Identification of suitable areas for the installation of hydroelectric projects based on the stream-power model

Identificação de áreas aptas para a instalação de empreendimentos hidrelétricos com base no modelo geomorfológico de potência fluvial

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Abstract

Hydropower is mostly driven by the river discharge and the gradient slope of the river channels. These two parameters constitute a classical geomorphological model, known as stream-power. Based on the stream-power model, this study aims to identify locations with greater potential for the installation of Small Hydroelectric Power Plants (SHPs) in the Meia Ponte River basin, situated in the central-southern region of the State of Goiás, in Brazil. To achieve this, hydrological data from six hydrometric stations and the Copernicus digital elevation model were utilized to pinpoint areas with higher river power. The results revealed 161.46 km of segments with river power ranging from 5000 to 30000 kW · m^{-1} and 23 points characterized by pronounced changes in channel slope, indicating a suitable potential for SHP installation. Besides the river-related data considered in this study, future research should encompass various other aspects, including environmental, social, economic, operational, and cultural factors when searching for the best locations for SHP installations.

Keywords:
Small Hydroelectric Power Plants, Knickpoints, Energy, Meia Ponte River.

Resumo

A energia hidrelétrica depende principalmente da vazão e do desnível topográfico dos canais fluviais. Esses dois parâmetros compõem um clássico modelo geomorfológico de potência fluvial, o *stream-power*. Com base no *stream-power*, este estudo visa identificar locais com maior potencial para a instalação de empreendimentos hidrelétricos, especificamente Pequenas Centrais Hidrelétricas (PCHs), na bacia do Rio Meia Ponte, localizada no centro-sul do Estado de Goiás. Para isso, foram utilizados dados hidrológicos de seis estações fluviométricas e o modelo digital de elevação Copernicus para determinar os locais com maior potência fluvial. Os resultados revelaram 161,46 km de segmentos com potência fluvial entre 5000 e 30000 kW · m^{-1} e 23 pontos

caracterizados por rupturas acentuadas na inclinação do canal, demonstrando um potencial favorável para a instalação de PCHs. Além das informações fluviais consideradas neste estudo, é importante ressaltar que outros aspectos devem ser levados em conta em trabalhos futuros, tais como aspectos ambientais, sociais, econômicos, operacionais e culturais, ao buscar os melhores locais para a instalação de PCHs.

Palavras-chave:

Pequenas Centrais Hidrelétricas, *Knickpoints*, Energia, Rio Meia Ponte.

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I. INTRODUCTION

Hydroelectric power plants are projects that generate significant environmental impacts and have high social costs. Therefore, they should undergo extensive debate with society to be justified from a technical and economic standpoint (SANTOS *et al*., 2012). Small Hydroelectric Power Plants (SHPs) offer a cost-effective and environmentally less impactful alternative to large hydroelectric projects, which inundate a much larger area (ANEEL, 2021). According to ANEEL (2020), hydroelectric developments with an installed capacity between 5000 kW and 30000 kW and less than 13 km^2 of reservoir area are classified as SHPs.

According to the Brazilian Electric System Operator (ONS), in 2021, Brazil faced its most severe hydrological crisis since the 1930s, with water levels in hydroelectric reservoirs staying below the historical average for the past seven years (ANEEL, 2021). Furthermore, ONS (2021) reports that 63.1% of the country's electricity is derived from hydroelectric sources (ANEEL, 2021). This underscores Brazil's significant dependence on this energy source and its strategic importance in a scenario of water scarcity in the country and a global shift towards renewable energy.

All planning for the implementation of hydroelectric projects, whether for large power plants or smaller ventures like SHPs, needs to undergo a comprehensive analysis to find the best location for their installation. In this regard, geotechnologies (e.g., remote sensing, Geographic Information System - GIS, digital cartography, etc.) have significant potential to assist in scenario creation and the final decision-making process (BREUNIG *et al*., 2019). This is because they are cost-effective, including orbital products derived from multisensors on a global or near-global scale that are freely available to the public. Geotechnologies enable the integration of various environmental, social, and economic variables into a single geospatial database and facilitate the analysis of extensive areas or areas with challenging field access in less time. Some studies have already utilized data manipulation and cross-referencing tools available in GIS for the purpose of determining

more favorable areas for hydroelectric project installation (e.g., LARENTIS *et al.*, 2010; CUYA *et al.*, 2013; TIAN *et al.*, 2020).

The initial assessment of potential sites for the installation of hydroelectric power plants is generally based on topographical parameters and hydrological factors, primarily the channel's gradient, and water volume, the latter being represented by river discharge (HIDAYAH; INDARTO; WAHYUNI, 2017). These two parameters constitute a classic geomorphological model of stream-power (BAGNOLD, 1966), which has been widely used in studies of water and sediment transport, as well as in landscape evolution and surface modeling processes associated with climate, tectonics, and lithology (PEIFER *et al.*, 2022). The determination of stream power in the stream-power model is given by:

