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# Utilization of satellite data in determining hydropower potential to support energy security in new capital city region of Indonesia

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The relocation of the national capital from DKI Jakarta to the East Kalimantan region and its people migration requires energy escalation. This project will require an additional 1,555 MW of electricity from existing conditions. In line with Indonesia's clean energy transition, this need can be addressed by developing renewable energy infrastructure, particularly hydropower. This study evaluates the hydropower potential in the Mahakam River using a run-of-river scheme. Given the limited availability of hydro-climatological ground stations, satellite data such as CFSR-TRMM, SRTM DEM, DSMW, and land-cover data were utilized, supported by the SWAT rainfall-runoff model for hydrological analysis. Data calibration was applied, and discharge results were analyzed using a new diversion algorithm to estimate potential power output. Innovative resampling of headrace arrangements was introduced to mitigate potential hydropower conflict sites. Social factors, including protected areas and water transportation routes, were also incorporated to minimize land disputes. The study identified 25 mini-hydropower sites and 16 micro-hydropower sites with a total capacity of 105.4 MW and 9 MW, respectively. These small-scale hydropower systems could supply 3.4% of the projected electricity demand for the new capital city called Nusantara (IKN), and potentially reduce annual carbon emissions by approximately 480,000 tons. The use of satellite data requires meticulous attention to ensure that data acquisition and processing yield reliable results while accurately reflecting field conditions. This research position also provides an initial overview of energy transition strategies in the IKN area through hydropower development and the subsequent potential assessment.

KEYWORDS

**the Nusantara capital city (IKN), energy transition, hydropower, potential, diversion algorithm, SWAT**

## 1 Introduction

Indonesia has been gradually relocating its capital from Jakarta to the North Penajam Paser area since the enactment of Law Number 3 of 2022. This move is driven by several factors including population density, economic contributions, land use, environmental degradation, and water issues (Kementerian PPN/Bappenas, 2021). The relocation will shift the governmental and administrative centers to the new location, while Jakarta will remain the economic hub of Indonesia. The population in the new capital is projected to reach 1.7–1.9 million by 2045 due to urbanization, significantly impacting the sustainability of energy resources, particularly in the electricity sector (Alsaleh et al., 2023). Currently, East Kalimantan's power supply capacity stands at 1,765.91 MW, requiring an additional 1,555 MW to meet the initial demands of the relocation.

Furthermore, Steam Power Plants (SPPs) contribute to over 60% of Indonesia's electricity production, a trend also observed in East Kalimantan where they produce 834.13 MW or 47.23% of the region's total output. This region holds the highest national coal potential, accounting for 83% of Kalimantan Island's total coal reserves (Afin and Kiono, 2021). However, the environmental impact of these SPPs is significant, contributing to greenhouse gas emissions, diminishing air quality, and increasing the frequency of extreme weather events globally (Intergovernmental Panel On Climate Change, 2023). Coal-fired power plants produce between 675 and 1,689 gCO2-eq/kWh of emissions, significantly higher than other types of electricity generation, which are generally below 100 gCO2-eq/kWh (Whitaker et al., 2012; Amponsah et al., 2014). In Europe, the use of fossil fuels has been linked to increasing water resource pollution (Alsaleh and Abdul-Rahim, 2022a).

Under the Paris Agreement, which aims to limit global warming to 1.5°C, reducing carbon dioxide emissions is crucial. One strategy is through the development of renewable energy sources (IRENA, 2023). Indonesia's Net Zero Emission (NZE) 2060 initiative aims to shift energy supply towards more efficient and sustainable sources by phasing out coal-fired power plants and reducing greenhouse gas emissions by 29% by 2030. By 2025, renewable energy is expected to contribute 23% to the energy mix, increasing to 26.5% by 2030, with a significant role played by hydropower, geothermal, and solar energy (Ministry of Energy and Mineral Resources (ESDM), 2021).

Since the first hydropower plant was built in 1771, hydropower has become a significant global energy source, contributing over 15% of the world's electricity in 2022 with a total installed capacity of 1,397 GW (International Hydropower Association, 2023). Indonesia, with its vast potential alongside countries like Colombia, Myanmar, and Madagascar, ranks sixth among over 20 countries in East Asia and the Pacific for hydropower capacity at 6,602 MW—much lower than the potential capacity of about 75,000 MW (Erinofiardi et al., 2017). With an average surface water potential of 2.78 trillion m3/year (Radhika et al., 2018), hydropower in Indonesia offers a clean energy solution, producing low greenhouse gas emissions between 2 and 75 gCO2-eq/kWh. It serves as a bridge between other renewable technologies like wind, tidal, wave, and geothermal energy (Amponsah et al., 2014; Ubierna et al., 2022). In the EU, hydropower supports the decarbonization of the economy and enhances the sustainability and security of the energy mix (Alsaleh and Abdul-Rahim, 2022b; 2023b). Given these benefits, further development of hydropower technology in Indonesia is essential.

An extensive study of hydropower potential was conducted in the Mahakam River area to support its development in the IKN area. Besides the potential for large-scale hydropower, which depends on sediment deposition, Indonesia also has opportunities to develop smaller-scale hydropower projects throughout the country based on run-of-river schemes (Soekarno, 2020; Ardiansyah, 2022).

Numerous studies have explored hydropower potential globally, encountering various limitations. For instance, the assessment of hydropower in the Indian region utilized historical hydrological models (Kusre et al., 2010), while global assessments often employ composite discharge data through climate water balance models (Hoes et al., 2017). Additionally, a recent study in Indonesia used a diversion algorithm to identify potential sites in two provinces, revealing that viable locations are often limited to one side of the river, leading to potential conflicts in usage (Kardhana et al., 2017; Wahab et al., 2023).

Moreover, the scarcity of observational data poses a significant challenge. According to World Meteorological Organization standards, the minimum coverage area for a manual rain gauge station in flat and hilly areas should be 575 km$^2$, and for discharge stations, 1,875 km$^2$ (World Meteorological Organization, 2008). In the study area, there are only 32 rainfall stations with an average density of 2.636 km$^2$ per station and five discharge stations covering 16.870 km$^2$ each. This limitation necessitates the use of satellite data as an alternative method for accurate assessments.

Open-source satellite climate data has become a valuable tool in exploring potential resources and studying water-related hazards (Burnama et al., 2023). The diversion algorithm, enhanced by the SWAT hydrological model and SRTM DEM, has been pivotal in calculating hydropower potential (Kardhana et al., 2017), according to the utilization of Information, Communication, and Technology (ICT) could lead to hydropower growth as well in the European area (Wang et al., 2024). SWAT is one of the most used hydrologic models in the world for eco-hydrologic modeling (Tan et al., 2019), provides spatial discharge data for each subwatershed with high accuracy, closely reflecting actual conditions (Farid et al., 2011). Combined with regional and river

