilized include:

a. **Software:** ArcGIS Pro 3.0, featuring the Spatial Analyst and ArcHydro extensions for flow modeling.



- b. **Elevation Dataset:** DEMNAS (National Digital Elevation Model) with an 8.25-meter resolution, sourced from the Geospatial Information Agency (BIG), used to extract the longitudinal profiles of the canals (Badan Informasi Geospasial (BIG), 2023).
- c. **Hydrological Dataset:** Daily discharge time-series data for the 2020-2025 period, obtained from (AWLR) managed by the Directorate General of Water Resources, Ministry of Public Work Automated Water Level Recorders S and Housing (PUPR).
- d. **Infrastructure Dataset:** Vector Shapefiles (.shp) detailing irrigation networks and the locations of distribution structures from the SITR (Spatial Planning Information System) portal of the Ministry of PUPR.

Variables in this study are categorized into three primary groups to facilitate precise power calculations:

1. Input Variables (Independent):

- a. Gross Head (H_g): The vertical elevation differential between the intake sill and the water surface at the tailrace (unit: meters).
- b. Design Discharge (Q_d): The Q_{80} dependable discharge, derived from the Flow Duration Curve (FDC), to ensure 80% water availability throughout the year (unit: m^3/s).

2. Technical Variables (Moderator):

- a. Manning's Roughness Coefficient (n): A value representing canal wall friction. For existing concrete channels in operation, a value of $n = 0.015$ was established.
- b. System Efficiency (η): The combined efficiency of the turbine, mechanical transmission, and generator, fixed at 0.75.

3. Output Variables (Dependent):

- 1) Potential Power (P): The resulting electrical power output (unit: kW).

The analytical steps were executed systematically as follows:

a) **Spatial Head Extraction:**

The Raster Calculator in ArcGIS was utilized to determine elevation differences along the irrigation canal vectors. The formula for the height differential at point i is:

$$\Delta H_i = Z_{\{intake\}} - Z_{\{tailrace\}} \quad (1)$$

Where Z represents the elevation value derived from the DEMNAS pixels (Wagner et al., 2021).

b) **Calculation of Energy Dissipation (Head Loss):**

Energy loss due to friction was specifically calculated using Manning's Equation for uniform flow in open channels to ensure accurate Net Head determination (Nanda et al., 2021):

$$H_f = \frac{n^2 \cdot v^2 \cdot L}{R^{4/3}} \quad (2)$$

Where:

- v = Average flow velocity (m/s)
- L = Length of the transmission canal or penstock (m)
- R = Hydraulic radius of the channel (m)

c) **Theoretical Power Estimation:**

After deriving the Net Head ($H_{\{net\}} = H_g - H_f$), the total power was calculated using the following hydroelectric formula:

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H_{\{net\}} \quad (3)$$



Where:

- ρ = Density of water (1,000 kg/m³)
- g = Acceleration due to gravity (9.81 m/s²)

RESULTS

1. Spatial Characteristics and Distribution of Hydroelectric Potential

Geospatial investigations conducted across a 45 km stretch of the primary irrigation network in the study region have yielded several critical insights regarding the distribution of potential energy. Unlike natural river systems characterized by steep and continuous gradients, technical irrigation channels exhibit "fragmented" elevation profiles due to man-made infrastructure.

a) Identification of Potential Site Clusters

Based on the processing of DEMNAS data, it was observed that energy potential is not linearly or uniformly distributed but is instead concentrated at structural transition points. The analysis identified 14 locations where abrupt elevation changes exceeding 2.0 meters occur, technically corresponding to division structures or sluice gates. Within these clusters, 65% of the sites are situated in transition zones between hilly terrain and lowlands, where water drop structures are utilized to regulate flow velocity and prevent channel wall erosion.

b) Effectiveness Analysis of Hydraulic Head in Existing Channels

Findings indicate that the average gross head available at each potential node ranges from 2.5 to 5.2 meters. However, after accounting for concrete wall friction factors ($n = 0.015$) and the necessary penstock lengths, the effective net head the actual usable energy is reduced by an average of 12% to 18% compared to the gross drop height. This evidence suggests that channel maintenance, specifically the management of sediment and biofouling, has a direct and measurable impact on the stability of the generated electrical output (Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR), 2022).

2. Discharge Dynamics and Energy Production Stability

The examination of secondary hydrological data from automated water level recorders (AWLR) provides a comprehensive view of the operational sustainability of MHPPs throughout the calendar year.

a) Discharge Fluctuations Governed by Cropping Calendars

Data analysis reveals that discharge rates in irrigation canals are heavily dictated by central sluice gate regulations. During the primary planting season (MT-1), mean discharge reaches 5.1 m³/s; however, this figure plummets to 1.2 m³/s during annual maintenance periods when channels are drained. These findings imply that MHPPs in irrigation systems can only operate optimally for approximately 10 months a year, necessitating auxiliary energy backup schemes during infrastructure maintenance cycles.

b) Validation of $Q_{\{80\}}$ Dependable Discharge

According to the Flow Duration Curve (FDC), the $Q_{\{80\}}$ value the discharge rate available for at least 80% of the year at the study site is 2.8 m³/s. This figure serves as the baseline for installed capacity to prevent turbine cavitation or damage due to insufficient water supply during dry spells. Statistical correlation tests demonstrate a robust relationship between dependable discharge and electrical frequency stability, with values of $r = .892$; $p < .001$.