$$\Omega = p \cdot g \cdot Q \cdot S \tag{1}$$

Where Ω represents the river power per unit flow length (W $\cdot$ m^{-1}); ρ is the water density (approximately 1000 kg $\cdot$ m^{-3}); g is the gravitational acceleration ($\sim$9.8 m $\cdot$ s m^{-2}); Q is the river discharge (m$^3 \cdot$ s^{-1}); and S represents the channel slope, determined by the segment's inclination (m $\cdot$ m^{-1}). Traditionally, for determining stream-power parameters, bankfull discharge is considered as the discharge rate, which is the discharge capable of filling the entire channel up to the level of the floodplain, with a temporal reference of the 2-3 year return period discharge (JAIN *et al.*, 2006; ROSA; FREDDUZZI; CENCETTI, 2019). Since ρ and g are constants, the variable parameters in this equation are Q and S. Q has a direct relationship with the contributing area parameter (A), also referred to as flow accumulation in GIS, which determines the area (or the number of pixels) that hydrologically flows to each point (pixel) in a digital elevation model (DEM). Consequently, it is possible to estimate Q based on A (PEIFER; CREMON; ALVES, 2020). S can be easily determined for any pixel in the DEM. Thus, it is possible to adapt the stream-power model using digital topographic data from DEMs for studies involving the identification of river segments with hydroelectric potential (TORREFRANCA; OTADOY; TONGCO, 2022).

The aim of this study was to identify, based on geomorphological analyses using the stream-power model based on DEMs, sections with higher potential for the installation of SHPs in the Meia Ponte River basin in the central-southern region of the State of Goiás, in Brazil.

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II. MATERIALS AND METHODS

The Meia Ponte River basin is located in the central-southern region of the State of Goiás, in the Central-West region of Brazil, encompassing 39 municipalities. This basin covers 4.2% of the territory of Goiás, where approximately 40% of the state's population lives (Figure 1). Due to its direct supply of water to industrial, livestock, mineral extraction, agricultural, and domestic activities, the Meia Ponte basin presents a scenario of significant conflict over water use (SEMAD, 2019).
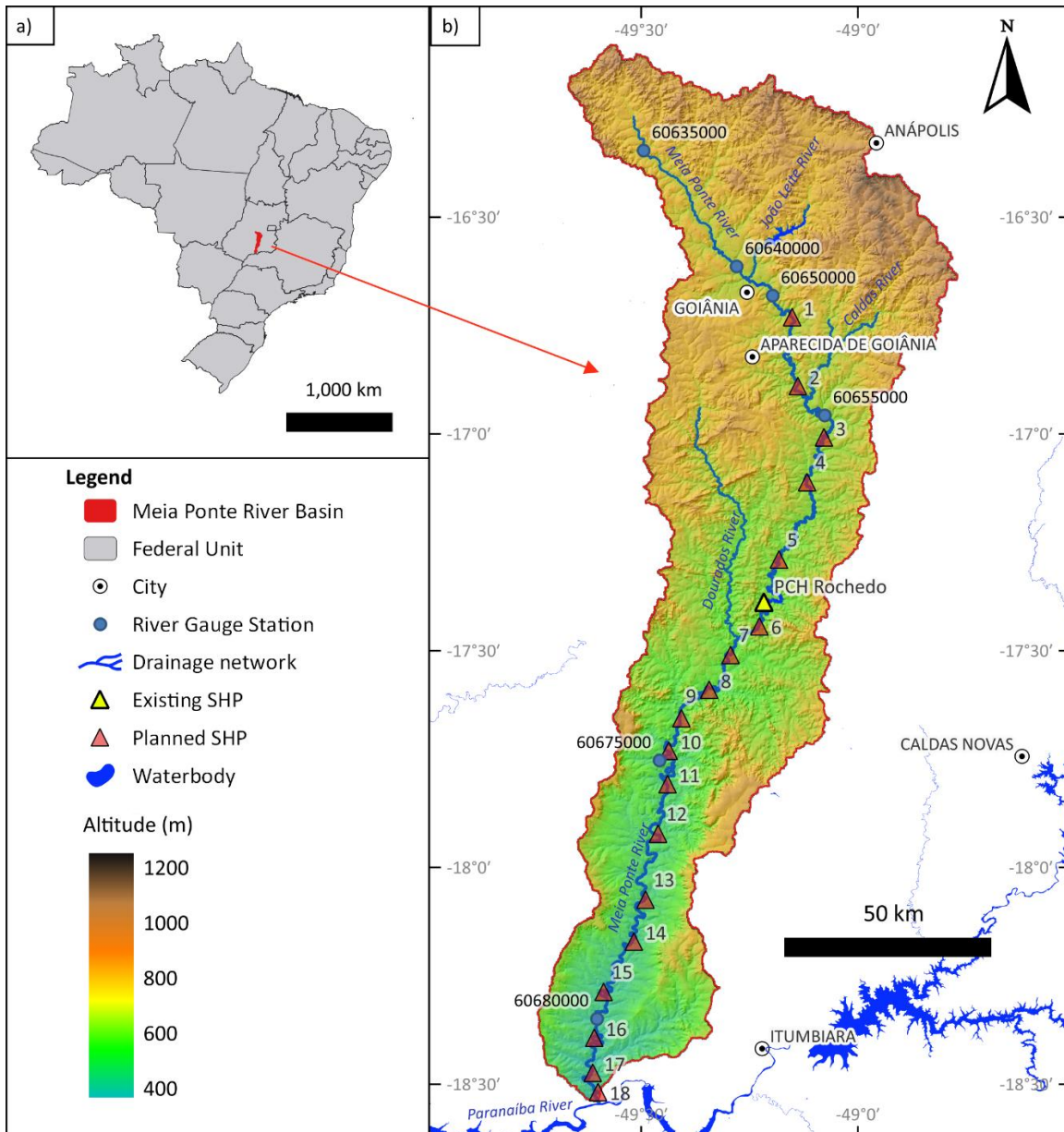

Figure 1 – Location of the Meia Ponte River basin, indicating active and planned SHPs (Small Hydroelectric Power Plants) and installed hydrometric stations along this river. Numbers from 1 to 18 correspond to the ID (identification) column in Table 1. Source: Authors' elaboration.