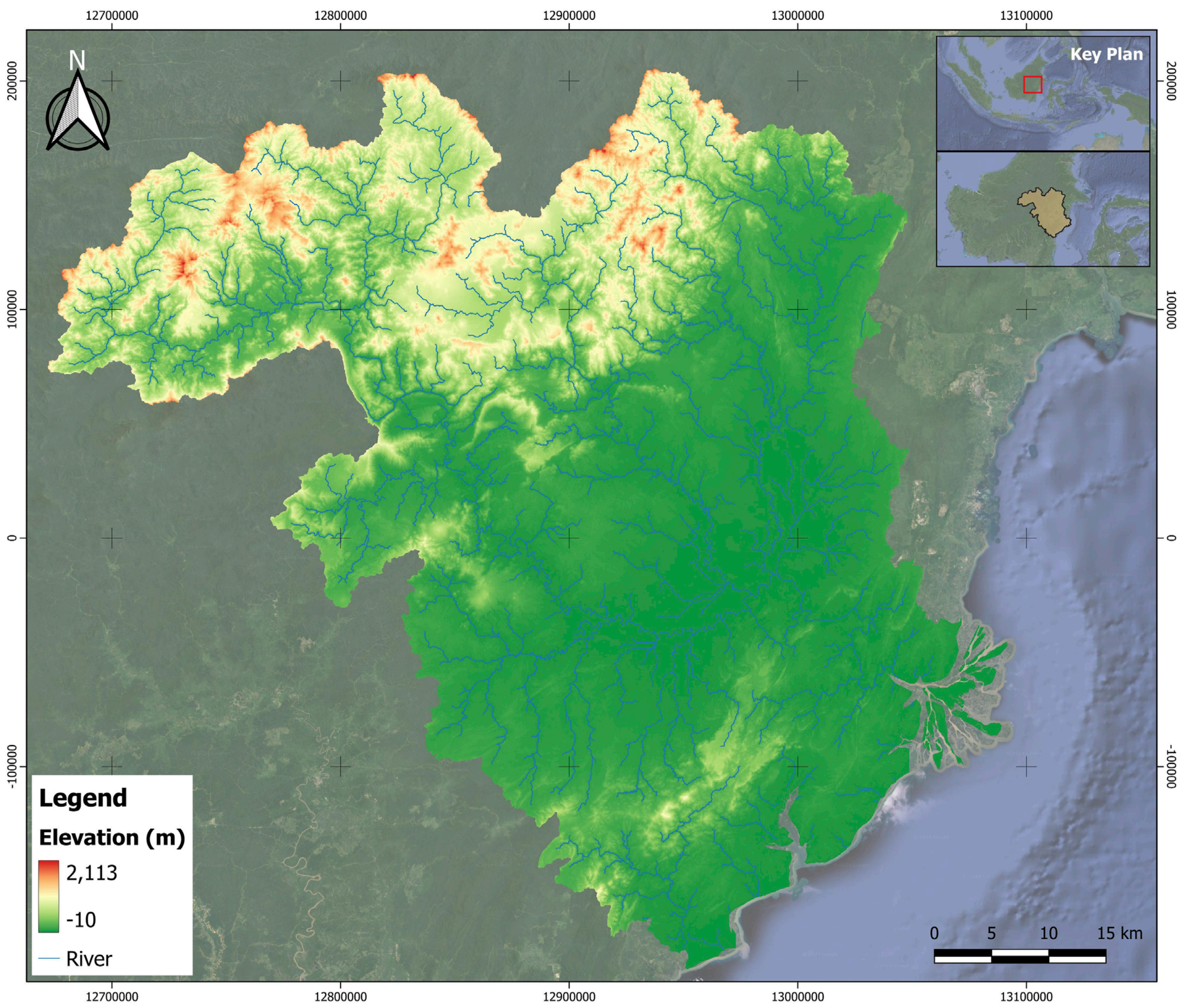


FIGURE 1
Mahakam River Area and its elevation.

DEM data and SWAT flow accumulation results, this approach helps identify optimal hydropower sites by evaluating both sides of the river. Additionally, headwater resampling minimizes conflicts within river reaches. A holistic approach that considers existing land use and water transportation routes is crucial to preserving natural resources and mitigating the potential environmental impacts of hydropower projects (Alsaleh et al., 2021; Alsaleh and Abdul-Rahim, 2021a; 2023a). This study offers preliminary insights into the potential of hydropower to meet Indonesia's future energy needs and supports the country's energy transition strategy.

## 2 Study area

This study focuses on identifying potential hydropower sites within the Mahakam River region, as illustrated in (Figure 1). The region encompasses diverse basins that traverse various regencies and cities across the island of Kalimantan, situated between longitudes $114^{0}53'49''$-$117^{0}57'43''$ and latitudes $0^{0}31'30''$-$1^{0}31'33''$. Covering an area of 85,236 $km^2$, most of this region 93.84% lies within East Kalimantan, encompassing six districts and two cities, with the remainder in Malinau Regency, North Kalimantan. The region includes 85 rivers, comprising main rivers and their tributaries, with gradients ranging from 0.0002 to 0.0077. The Mahakam River, the longest river in the area, stretches approximately 980 km southeast before discharging into the Makassar Strait, covering a basin area of 77,100 $km^2$ (Hadibarata et al., 2020). The topography of the country is predominantly flat, with steeper areas located on the northwestern side of the river basin near the Indonesia-Malaysia border.

The upland area of East Kalimantan significantly influences the Mahakam River region. Meteorological data from the Temindung area, spanning 2019 to 2021, indicates an average annual rainfall

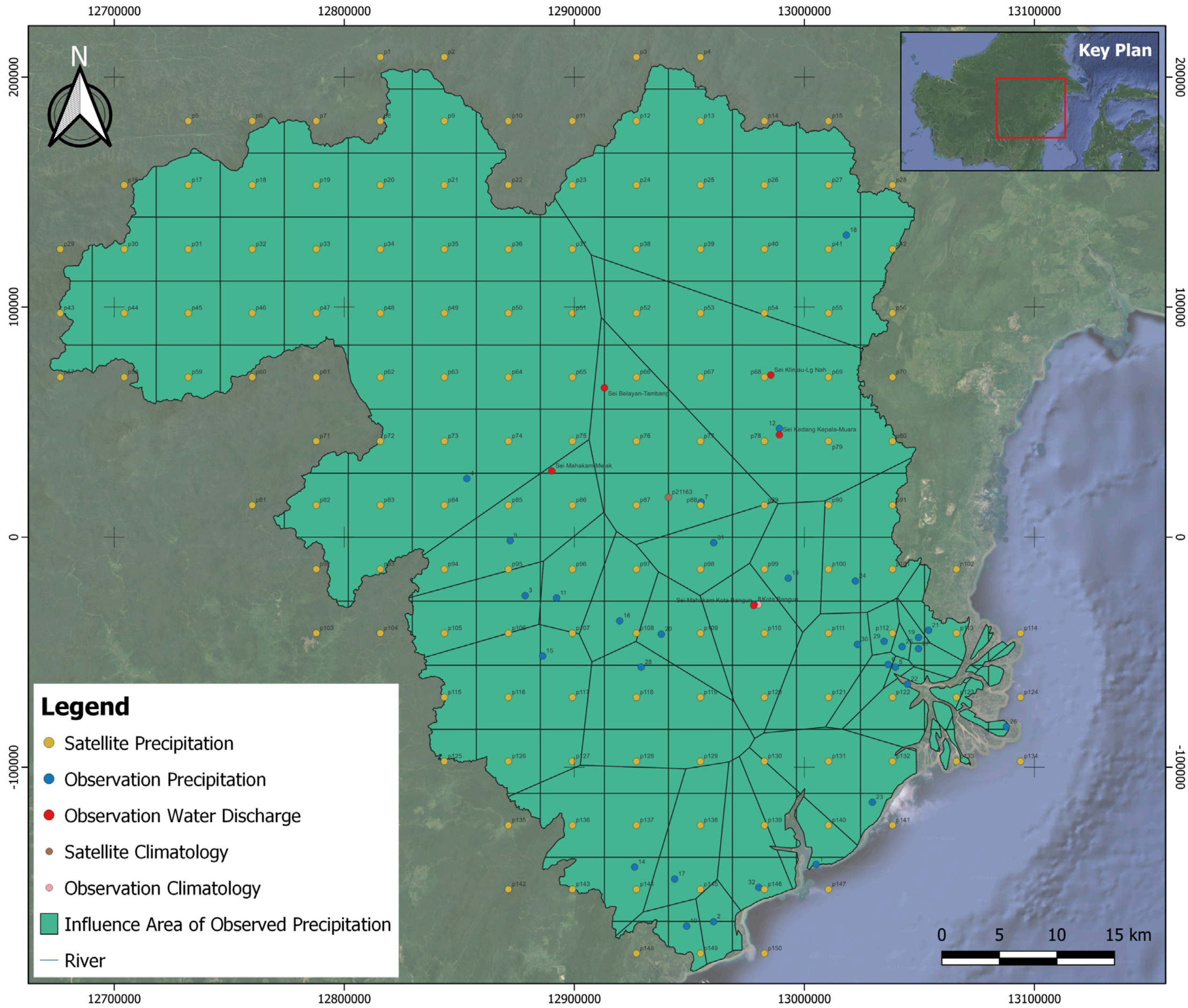


FIGURE 2
Precipitation-discharge-climatology data with influence area of observed precipitation.

of 3,108 mm and an average of 241 rainy days per year. The region experiences an average monthly temperature of 27.64°C with humidity levels at 85%, atmospheric pressure at 1,009.97 mb, solar irradiation of 48.52%, and wind speeds average between 2.1 and 3.8 m/s.

Currently, East Kalimantan has a hydropower capacity of 0.34 MW (Ministry of Energy and Mineral Resources, 2021). However, detailed data on the location, scheme, and other relevant factors remain unavailable for this research. The region has plans for three hydropower projects: Kelai, Tabang, and Lambakan. The Kelai Hydropower project, expected to be operational by 2025, aims for a capacity of 55 MW. The Tabang Hydropower project, with a planned capacity of 90 MW, is still in the preliminary stages of development and is expected to commence operations in 2028. The Lambakan Hydropower project is also slated for completion in 2025, with a capacity of 18.2 MW. Unfortunately, detailed site information for these projects is lacking, which limits their inclusion in this study.