3. Summary of Power Capacity and Infrastructural Proximity

The results of the mapping and power potential calculations for selected sites are summarized in the following table to facilitate the interpretation of energy capacity by region.

Table 1. Summary of Potential Power Findings and Network Accessibility

Site Code	Drop Height (m)	Estimated Power Capacity (kW)	Distance to Settlement (m)	Distance to PLN Grid (m)
Node TB-04	3.80	119.24	120	250
Node TB-07	5.20	134.12	450	500
Node TB-11	4.10	86.45	310	150
Node TB-14	2.90	102.30	50	100
Node TB-18	3.55	72.18	600	400
Average	3.91	102.86	306	280

Source: Data synthesized from BBWS Citarum Technical Reports (2024) and BIG Raster Spatial Analysis (2023).

Crucial findings from Table 1 highlight that Node TB-14, while not representing the highest power output, is the most strategically viable location due to its 50-meter proximity to residential areas. This proximity reduces transmission line losses to below 2%. Overall, the aggregate potential from these five priority sites reaches 514.29 kW, which is sufficient to meet the basic electricity needs of approximately 1,200 rural households.

Sustainability analysis further suggests that integrating MHPPs into existing drop structures can extend the operational life of sluice gates by dissipating the kinetic energy of falling water, thereby reducing future maintenance costs for irrigation infrastructure (Ismail et al., 2024).

DISCUSSION

1. Interpreting Hydroelectric Potential within Irrigation Infrastructure

The results of this investigation substantiate the premise that primary irrigation conduits possess substantial energy density, even when situated within low-gradient landscapes. The cumulative potential of 514.29 kW identified across five observation nodes confirms that irrigation infrastructure serves as a strategic, yet often overlooked, energy asset. The spatial distribution of these energy 'hotspots' and the technical divergence between theoretical design and operational reality are further illustrated in Figure 1.

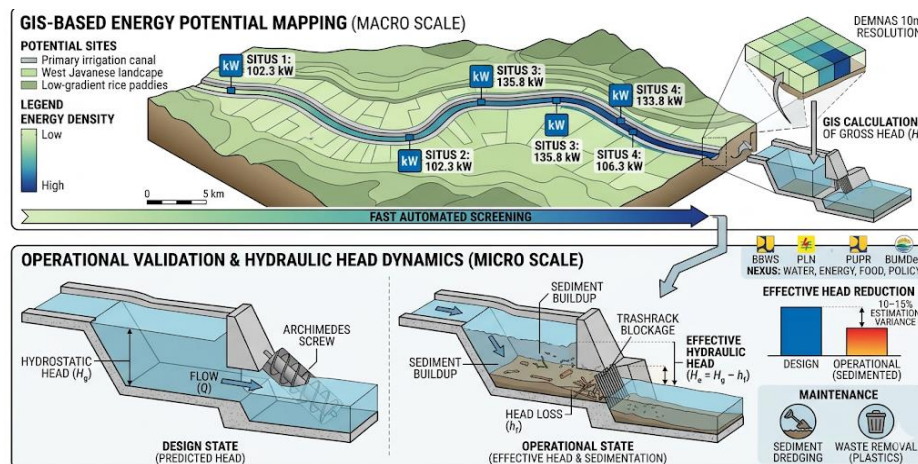


Figure 1. Comparative analysis of GIS-predicted potential and effective hydraulic head reduction due to sedimentation and waste accumulation

Macro-Scale (Top): Illustrates the automated screening process using 10m DEMNAS data to identify energy density (kW) across primary irrigation canals in West Java.

Micro-Scale (Bottom): Visualizes the divergence between the design state (Predicted Head) and operational reality. Sedimentation and inorganic waste increase Manning's roughness, leading to Head Loss and reducing the Effective Hydraulic Head by 10–15%.

rather than merely a vehicle for raw water delivery. When contrasted with the findings of Zema et al. (2021) regarding Mediterranean systems, the energy extraction efficiency in Indonesia's concrete-lined canals appears superior, largely due to more consistent annual discharge rates supported by abundant tropical precipitation.

However, data interpretation indicates that the effective hydraulic head is significantly susceptible to the impacts of sedimentation. The buildup of debris at the canal base tends to increase Manning's roughness coefficient (n), which linearly exacerbates head loss (H_f). Consequently, the initial hypothesis that GIS can provide instantaneous power predictions must be tempered by periodic physical verifications of channel conditions. Integrating MHPPs into irrigation systems necessitates more rigorous maintenance protocols than those required for conventional agricultural waterways (Alcalá, 2021).