With a length of approximately 560 km, from its source to its mouth at the Paranaíba River on the border between Goiás and Minas Gerais states, the Meia Ponte River, in its upper course, crosses a 35 km stretch that goes through the metropolitan region of Goiânia. The altitude within the Meia Ponte River basin varies between 400 and 1,140 meters. Areas with higher altitudes, exceeding 1000 m, are located in the northern part of the basin, while lower altitudes are found to the south. There is also a significant variation in slope within the basin, with predominantly flat regions. Much of the basin exhibits slopes of less than 8%, associated with flat and gently undulating terrains resulting from the modeling of plains and fluvial terraces. About one-third of the basin slopes ranging from 8 to 20%, associated with undulating terrain, and, to a lesser extent, areas with slopes exceeding 20%, where strongly undulating to mountainous terrain occurs, related to dissection modeling.

Cerrado is the predominant biome in the Meia Ponte River basin, occupying 89% of its total area. This biome contains high biological diversity, with a wide presence of endemic species. The other biome present in the basin is the Atlantic Forest, accounting for only 11% of the basin's area.

The Meia Ponte River has one installed SHP (Rochedo SHP) on its main trunk and 18 planned SHPs, with some in advanced stages of installation process, such as Santa Rosa II SHP and Cachoeira do Meia Ponte SHP. Table 1 presents the planned SHPs, their respective capacities, and the municipalities they will affect. The location of the SHPs and their capacity data were sourced from the SIGEL platform (Electric Sector Information System), managed by the National Electric Energy Agency (ANEEL, 2021), and the Diagnosis of the Meia Ponte River Hydrographic Basin Water Resources Planning and Management Unit (SEMAD, 2019).

In the State of Goiás, the Meia Ponte River has the highest number of hydrometric stations with time series data for hydrological analyses (SANTOS; VESPUCCI; BAYER, 2017). According to data from the HidroWeb database, the Meia Ponte River has 21 hydrometric stations. Criteria considered for the selection of hydrometric stations included data consistency and monitoring duration. For instance, stations with data gaps and those with monitoring durations of less than 20 years were excluded from the analysis. Following these criteria, from a total of 21 stations registered in HidroWeb that monitor the Meia Ponte River, only six have sufficient discharge data to perform time series analysis (Table 2).

Table 1 –Planned SHPs for the Meia Ponte River. See the location of the SHPs in Figure 1.

ID	Name	Power (MW)	Municipalities to be affected
1	Vau das Pombas	5,0	Goiânia, and Senador Canedo
2	Caldas	12,0	Goiânia, Senador Canedo, Aparecida de Goiânia, Bela Vista de Goiás, and Hidrolândia
3	Pontal	12,0	Aparecida de Goiânia, Bela Vista de Goiás, and Hidrolândia
4	Areias	7,5	Bela Vista de Goiás, Hidrolândia, and Piracanjuba
5	Saltador	17,0	Piracanjuba, and Professor Jamil
6	Rochedo II	11,5	Piracanjuba
7	Entre Pontes	18,0	Piracanjuba, Professor Jamil, and Mairipotaba
8	Mota	26,0	Pontalina, and Morrinhos
9	Chapéu	27,0	Pontalina, and Morrinhos
10	Aloândia	19,0	Morrinhos, and Aloândia
11	Volta Grande	20,0	Joviânia, Morrinhos, and Aloândia
12	Jacaré	10,0	Joviânia, Morrinhos, and Goiatuba
13	Goiatuba	18,0	Goiatuba
14	Cachoeira do Meia Ponte	29,0	Goiatuba, and Panamá
15	Campo Limpo	25,5	Goiatuba, Panamá, Bom Jesus de Goiás, and Itumbiara
16	Meia Ponte	22,0	Bom Jesus de Goiás, and Itumbiara
17	Santa Rosa II	26,0	Itumbiara, and Cachoeira Dourada
18	Tabocas	12,0	Cachoeira Dourada

Source: ANEEL (2021) and SEMAD (2022).

For estimating bankfull discharges at the 6 selected hydrometric stations, we used SisCAH 1.0, a software developed by the Water Resources Research Group within the Department of Agricultural Engineering at the Federal University of Viçosa. SisCAH enables the determination of maximum, minimum, and mean discharges based on hydrometric data provided by ANA (Brazil's National Water Agency). The software utilizes probability distribution functions, such as Gumbel, Log-normal II, Log-normal III, Pearson III,

LogPearson III, and Weibull (BOF; SOUSA; PRUSKI, 2009), to estimate maximum discharges from the input data series. The time series data from each station were input into the SisCAH software and processed to identify the most suitable distribution function for estimating maximum discharges, considering a 3-year return period.