# 3 Datasets

## 3.1 Digital Elevation Model (DEM)

This research utilizes the NASA Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) to represent the Earth's topographic surface. SRTM DEMs, which are available free of charge, are renowned for their homogeneous quality across various fields such as geology, geomorphology, water resources, and hydrology (Yang et al., 2011). The resolution of the DEM used is three arc seconds, approximately 90 m horizontally, providing a more accurate topographic representation compared to the ASTER GDEM (Lahsaini et al., 2018). This data is crucial for initially identifying potential hydropower locations across extensive areas. The vertical accuracy of the SRTM DEM is noted to be 16 m (Rodríguez et al., 2006), and it is instrumental in analyzing basin areas, slopes, discharge rates, stream power, erosion rates, and more. (Preety et al., 2022).

TABLE 1 Land cover SWAT classification.

| No. | Type of land cover | Area ($km^2$) | SWATname | SWATid |
|---|---|---|---|---|
| 1 | Airport/Port | 5.16 | UTRN | 26 |
| 2 | Primary dryland forest | 20,356.65 | FRSD | 41 |
| 3 | Secondary dryland forest/Former logging | 22,933.08 | FRSD | 41 |
| 4 | Primary mangrove forest | 23.39 | WETF | 91 |
| 5 | Secondary mangrove forest/Former logging | 283.01 | WETF | 91 |
| 6 | Primary swamp forest | 203.49 | WETF | 91 |
| 7 | Secondary swamp forest/Former logging | 957.40 | WETF | 91 |
| 8 | Plantation forest | 2,385.17 | FRSE | 42 |
| 9 | Open land | 1,392.04 | FLAX | 1 |
| 10 | Plantation | 7,632.35 | ORCD | 61 |
| 11 | Settlements/Built-up land | 449.47 | URML | 21 |
| 12 | Mining | 771.95 | SWRN | 32 |
| 13 | Dryland farming | 311.40 | AGRL | 85 |
| 14 | Dryland farming with bushes/Mix plantation | 2,185.17 | AGRL | 85 |
| 15 | Swamp | 856.05 | WATR | 11 |
| 16 | Rice field | 163.34 | RICE | 2 |
| 17 | Shrubs | 17,759.41 | RNGB | 51 |
| 18 | Swamp shrubs | 4,218.62 | WETN | 92 |
| 19 | Ponds | 326.53 | WATR | 11 |
| 20 | Transmigration | 153.13 | UTRN | 26 |
| 21 | Water body | 986.77 | WATR | 11 |
| Total Area | | 84,353.55 | | |

## 3.2 Hydro climatology data

Hydroclimatological data utilized in this study encompasses precipitation, climate, and runoff data. Precipitation data is sourced from the Tropical Rainfall Measurement Mission (TRMM), specifically the seventh version of TRMM 3B42, which offers daily precipitation records from 1998 to 2015 with a spatial resolution of 0.25$^0$ x 0.25$^0$, covering latitudes from 50$^0$N to 50$^0$S (Michot et al., 2018). For this study, data from 2004 to 2013 are used to meet the Indonesian standard requirement of a 10-year baseline for mainstay discharge data. However, TRMM data tends to overestimate precipitation in both light and heavy rainfall conditions, and its accuracy varies across different seasons (Guo and Liu, 2016). Therefore, more reliable ground-based rainfall data is needed to calibrate the satellite data. Rainfall observation data, sourced from the Directorate of Water Resources Engineering (Bintek SDA), vary in duration and are collected from 32 rain measurement stations. Applying bias correction to TRMM and rain gauge data reduces errors and enhances their correlation with extended rainfall records (Mohd Zad et al., 2018).

Global hydroclimatological data from the Climate Forecast System Reanalysis (CFSR) by the National Oceanic and Atmospheric Administration's National Center for Environmental Prediction are also employed. CFSR provides a resolution of 0.3125$^0$ or about 38 km, which is useful for simulating watershed runoff (Fuka et al., 2014). Besides rainfall, CFSR data include daily maximum and minimum temperatures, relative humidity, wind speed, and solar radiation for each grid satellite (Dile and Srinivasan, 2014). Widely used in the SWAT hydrological model, CFSR data are formatted to meet SWAT's requirements (Zhu et al., 2016). This data was notably evaluated in areas like the Karuvannur River in India, where observational data are scarce (Tomy and Sumam, 2016).

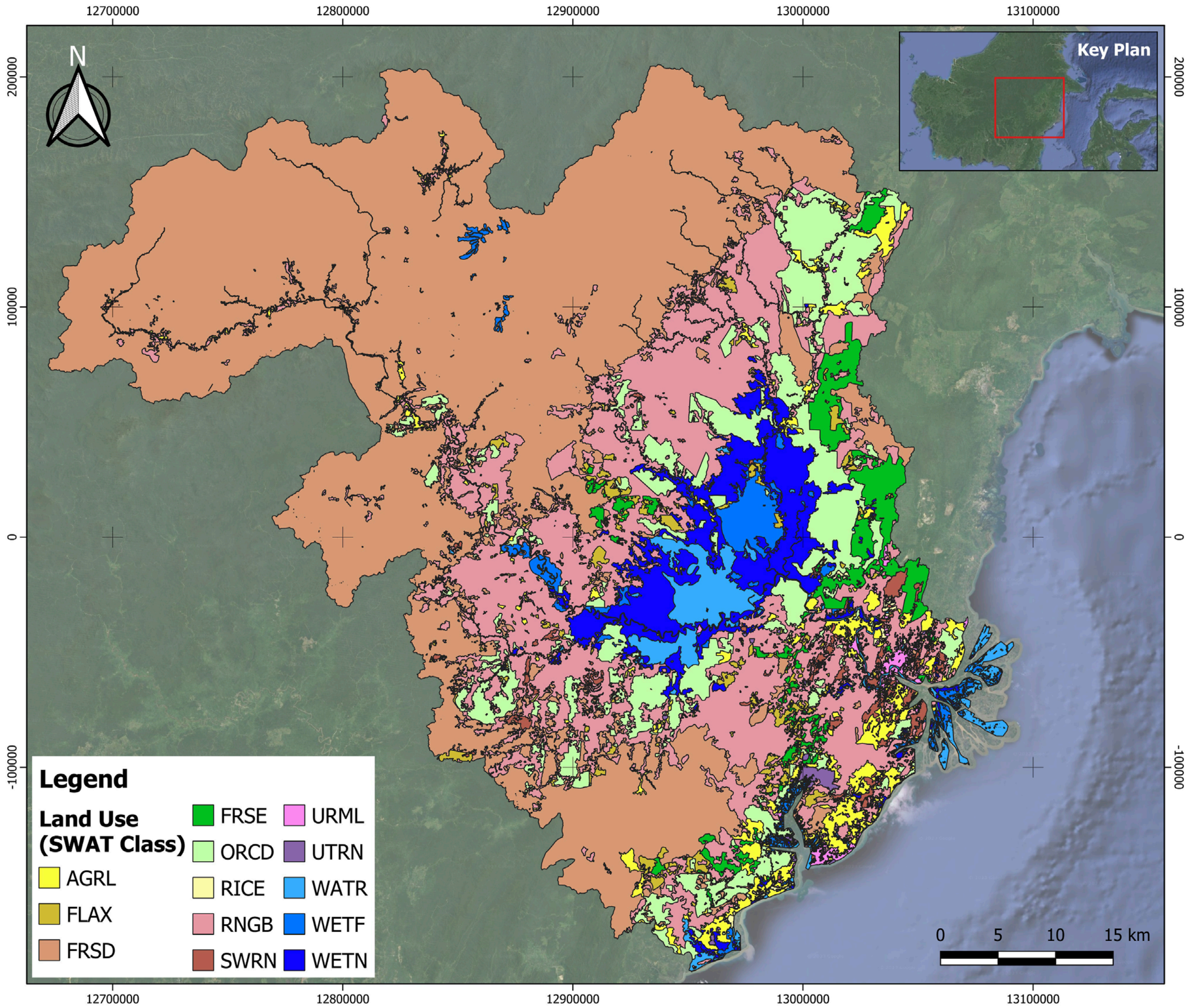


FIGURE 3
Land cover data.

However, caution is advised as CFSR tends to overestimate rainfall, particularly noted in regions like Bolivia (Blacutt et al., 2015), necessitating calibrated temporal runoff values for accurate rainfall-runoff modeling.

Discharge data is crucial for calibrating the rainfall-runoff hydrological model (Mengistu et al., 2019), were obtained from the Research and Development Center of Water Resources (PUSAIR) at five locations: Sei Mahakam Kota Bangun, Sei Mahakam-Melak, Sei Kedang Kepala-Muara, Sei Belayan-Tambang, and Sei Klinjau-Lg Nah, spanning from 2005 to 2012. Some datasets contained discrepancies, such as mismatched coordinates and quality issues labeled "should not be used." Thus, the data from Sei Belayan-Tambang in 2009 was selected as the most reliable for this study. See Figure 2 for a detailed visualization of the precipitation-discharge-climatology data.