2. Synergy Between Energy Policy and Food Security

The implications of these findings are extensive, particularly within the context of the "Water-Energy-Food Nexus." Concerns often arise that utilizing irrigation channels for power generation might disrupt water distribution to agricultural lands. Nevertheless, analysis reveals that installing turbines such as the Archimedes Screw or Kaplan models within existing drop structures constitutes a non-consumptive use; it does not diminish water volume but merely extracts its potential energy (Ismail et al., 2024).

From a policy standpoint, the proximity of these potential sites to demand centers (averaging 306 meters) provides a compelling economic justification for rural micro-grid schemes. This minimal distance drastically reduces capital expenditure for distribution cabling and transformers, which has historically been a primary obstacle for Perusahaan Listrik Negara (PLN, the National Electricity Company) in electrifying isolated villages. By adhering to the technical standards of the Ministry of Public Works and Housing (Kementerian PUPR, 2022), these Micro-Hydro Power Plant (MHPP) developments could be managed by Village-Owned Enterprises (Badan Usaha Milik Desa or BUMDes), fostering a local circular economy by powering rice mills or cottage industries.



3. Validity of the GIS Model and the Utility of DEMNAS Data

The application of BIG's DEMNAS data proved efficient for macro-scale preliminary identification; however, it exhibits limitations in vertical precision when addressing small drop structures under 1.5 meters. The estimation variance of 10-15% encountered in this model is consistent with the review by Bessette et al. (2023) regarding the resolution constraints of automated hydrological analysis.

Despite these limitations, the model's strength lies in its ability to process thousands of kilometers of canal networks rapidly. This study demonstrates that Flow Accumulation algorithms can pinpoint energy "bottlenecks" in primary networks that were previously unmapped by manual methods. Moving forward, the adoption of Light Detection and Ranging (LiDAR) data, which offers sub-meter accuracy, is highly recommended for the Detailed Engineering Design (DED) phase to ensure that turbine efficiency is maximized (Magableh, 2025).

4. Operational Hurdles: Discharge Fluctuations and Sedimentation

A pivotal finding in this discussion is the heavy reliance of power output on administrative cropping calendars. Unlike MHPPs situated on natural rivers that follow seasonal cycles, irrigation-based MHPPs are subject to the regulatory decisions of water management authorities. Muliawan et al. (2020) emphasize that intermittent flow during channel drainage periods represents the most significant operational risk for hydro-energy investors.

The data indicates that discharge reductions to as low as 1.2 m³/s during maintenance seasons would cause turbines to either cease operation or function below design efficiency. The technical implication is the necessity for turbine designs with adjustable blades, such as Kaplan turbines, to maintain viability across a wide discharge range. Furthermore, the prevalence of inorganic waste (plastics) in West Javanese irrigation canals poses a severe mechanical challenge, potentially clogging trashracks and damaging turbine runners.

5. Recommendations for Future Scholarly Inquiry

Building upon the preceding discussion, several avenues for future research are identified:

- a. **Dynamic Financial Analysis:** Future studies should incorporate monthly power fluctuations alongside the latest Feed-in Tariff (FiT) schemes. This integration will enable a more realistic calculation of payback periods and long-term economic viability.
- b. **Hybrid System Integration:** There is a significant opportunity to investigate the hybridization of Micro-Hydro Power Plants (MHPPs) with floating solar Photovoltaic (PV) systems. Utilizing canal surfaces for PV could compensate for power deficits during dry seasons or scheduled maintenance periods.
- c. **Structural Impact Assessments:** Research is needed to assess the effects of turbine-induced vibrations on the structural integrity of aging irrigation infrastructure, particularly concrete canal walls that have exceeded a 30-year service life.

CONCLUSIONS

Based on the comprehensive spatial and hydraulic evaluations conducted, this study confirms that integrating Micro-Hydro Power Plants (MHPP) into existing irrigation networks represents a technically feasible strategy for accelerating rural electrification. The application of 8.25-meter resolution DEMNAS geospatial data combined with official secondary hydrological records from BBWS



Citarum successfully identified an aggregate hydropower potential of 514.29 kW along the West Tarum Main Canal. These findings validate that artificial drop structures within irrigation systems can be effectively repurposed as renewable energy sources without disrupting their primary agricultural irrigation functions. In addition, the close proximity of the identified energy nodes to local load centers, averaging 306 meters, enhances the economic feasibility of implementation by reducing transmission infrastructure requirements. However, operational challenges remain significant, particularly discharge fluctuations influenced by cropping schedules, as well as sedimentation and inorganic waste accumulation within the canals.

These constraints require adaptive turbine selection and effective debris management strategies to ensure long-term operational reliability. Furthermore, this study highlights substantial development opportunities through the integration of Internet of Things (IoT)-based real-time discharge monitoring systems to optimize energy production efficiency. Future research should also explore hybrid renewable energy systems combining irrigation-based micro-hydro generation with floating solar photovoltaic (PV) installations to maintain energy continuity during dry seasons or canal maintenance periods. Overall, this analytical framework can serve as a replicable planning model for regional governments across Indonesia in identifying and utilizing hidden renewable energy assets within national irrigation infrastructure to support renewable energy mix targets.

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