Table 2 - Hydrometric stations on the Meia Ponte River used in this study. Refer to Figure 1 for station locations.

Station Name	Station Code	Beginning	End	Monitoring duration
Inhumas	60635000	1947	2019	72 years
Montante de Goiânia	60640000	1975	2020	45 years
Jusante de Goiânia	60650000	1978	2020	42 years
Faz. Bonita de Baixo	60655000	1956	1998	42 years
Aloândia	60675000	1975	1995	20 years
Ponte Meia Ponte	60680000	1951	2020	69 years

Source: ANA (2022).

Altimetric data for the study area were extracted based on the Copernicus GLO-30 DEM (COP-30). These data were obtained from the OpenTopography platform (ESA, 2021), which provides free altimetric data. The Copernicus DEM has a pixel size of 1 arc-second (approximately 30 meters), referenced in geographic coordinate system with WGS84 horizontal datum and orthometric altitudes relative to the EGM2008 geoidal model, with vertical accuracy less than 2 meters (AIRBUS, 2020). This DEM was chosen over other available DEMs with open access (e.g., SRTM, NASADEM, and AW3D30) because it demonstrated the best altimetric quality results in the study area, according to previous studies (BETTIOL *et al*., 2021; GUTH; GEOFFROY, 2021; CREMON *et al*., 2022).

After acquiring the elevation data, the preprocessing stage was initiated. The elevation data was processed using the TerraHidro software (TerraHidro Development Team, 2019). TerraHidro has potential to correct various elevation data inconsistencies, such as gap filling and peak smoothing, making the digital elevation model hydrologically consistent based on Jardim's (2017) proposal. From the hydrologically corrected DEM, it was possible to determine the drainage basin's contributing area for each pixel of the DEM using a threshold greater than 300 pixels through the D-Inf algorithm (TARBOTON, 1997). The drainage network of the Meia Ponte River basin was extracted, as well as the channel slope.

Based on the maximum discharge (Q_{max}) data obtained from the SisCAH software and the contributing area extracted from the Copernicus DEM, a linear regression equation was generated for each hydrometric station. The resulting equation from this linear relationship was input into the native tool of QGIS 3.22, the "Raster Calculator," to spatialize discharge values for each pixel of the DEM. Lastly, the river power in $kW \cdot m^{-1}$ was also calculated for each pixel of the DEM using discharge and channel slope data, as well as the constants of water density and gravitational acceleration (Figure 2).
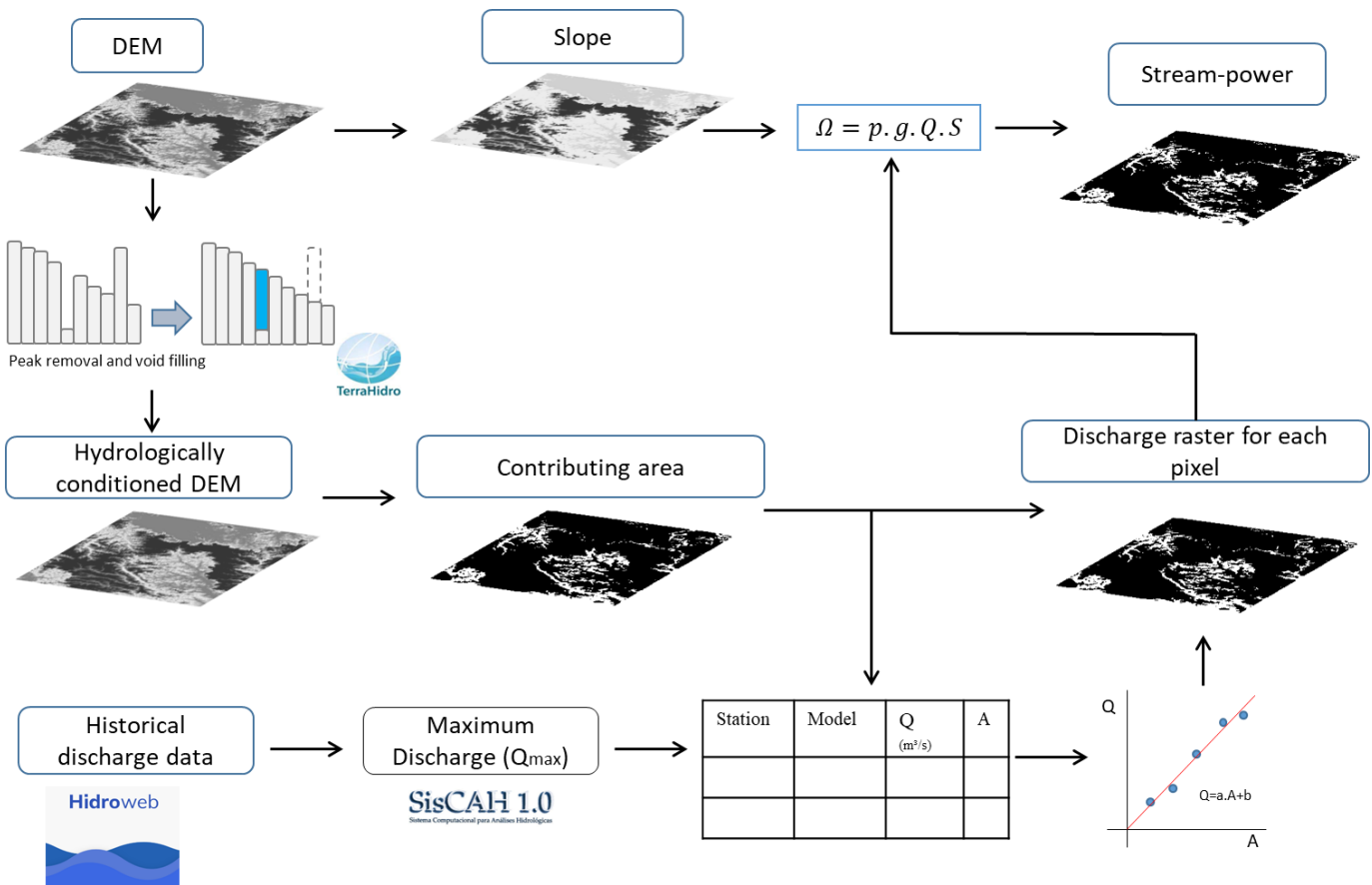