## 3.3 Land cover data

Land cover data, a critical parameter in the SWAT hydrologic model, influences the model's output in a watershed. For instance, land cover changes towards built-up areas in Brantas have been shown to increase water runoff values (Astuti et al., 2019). The land cover data for this study, sourced from the Ministry of Environment and Forestry of the Republic of Indonesia (KLHK), is mapped at a 1:250,000 scale from 2018. This data forms the basis for defining Hydrologic Response Units (HRU), which are then converted into Curve Number (CN) values. Due to the local origin of this data, it is necessary to reclassify land cover definitions to align with the SWAT model's standards. Table 1 outlines the land cover classification process, and Figure 3 displays the resulting classifications.

TABLE 2 Descriptions of soil type data.

| No | Name | Dominant soil | Texture | Associated soils | Inclusions | Slope class |
|---|---|---|---|---|---|---|
| 1 | Af11-2/3a | Ferric Acrisols | Medium to fine | - | Xanthic Ferralsols and Dystric Fluvisols | Level to undulating |
| 2 | Ah25-2c | Humic Acrisols | Medium | - | Orthic Acrisols, Humic Ferralsols, and Lithosols | Steeply dissected to mountainous |
| 3 | Ah27-2/3c | Humic Acrisols | Medium to fine | Lithosols | Dystric Nitosols | Steeply dissected to mountainous |
| 4 | Ao104-2/3c | Orthic Acrisols | Medium to fine | Humic Acrisols and Dystric Cambisols | Chromic Cambisols and Gleyic Acrisols | Steeply dissected to mountainous |
| 5 | Ao70-2/3b | Orthic Acrisols | Medium to fine | Dystric Cambisols | Dystric Fluvisols, Gleyic Acrisols, and Ferric Acrisols | Rolling to hilly |
| 6 | Bf13-2/3b | Ferralic Cambisols | Mediun to fine | | Humic Acrisols and Orthic Ferralsols | Rolling to hilly |
| 7 | Gh20-3a | Humic Gleysols | Fine | Dystric Fluvisols | Dystric Histosols and Thionic Fluvisols | Level to undulating |
| 8 | Jd9-2/3a | Dystric Fluvisols | Medium to fine | Dystric Gleysols | Dystric Cambisols, Dystric Regosols, and Dystric Histosols | Level to undulating |
| 9 | Lo66-2/3c | Orthic Luvisols | Medium to fine | - | Chromic Luvisols, Eutric Fluvisols, and Lithosols | Steeply dissected to mountainous |
| 10 | Nh10-3b | Humic Nitosols | Fine | - | Humic Andosols and Eutric Cambisols | Rolling to hilly |
| 11 | Od19-a | Dystric Histosols | - | - | Dystric Fluvisols and Humic Gleysols | Level to undulating |
| 12 | Qc59-1 ab | Cambic Arenosols | Coarse | Dystric Cambisols | Humic Acrisols and Dystric Fluvisols | Level to undulating and Rolling to hilly |
| 13 | WAT | Water | - | - | - | - |

## 3.4 Soil type data

The Food and Agriculture Organization and the United Nations Educational, Scientific and Cultural Organization (UNESCO) provide the Digital Soil Map of the World (DSMW), freely available online. Updated in 2007, the DSMW offers a vast scale of 1:5,000,000, representing most soil types across various countries in soil map polygon units (Grunwald et al., 2011). Streamflow results from DSMW usage in the SWAT model are competitive with those derived from local soil data, despite the DSMW's relatively coarse resolution (Busico et al., 2020). Table 2; Figure 4 illustrate the soil condition identification in the study area.

# 4 Methods

This research commences with the collection of various data types, including DEM topographic data, CFSR climatology, land cover, soil type, precipitation, and observed runoff. These datasets are processed using the SWAT hydrological model to generate spatial discharge values. These values, along with topographic data and flow accumulation, are utilized in a diversion algorithm to identify potential hydropower sites. The selection of these sites also considers social aspects, such as land cover conditions and existing water transportation routes, which are identified through satellite imagery. Refer to Figure 5 for more details.

 

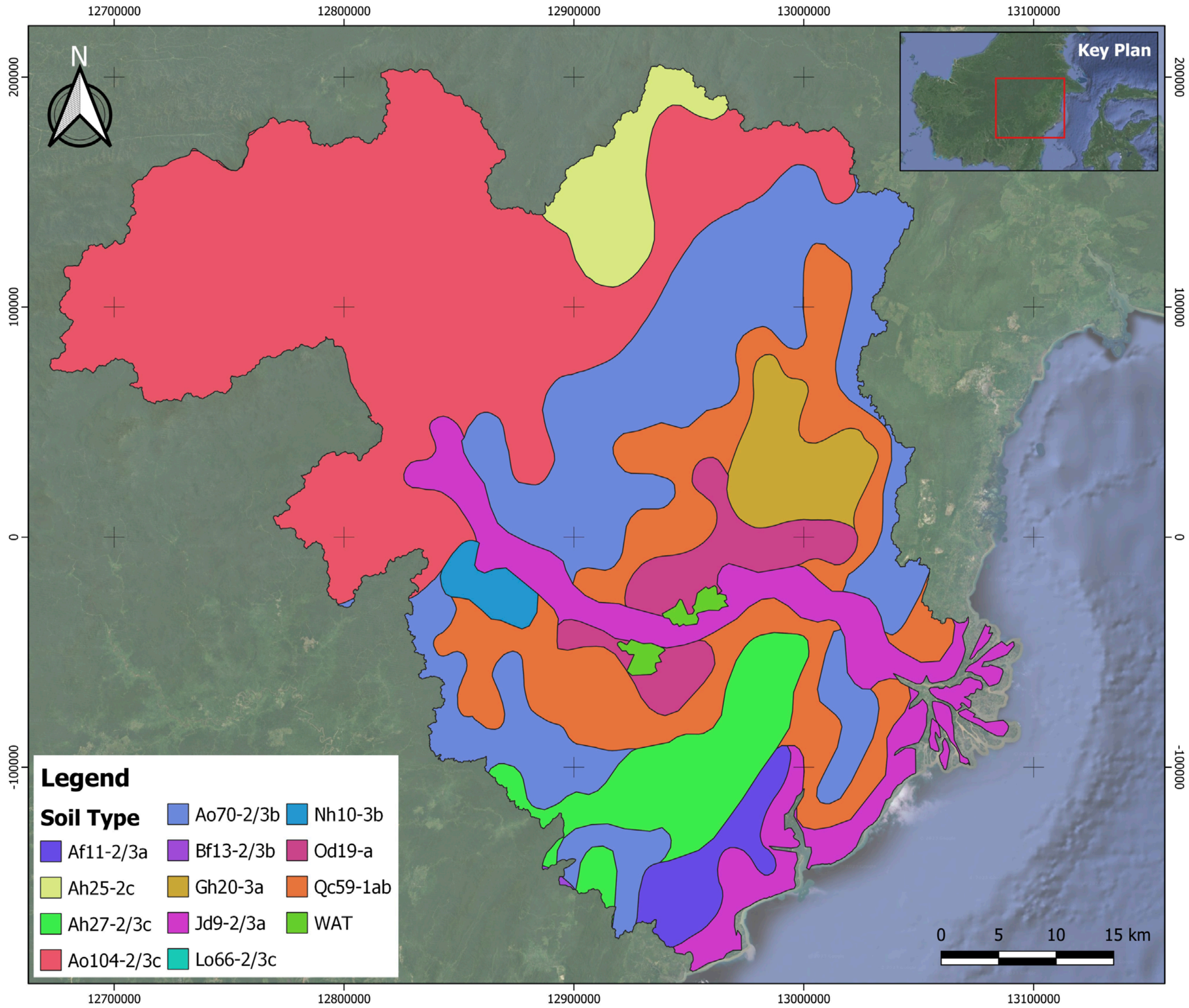


FIGURE 4
Soil type data.

## 4.1 Soil and Water Assessment Tool (SWAT)

The data processing starts with the creation of subwatershed delineations using the SWAT software integrated with ArcMap. SWAT, a daily continuous-time hydrologic model, manages water resources within a watershed or large river basin (Arnold et al., 1998). Watershed delineation is informed by topographic data, administrative boundaries, existing river networks, and streamflow gauging stations. Additionally, the model generates essential outputs like flow accumulation, streamflow, and outlet points for each sub-basin.

Land use data are classified according to SWAT model standards, as they are initially defined based on Indonesian guidelines. Meanwhile, soil type data from DSMW are already classified to fit SWAT standards. The model also requires slope discretization, categorized by the Ministry of Environment and Forestry into five levels based on steepness (0%–8% flat, 8%–15% gentle, 15%–25% reasonably steep, 25%–45% steep, and >45% very steep), which are crucial for determining the Hydrologic Response Units (HRU) in each sub-watershed (Abbaspour et al., 2007).