Figure 2 - Methodological flowchart of the operations performed in this study. Source: The authors

As mentioned earlier, for a hydropower plant to be considered an SHP, the installed power must range between 5000 kW and 30000 kW. To assess the suitability of this criteria in the Meia Ponte River basin, a reclassification of pixel values for stream-power within the afore mentioned range along the drainage network of this basin was conducted to identify areas with the potential for SHP installation. In addition to identify areas with SHP installation potential, the locations of possible knickpoints were analyzed along the main river channels in the Meia Ponte River basin. In geomorphology, a knickpoint corresponds to a specific point or region (knickzone) in the river channel where there is an abrupt change in its gradient (slope), typically

characterized by a waterfall or rapids (BOULTON, 2020). Knickpoints generally reflect conditions and processes associated with river channel erosion, induced by variations in lithology, climate, and surface uplift rates.

The identification of knickpoints was performed using the knickpointfinder algorithm implemented in the TopoToolbox package (SCHWANGHART; SCHERLER, 2014; STOLLE *et al.*, 2019). Essentially, this algorithm compares a theoretical concave profile to the current longitudinal profile (i.e., extracted from the DEM) and identifies points above a vertical displacement threshold (Δz) between the theoretical and current profile, as defined by the tolerance parameter ("tol"). To carry out iterative processing, the algorithm initiates the search for knickpoints considering the longitudinal profile as a whole. If a knickpoint is identified, the algorithm adjusts the theoretical profile for segments upstream and downstream of the knickpoint, and a new knickpoint search is initiated. The algorithm stops operating when Δz falls below the value defined by the tolerance parameter. Since the tolerance varies with the inherent uncertainties in elevation errors of the DEM in the longitudinal profiles (SCHWANGHART; SCHERLER, 2017), low tolerance values can result in artifacts related to knickpoints. As the error in the COP-30 DEM is less than 2 meters for the study area (cf. CREMON *et al.*, 2022), this value was used as the optimal tolerance threshold for knickpoint identification in the Meia Ponte River basin. It was assumed that among the areas with stream-power potential between 5000 and 30000 kW · m^{-1}, those with knickpoint locations would naturally be the most favorable for SHP installation. Finally, a comparison was made between the final river power product, knickpoint and planned SHPs locations.

III. RESULTS

The linear regression between the maximum discharge values with a 3-year return period and the contributing area of each hydrometric station is presented in Figure 3. The larger the contributing area, the higher the discharge at the respective monitoring point. As observed in Figure 3, an R-squared (R^2) value exceeding 98% was obtained, indicating that the model can explain a significant portion of the observed values, despite the limited number of observations used in this analysis.
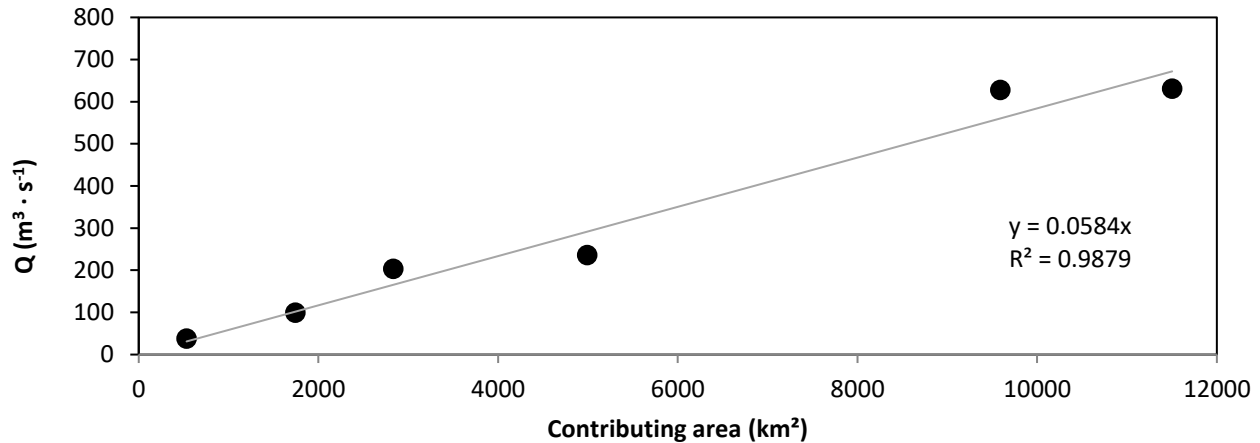
Figure 3 - Linear regression between discharge (Q) values and contributing area derived from the Copernicus DEM. Source: The authors.

For all six hydrometric stations used in this study, the distribution model indicated by the SisCAH 1.0 software was the Log-normal III, which has a positive skew and a non-fixed value greater than zero, making it suitable for modeling maximum discharges (NAGHETTINI; PINTO, 2007). A summary of the river power values classified into 5000 kW · m^{-1} intervals is presented in Table 3. It is observed that river segments with power potential ranging from 5000 to 30000 W · m^{-1} correspond to 161.46 km of the Meia Ponte River basin. From this total, nearly one-third (28%) falls within the 5000 to 10000 kW · m^{-1} intervals. Between 10000 and 20000 kW · m^{-1}, there is an extension of 62.53 km of river segments, representing 39% of the total with power potential for SHPs. Additionally, 52.68 km of river length showed power above 20000 kW · m^{-1}, accounting for 33% of the total.

Table 3 - Summary of stream-power intervals for the Meia Ponte River basin, with values of total length of river segments in each power interval and the percentage.

Stream-power (kW . m^{-1})	Length (km)	Percentage
5000 – 10000	45.247	28%
10000 – 15000	33.831	21%
15000 – 20000	29.703	18%
20000 – 25000	26.766	17%
25000 – 30000	25.919	16%

Source: The authors.

Along the Meia Ponte River drainage basin, 28 knickpoints were identified (Figures 4 and 5a-d), where 23 occurred at the main river and in areas with river power between 5000 and 30000 kW · m^{-1}. The highest

number of knickpoints is concentrated in the central region of the basin (midstream of the Meia Ponte River; Figure 5b), between the Rochedo II SHP (SHP in operation; number 6 in Figure 5) and the Chapéu SHP (still in the installation phase; number 9 in Figure 5). It's worth noting that Rochedo II SHP, despite having only 4000 kW of power, was classified as an SHP with the start of operations in 1955, a date prior to the current legislation, which defines a minimum limit of 5000 kW. However, Rochedo II SHP has an ongoing expansion project to reach 13000 kW (ANEEL, 2021).
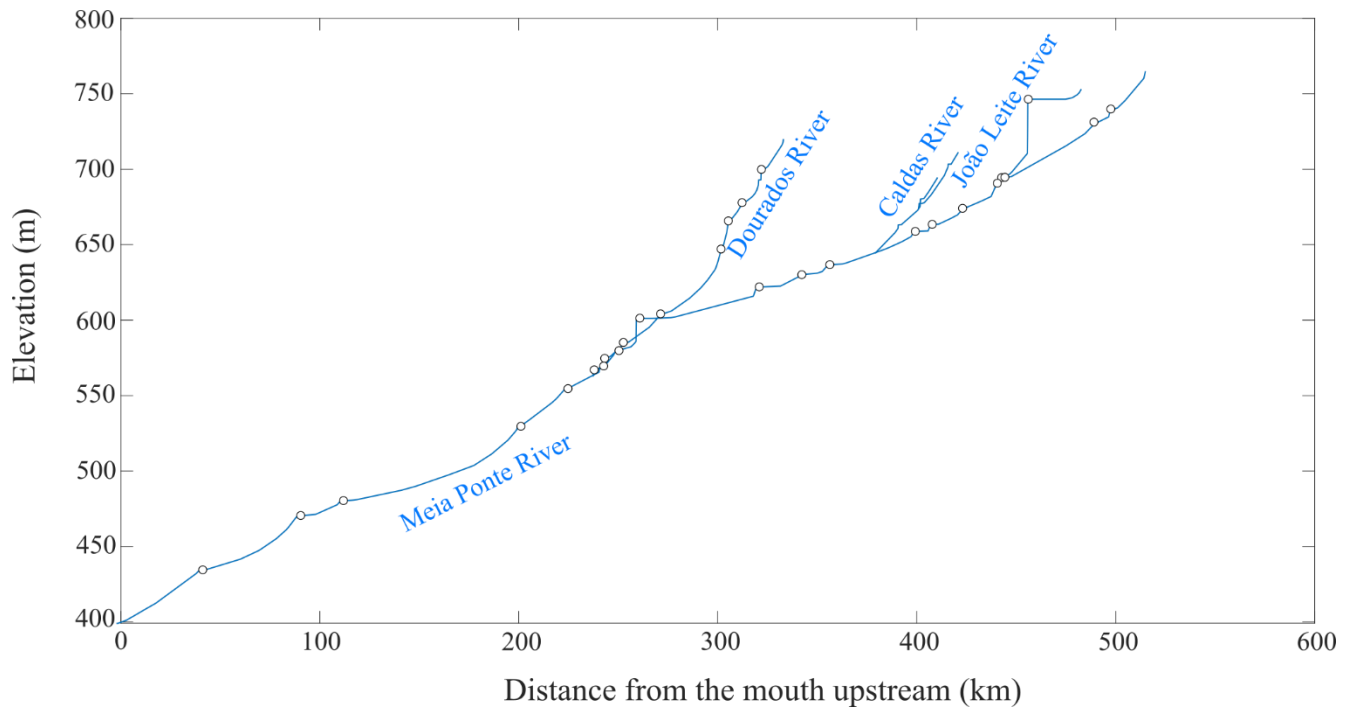

Figure 4 - Longitudinal profile of the main channels in the Meia Ponte River basin with the location of knickpoints in areas with river power suitable for SHP installation. Source: The authors.