Weather data processing begins with aligning global rainfall data to observational data using the Quantile-Weibull calibration method. This calibration, performed on 150 CFSR grid data against data from 32 observation stations for 2009, produces correction factor equations based on rainfall intensity, applicable to other years. Calibration is evaluated on a probabilistic basis, aiming to minimize discrepancies. The calibrated precipitation data, along with CFSR climatology data, are then formatted to be compatible with SWAT.

The model's output includes runoff values for subwatersheds, which are further calibrated against observational data using two methods: SWAT-CUP software and manual adjustments. SWAT-CUP employs a Sequential Uncertainty Fitting Version two optimization algorithm for sensitivity analysis and model calibration (Yang et al., 2008; Abbaspour et al., 2015; Hosseini and Khaleghi, 2020). Parameters such as CN2, Alpha BF, GW Delay, GWQMN, and

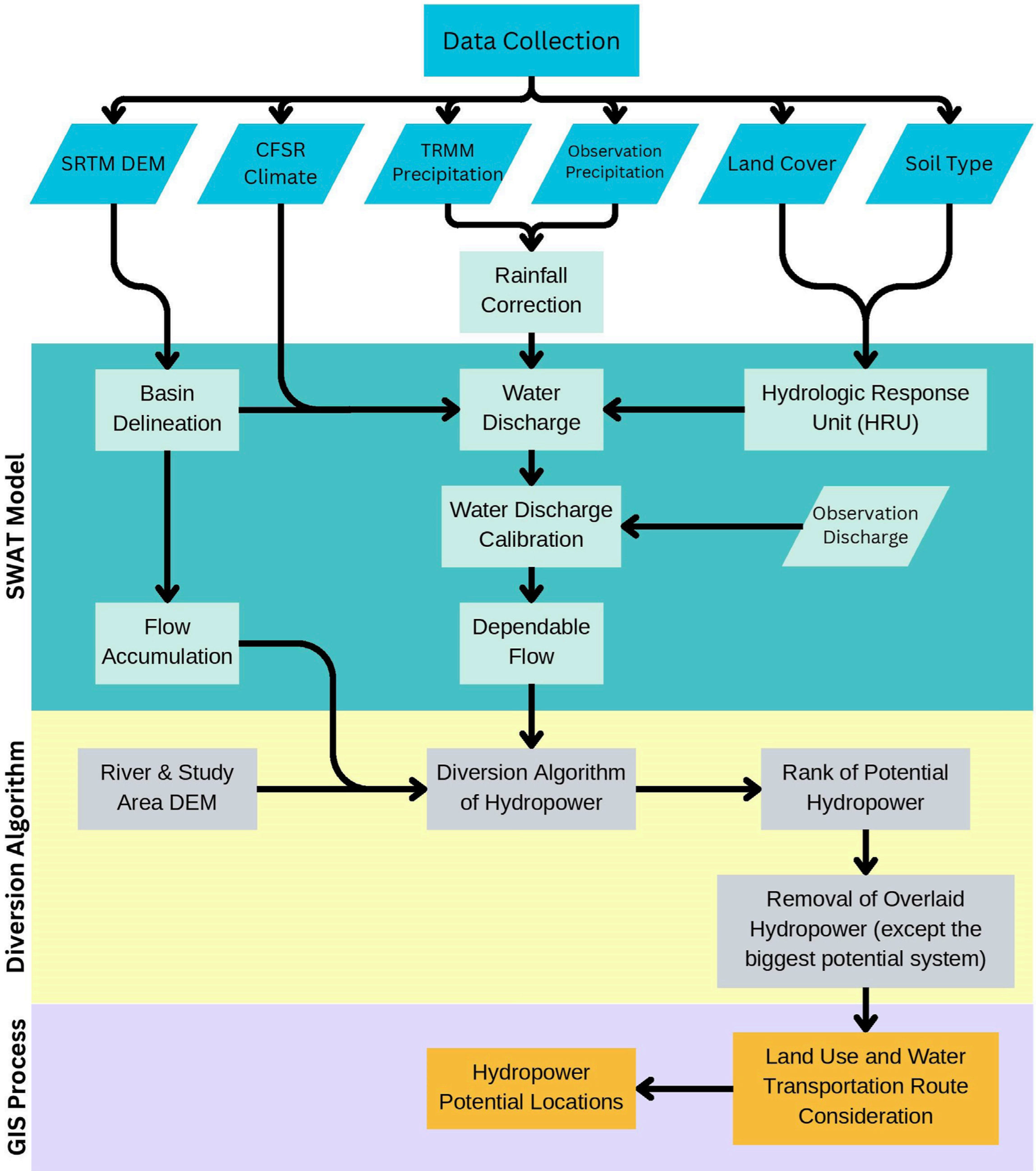


FIGURE 5
Research methodology.

GW Revap are optimized during this process (Singh et al., 2013). The hydrological model's calibration is evaluated using the Nash-Sutcliffe Efficiency (NSE) method, which is adaptable to various model types but requires careful sample distribution to achieve optimal NSE values (McCuen et al., 2006). Based on various studies, the annual minimum flow for run-of-river hydropower is typically 75% (Kuriqi et al., 2019a; 2019b). However, this study has chosen to use 80% to better accommodate environmental considerations. The discharge values were then converted into an ASCII file for processing in the diversion algorithm.

## 4.2 Diversion algorithm and resample headrace

The diversion algorithm inputs include DEM data, river elevation, and flow accumulation (Kardhana et al., 2017). The algorithm begins by identifying grids defined as rivers with specific discharge values, known as headraces. The route of the headrace is traced by selecting grids with the smallest elevation difference to minimize head loss, while also considering certain elevation limits for excavation or landfill efforts (Farid et al., 2021). This parameter

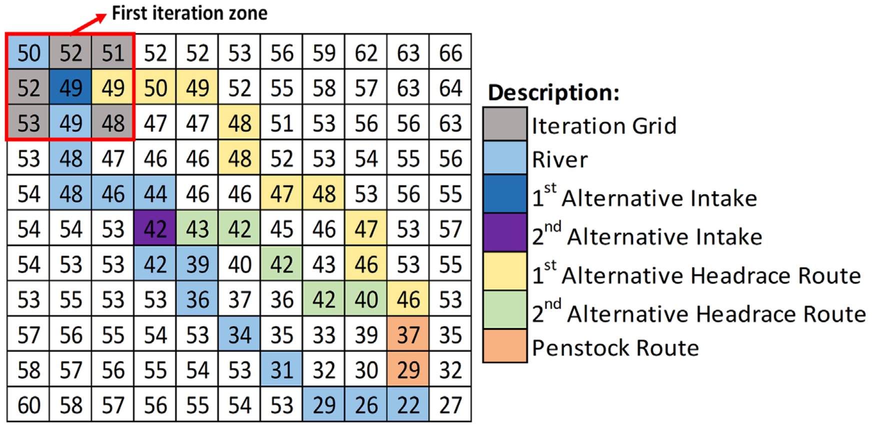


FIGURE 6
Diversion algorithm and resample headrace.