The stretch downstream from Caldas SHP to Saltador SHP (numbers 2 and 5 in Table 1, respectively) has six knickpoints (Figure 5a). Further downstream from Rochedo II SHP to Chapéu SHP (numbers 6 and 9 in Table 1) is the stretch with the highest occurrence of knickpoints along the Meia Ponte River, a total of 11 knickpoints (Figure 5b-c), but it has few SHPs or energy utilization projects. The southern region of the Meia Ponte River drainage basin also recorded some knickpoints (Figure 5d).
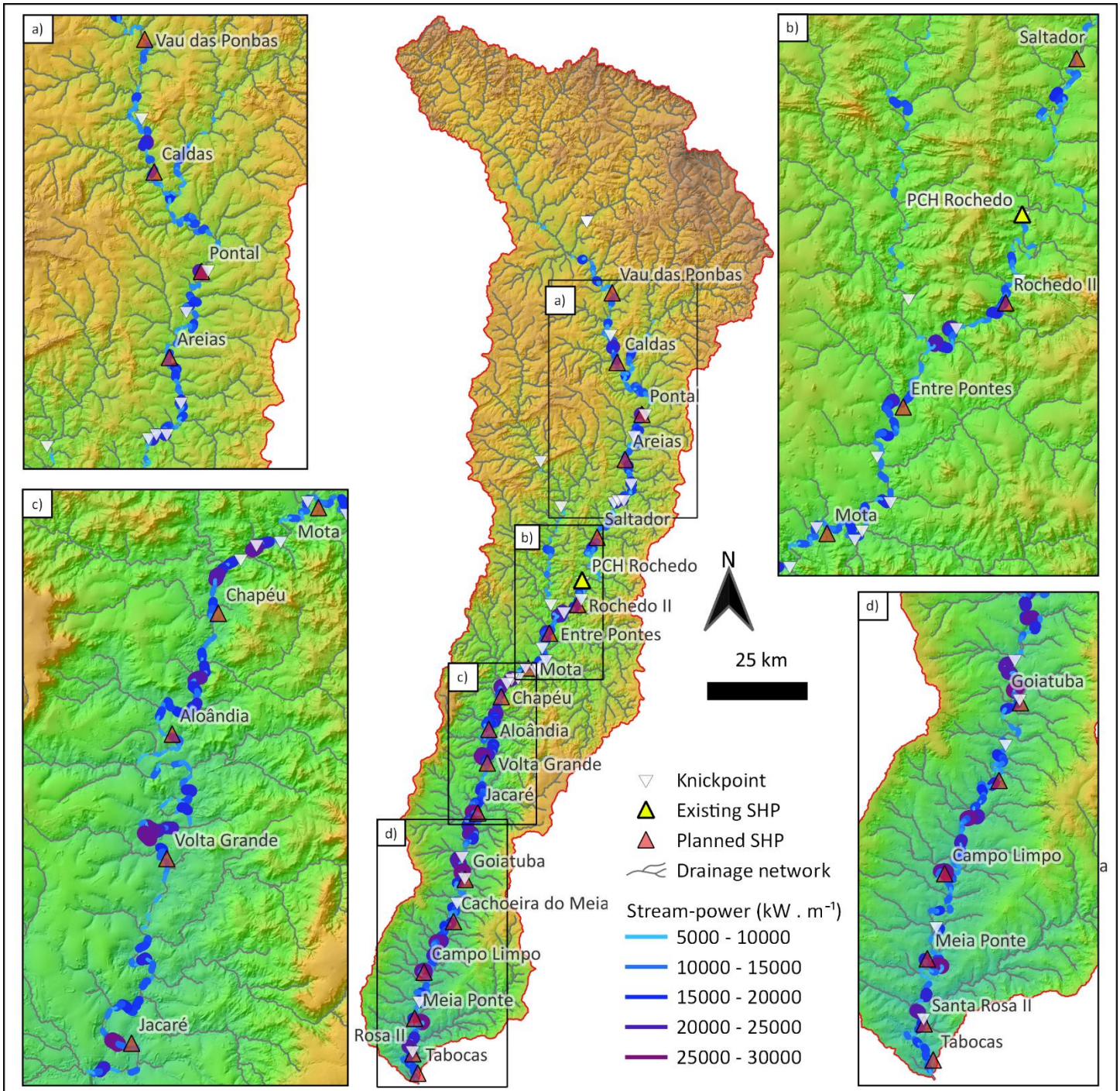
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Figure 5 - Location of SHPs (in operation and planned) and knickpoints along the Meia Ponte River basin, with stream-power segments classified within the intervals of 5000 to 30000 W · m⁻¹. Source: The authors.

IV. DISCUSSION

There is a series of studies in the literature that have used geotechnologies to identify suitable areas for the installation of hydroelectric dams. These studies present different approaches, but most are based on

assumptions where spatialized discharge data and topographic elevation data are used (e.g., GOVERNO DO ESTADO DE SÃO PAULO, 2016; ROSA; FREDDUZZI; CENCETTI, 2019; WEGNER *et al*., 2020). The discharges regionalization for a specific geographical area has generally been carried out using point data from hydrometric stations in combination with contributing area data (or accumulated flow) derived from DEMs (GOVERNO DO ESTADO DE SÃO PAULO, 2016), as done in this study for the Meia Ponte River basin. While some studies focus on using mean discharge values (GOVERNO DO ESTADO DE SÃO PAULO, 2016), others have used the approach of utilizing 70% of the estimated annual mean discharge for the assessment of river energy potential. Examples of the use of this latter approach include the studies by Larentis *et al*. (2010) in the Taquari-Antas basin in Rio Grande do Sul and Wegner *et al*. (2020) in the Paraná 3 basin, western Paraná State. In the case of this study, however, we choose to use the maximum discharge with a 3-year return period, an approach with significant potential application, as observed in previous works (ROSA *et al*., 2019).

Regarding topographic parameters, local relief has been obtained using moving windows on a DEM, calculating the difference between the pixel with the highest and lowest values (GOVERNO DO ESTADO DE SÃO PAULO, 2016), or by analyzing river channel segments (WEGNER *et al*., 2020). In this study, we choose to use slope values directly from digital elevation models (DEMs), considering only the pixels within the river channel to avoid contamination of neighboring pixels due to edge effects. Slope was employed as an indicator of the channel's gradient, which was used to assess the hydroenergy potential of the Meia Ponte River basin.

Some similar studies in Brazil have used a formula to define the average hydropower potential (kWatts) by multiplying discharge ($m^3 \cdot s^{-1}$), the height difference between a section of the river channel (m), and a dimensionless efficiency coefficient, typically around 8.85 (LARENTIS *et al*., 2010; WEGNER *et al*., 2020). In this study, we decided to work with the stream-power model formulation (equation 1) because of its strong physical basis and its widespread application in geomorphological and geological studies of fluvial landscapes (PEIFER; CREMON; ALVES, 2020; PEIFER *et al*., 2022; TORREFRANCA; OTADOY; TONGCO, 2022). In practice, both approaches yield results in different units and are influenced by discharge and channel slope parameters, as the other variables are held constant.

A similar approach to this study was undertaken by Zaidi and Khan (2018) in the Kunhar River basin, northern Pakistan, where they applied a formulation similar to equation 1. They concluded that this approach is more advantageous during the exploratory and preliminary evaluation phase of a hydroelectric project, as it enables to focus only on the most promising locations. In the case of this study, we share a similar perspective,

as the approach used here allowed a cost-effective exploratory analysis within a shorter timeframe, identifying areas suitable for hydroelectric development in the Meia Ponte River basin. However, caution must be taken regarding the obtained scenarios, as regional-scale data were used, and further studies at finer scales are required to achieve a higher level of project detail. Nevertheless, the spatial analysis performed in this study can serve as a basis for the future planning of SHPs, directing activities to specific locations rather than covering the entire watershed, which can help reduce costs associated with field campaigns and human resource allocation.

Despite the increasing demand for new renewable energy sources in the State of Goiás, such as photovoltaic (ALVES, 2018) and biomass (SECIMA, 2018), the potential for hydroelectric power through SHPs cannot be ignored, given the state's high hydroelectric potential. Furthermore, the application of geotechnologies, as demonstrated in this study, has allowed for the assessment of more suitable locations for the installation of such projects. In this regard, the southern part of the Meia Ponte basin, situated away from the metropolitan region of Goiânia and offering lower land prices compared to more urbanized areas, appears to be an area with a greater potential for SHP installation. In this region, where some knickpoints are located (Figure 5d), there are proposals for the installation of two SHPs that are already in a more advanced stage of installation and licensing, such as the Cachoeira do Meia Ponte and Santa Rosa II SHPs (numbers 14 and 17 in Table 1, respectively) (ANEEL, 2021). Additionally, the stretch between the planned SHPs Rochedo II and Chapéu demonstrates significant energy potential and can be further analyzed for SHP construction.

V. Conclusions

The identification of river segments with greater suitability for the installation of SHPs aimed to select locations along the Meia Ponte River with higher hydroelectric potential based on the stream-power model, considering some physical parameters, such as slope and discharge, using data from hydrometric stations and DEMs. Based on the results obtained, it was observed that the Meia Ponte River has over 52 km of river course with river power exceeding 20000 kW · m^{-1}, which represents 33% of the suitable intervals for SHP installation. Initially, these river segments have the highest potential for SHP installation in the Meia Ponte River basin in the State of Goiás.

Although it was not the focus of this study, it is worth noting that other environmental, social, economic, operational, and even cultural aspects should also be considered when seeking to identify the most

appropriate locations for SHP implementation, as they impact both communities and the environment. This study demonstrated that the use of geotechnologies to identify areas with the best energy utilization potential can be a powerful tool for aiding in the selection of areas for further investigation in the future.

Acknowledgments

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