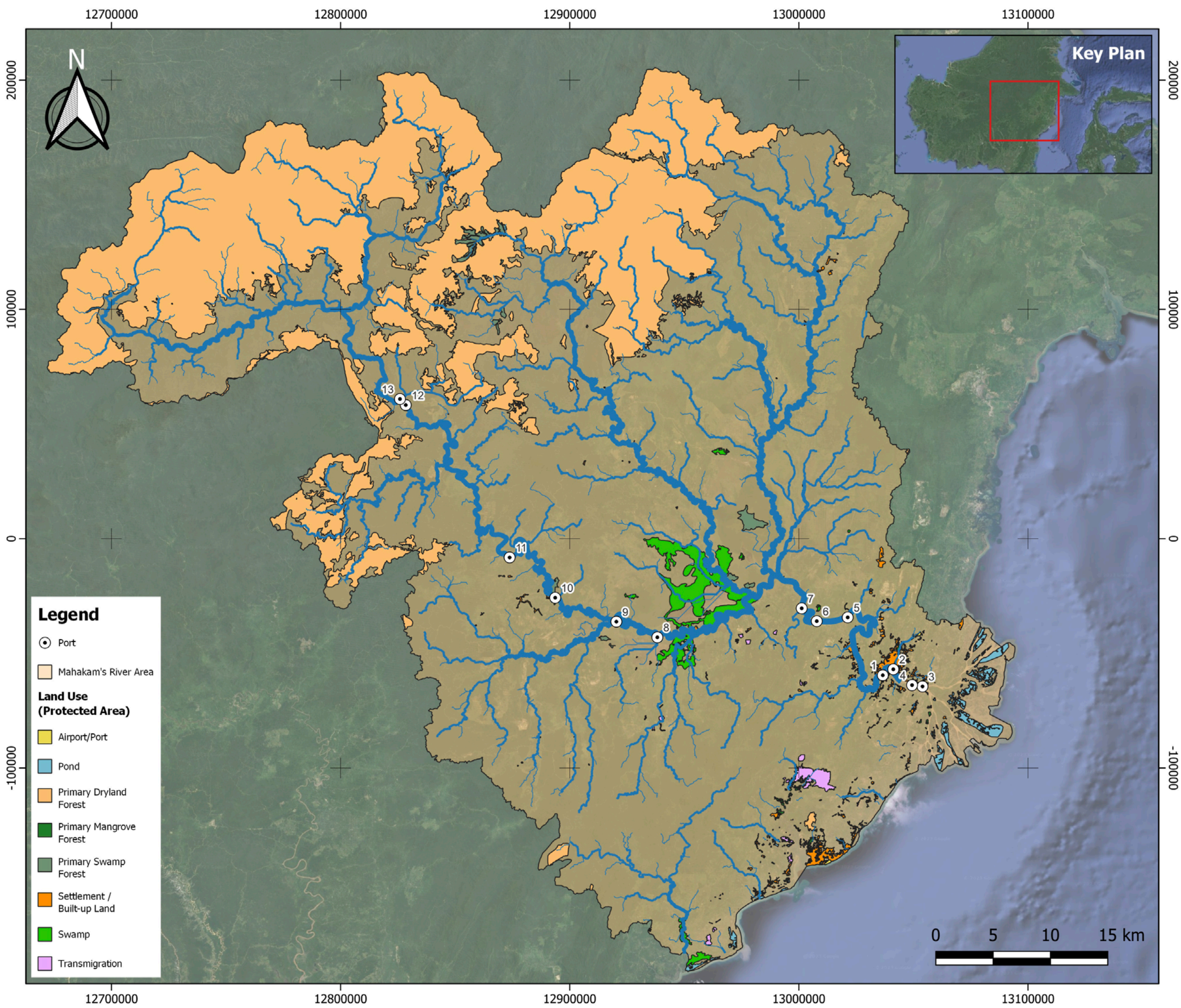


FIGURE 7
Protected areas with water transportation route.

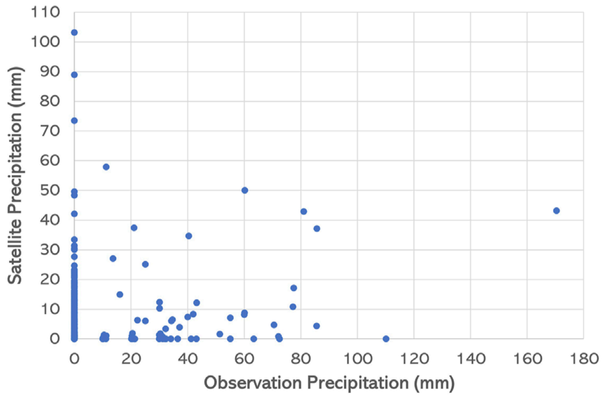


FIGURE 8
Comparison of satellite-observation rainfall data.

significantly impacts energy output, with other studies indicating a range of 1800–2000 m (Larentis et al., 2010; Yi et al., 2010). In contrast, this study has opted for a maximum of 30 iterations to reduce construction costs, corresponding to a maximum headrace length of 2,700 m. Additional technical considerations include avoiding river crossings to reduce the complexity of water infrastructure and maintaining angles less than 45$^0$ to minimize head loss along the headrace route.

Each grid is assessed to determine the potential hydraulic head (Larentis et al., 2010), calculated as the difference in elevation between the intake and the nearest river, within a two-grid radius to avoid barriers, minimize penstock length, and optimize tailrace points. This process continues until a forebay point is identified that offers the maximum head with the shortest headrace. The flow accumulation value, representing the river order in the downstream section, must exceed that of the upstream section (Yi et al., 2010).

A resample headrace technique was developed to prevent overlay in hydropower applications, where one site might impinge on another's water use path (see Figure 6). This technique involves storing and sorting power data from the river network from highest to lowest, prioritizing the hydropower plant with the highest potential. The path from intake to tailrace is then traced, removing any overlapping hydropower sites and those with power levels below 500 kW to prevent overestimation of the model's runoff potential.

## 4.3 Land cover and existing water transport route filter

In determining potential hydropower sites, factors such as land cover and existing water transportation routes are considered. Areas unsuitable for development, such as protected forests, peaty and coastal areas, nature reserves, and zones prone to natural disasters, are excluded based on Presidential Regulation No. 32 of 1990. Existing water transportation routes are identified using 2022 Google satellite imagery, noting the presence of boats and other watercraft along river segments or docks (see Figure 7 for locations of protected areas and ports).

# 5 Results and discussion

## 5.1 Hydro climatology analysis

Before inputting data into the hydrological model, a consistency assessment was conducted, particularly focusing on hydroclimatology data. This data includes satellite-observed rainfall, runoff, and climatology. The Sei Kedang Kepala-Muara area was selected for verification due to its proximity of data points within a grid scope. TRMM satellite precipitation data were compared with data from the Muara Ancalong Observational Rain Station and the Sei Kedang Kepala-Muara Observational Discharge Station, using 2009 as the reference year, aligned with the availability of discharge data.

The correlation check was conducted at daily intervals, as shown in Figure 8. The correlation between satellite rainfall data and ground observations resulted in an NSE value of −0.19, indicating a weak correlation with notable discrepancies. This is evident in several rain events where the satellite data either failed to capture the rainfall or significantly overestimated it. Furthermore, satellite data frequently overestimate rainfall when no precipitation is recorded at observation stations, which can lead to overestimation in the hydrological model during dry conditions. This issue is consistent with findings from other studies, which indicate that the correlation between satellite and rain gauge data in East Kalimantan is low to nonexistent (Prasetia et al., 2013) and that the TRMM rainfall product shows a weak correlation in the flat areas of Kalimantan compared to ground data (Giarno et al., 2018).

Visual comparisons were conducted between satellite-recorded rainfall data, observed rainfall data, and field-measured discharge data. Typically, rainfall events in a region should lead to increased runoff in streams. However, as illustrated in Figure 9, some field runoff events did not coincide with increased rainfall observed or recorded by satellites, particularly in June and September. This discrepancy may occur if the rainfall occurs upstream, where conditions differ from those at the assessment location. Conversely, there were periods, such as from October to December, where field-recorded rainfall did not align with increased discharge. These inconsistencies underscore the lack of synergy between observational and satellite data, necessitating careful consideration when utilizing these datasets. Similar inconsistencies have been observed in other regions of Indonesia, including Java Island, where only five out of thousands of watersheds meet the consistency requirements (Yanto et al., 2017). Consequently, this research will focus on aligning conditions as closely as possible with field realities.

An additional assessment was conducted on temperature, one of the climatological parameters. Using CFSR satellite climatology data, a comparison was made with data from the Kota Bangun ground observation climatology station. The evaluation covered data from January to November 2009, with 3 days of missing data. The NSE (Nash-Sutcliffe Efficiency) value calculated from these datasets was −0.69 for the maximum condition and −0.16 for the minimum condition, indicating an unsatisfactory correlation (see Figure 10 for the maximum condition illustration). More comprehensive satellite data tend to show higher maximum temperatures and lower minimum temperatures. This discrepancy may affect the evapotranspiration values calculated by the hydrologic model, potentially resulting in higher values than actual field events.

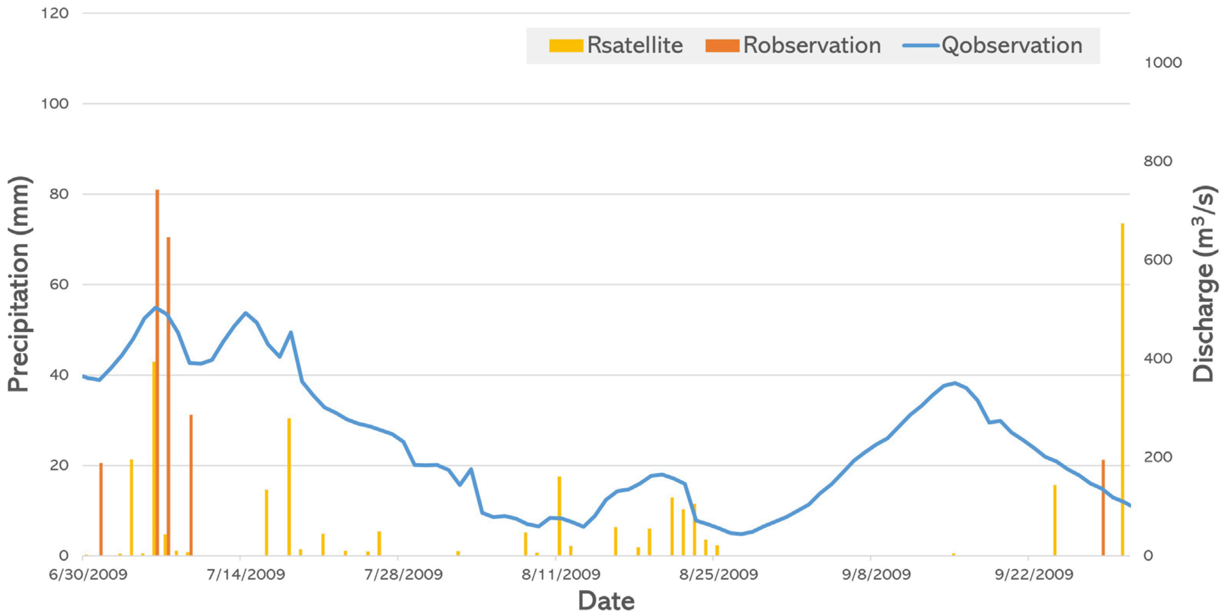


FIGURE 9
Satellite-observation precipitation and observation discharge data consistency comparison in July-September.

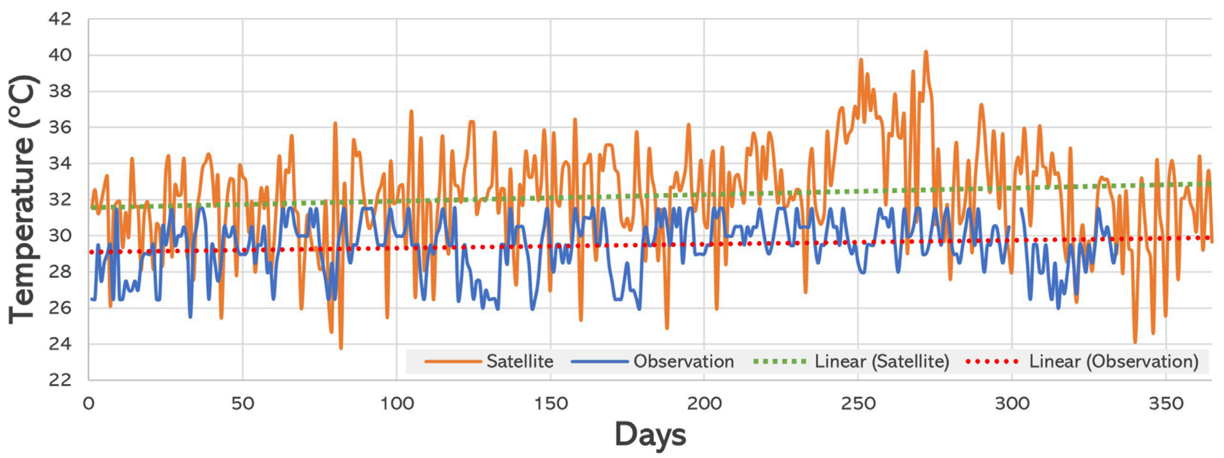


FIGURE 10
Maximum temperature comparison of satellite and observation in 2009.

Although these discrepancies have minimal impact on the hydrological data, the field approach will prioritize model runoff results. Climatological satellite data will still be used as the foundation for the model due to its longer time parameter availability and broader maximum-minimum temperature ranges.

## 5.2 Discharge calculation with SWAT model

The TRMM rainfall data approach was applied to observation data spatially, based on the grid and influence of observation stations in the study area. This approach helps mitigate issues related to the uneven distribution of observation stations and incomplete rainfall data. Observation stations often face disruptions, such as equipment damage, repair periods, or manual recording errors, like missed rain measurements. Calibration was performed on 2009 data, resulting in an NSE (Nash-Sutcliffe Efficiency) value of 0.97 (see Figure 11). This high value indicates a very strong correlation between the datasets. However, this result was influenced by the fact that many observations recorded zero or no rainfall. In the 2009 dataset, zero rainfall values were found starting from the 127th data point out of 365 daily entries. Satellite data also indicated that rainfall values below 9 mm were adjusted to be close to or equal to zero, based on comparisons with observation data. A correction factor derived from each adjustment was applied as a multiplier to the original satellite rainfall value for other satellite data.

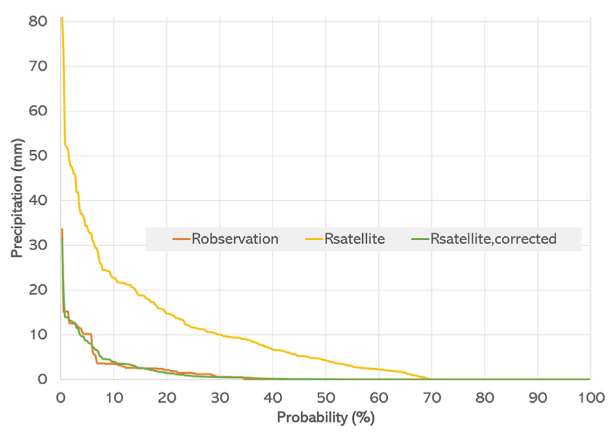


FIGURE 11
Probability distribution of rainfall calibration process in grid p3.

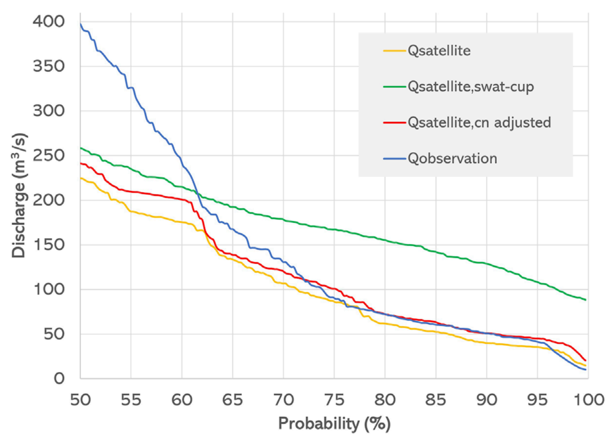


FIGURE 12
Sei Belayan-Tambang Point: Flow duration curve in 50–100 percentage.

In addition to rainfall calibration, the discharge values generated by the SWAT hydrological model were also calibrated. This was done daily for 2009, using the Sei Belayan-Tambang site as the calibration point, which correlated with the 416th sub-basin data. Calibration involved trial and error adjustments on five SWAT parameters: CN2, ALPHA_BF, GW_REVAP, GW_DELAY, and GWMQN, using SWAT-CUP. Additionally, manual calibration was performed by adjusting CN2 values. The best discharge calibration was achieved by manually reducing the CN2 value by 3, resulting in an NSE of 0.57 (see Figure 12). In contrast, calibration using SWAT-CUP yielded an NSE of 0.51. In this case, the SWAT-CUP iteration could not adequately align model runoff with observed runoff.

Furthermore, some limitations were generated by the model. First, the model struggled to account for high discharge areas, particularly at probabilities below 60%. This issue may arise in small watersheds with high infiltration, where significant water absorption reduces discharge. Second, the calibration site in Sei Belayan-Tambang spans a large area of 5,600 $km^2$, the discharge observation data indicating a high base flow influence. Upstream rainfall events may not significantly impact discharge fluctuations in this area, as evidenced by stable, less fluctuating graphs.

It is recommended that discharge measurement points in the field be evenly distributed across both small and large basins. This approach enhances the reliability of the hydrological model by providing more comprehensive data. Additionally, the calibration parameters used in this study are only valid for large basins, as the calibration was based on large basin data. This raises concerns about the model's applicability if these parameters are used for smaller basins.

## 5.3 Hydropower potential locations

This analysis identified 79 potential hydropower sites with a total potential power of 240 MW. When classified by scale, 55 sites are identified as mini-hydropower, with a total power of 227 MW, and 24 sites as micro-hydropower, with a total power of 13 MW.

Considering these values, it is important to account for existing land use conditions to minimize potential social conflicts arising from hydropower development. Areas to be excluded include airports or ports, primary dry forests, primary mangrove forests, primary swamp forests, settlements or built-up areas, swamps, ponds, and transmigration areas. After these exclusions, 73.48% of the total land area remains as potential sites for hydropower development (see Figure 13). Following this filtration, there are 25 mini-hydropower sites with a total capacity of 105.4 MW and 16 micro-hydropower sites with a total power potential of 9 MW.

In comparison, a World Bank study shows that there are 69 hydropower sites with a total capacity of 10,817 MW, the largest in East and North Kalimantan (The World Bank, 2017). Based on this value, a potential site will likely have a value of more than 100 MW. On the contrary, this study provides an upper limit to this value considering the technical capabilities of implementing small hydropower.

The World Bank did not provide detailed information on their search methodology, making it difficult to directly compare their process with this study. But interestingly, both the World Bank results and this study show a tendency for potential locations to cluster in the western upstream area. This suggests that the region likely has significant elevation differences compared to other areas, making it a promising area for further study.

Another aspect considered in this study is water transportation. The Mahakam River, known for its width, serves as a vital transportation channel for local communities (Effendy, 2022). This presents a limitation for hydropower development, as the river's depth must be maintained, preventing damming or tapping that would obstruct planned ship passage. Transportation routes were identified using Google Earth satellite imagery, which showed ports along the riverbanks and captured images of ships in transit. This identification revealed 13 ports or crossings in the river channel, from the Sungai Kapal and Barang ports on the Kunjang River to the Batu Majang port upstream. Based on our results, no potential power plant sites were found that would interfere with navigation channels.

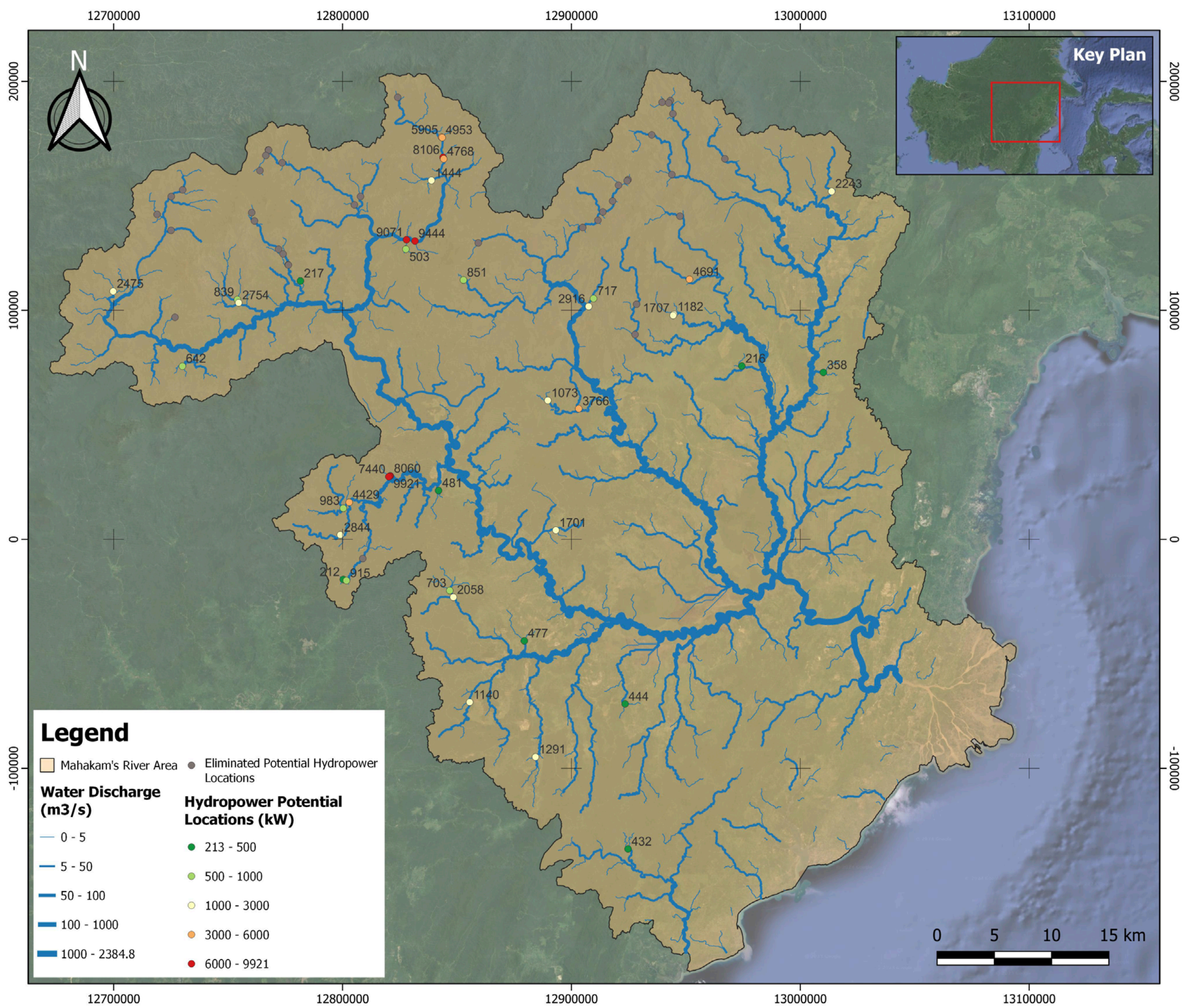


FIGURE 13
Run-of river hydropower potential in Mahakam River Area.

## 5.4 General hydropower contribution in IKN relocation and energy transition

With a total projected hydropower potential of 114.4 MW, if fully utilized, it can contribute to the projected electricity system by 3.4% (including existing and additional). This could have an impact on the local energy transition process. Although it cannot replace the still dominating position of coal-fired power plants, this study emphasizes that the government plays an important role in hydropower planning, because weak governance organizations could drive inadequate hydropower development (Alsaleh and Abdul-Rahim, 2021b).

In addition to its contribution to total electrification, hydropower can also benefit the environment. Based on the maximum emission values of hydropower (Amponsah et al., 2014; Ubierna et al., 2022), hydropower can reduce carbon emissions that would be released if coal-fired power plants continued to operate in East Kalimantan. The total emissions from coal-fired power plants (PLTU) with the same amount of energy generation can reach 540 thousand tons of CO2 per year. Meanwhile, hydropower only produces about 60 thousand tons of CO2, which is even 1/9 of that amount. This can significantly reduce emissions and mitigate the environmental impact of power generation activities.

## 6 Conclusion

Identifying potential hydropower locations can be accomplished through the development of rainfall-runoff hydrological models and the application of diversion algorithms. Using TRMM rainfall data addresses the limitations of CFSR data, while the Quantile-Weibull grid calibration method improves the spatial distribution of rainfall. However, this approach requires support from several evenly distributed observation stations covering the entire study area.

The limitations of the model in generating discharge present a challenge. The discharge values obtained in this study are generally valid for large basin conditions, but reliability decreases as the basin area becomes smaller. Therefore, we used 80% as the minimum flow for hydropower utilization to reduce overestimation and improve reliability. In cases where the model and observations align, an approach that considers periodic discharge and flow duration curves above 55% is needed to maximize energy values.

Additionally, the use of diversion algorithms, leveraging SRTM DEM and runoff discharge, can identify initial potential hydropower location points. The resolution and vertical accuracy of the DEM are crucial in determining the calculated potential height difference. Higher values of these factors enhance model reliability, though the algorithm process becomes longer and demands higher hardware specifications. In this research, due to the limitations of the resulting discharge model, the potential height difference value serves as a benchmark parameter defining hydropower potential.

This study provides an overview of energy potential and emission reduction. The potential generation capacity of mini hydropower is 25 sites with a total power of 105.4 MW, and micro-hydropower is 16 sites with a total power of 9 MW. These values were determined after considering potential locations against social aspects of land use and water transportation flows. Further verification is needed to refine model results using improved elevation data, observation data, and field surveys, which can provide a comparison between the model and existing conditions. Moreover, these findings contribute 3.44% to the electricity supply and reduce CO2 emissions by 480,000 tons compared to fossil fuels, positioning this research as a pre-feasibility study for hydropower's role in the IKN energy plan. Future research should include assessing climate change impacts on hydropower infrastructure, conducting economic analyses to enhance reliability, and integrating hydropower energy into the energy mix network of the IKN area.

## Data availability statement

The datasets presented in this article are not readily available because several datasets have been restricted. It was obtained from the Directorate for Engineering Development of the Ministry of Public Works and Housing of Indonesia (Direktorat Bintek SDA, Kementerian PUPR) and the Ministry of Environment and Forestry of Indonesia (Kementerian LHK). Request access to those datasets should be directed to Bintek SDA, informasibinteksda@gmail.com and Sigap KLHK, sigap@menlhk.go.id..

## Author contributions

AAK: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing, Writing–original draft. AR: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Software, Visualization, Writing–original draft, Writing–review and editing. MF: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing–original draft, Writing–review and editing. HK: Conceptualization, Formal Analysis, Methodology, Supervision, Writing–original draft. FR: Conceptualization, Formal Analysis, Methodology, Supervision, Writing–original draft. AR: Conceptualization, Software, Writing–original draft. MK: Conceptualization, Supervision, Writing–original draft. MA: Conceptualization, Supervision, Writing–original draft. AW: Writing–original draft, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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