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Tool for Prospecting of Remaining Hydro-Energetic Potential
Ferramenta para Prospecção de Potencial Hidroenergético Remanescente

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Abstract

In the context of renewable energy sources, small hydropower plants are a good cost-benefit alternative and they can be implemented in remote communities that have waterfalls. The objective of this study was to develop and apply a tool in a GIS environment capable of pointing out sites for the remaining hydro-energy utilization in three hydrographic basins based on altimetric data and regionalization of flow rates. The results were verified by comparing hydro-energetic potentials identified with previously inventoried sites. From the comparative analysis, it was possible to identify the remaining potentials efficiently and quickly, being the tool an important instrument to assist in the prospecting of hydro-energetic potential.
Keywords: GIS; Hidropower; Water Resources

Resumo

No contexto de fontes de energia renováveis as pequenas centrais hidrelétricas apresentam-se como uma boa alternativa em relação ao custo benefício podendo ser implantadas em comunidades remotas que disponham de queda d'água. Este estudo teve por objetivos desenvolver e aplicar uma ferramenta em ambiente SIG capaz de apontar locais para o aproveitamento hidroenergético remanescente em três bacias hidrográficas a partir de dados altimétricos e regionalização de vazões. Os resultados foram verificados a partir da comparação dos potenciais hidroenergéticos identificados com locais previamente inventariados. Da análise comparativa realizada verificou-se a possibilidade de identificar os potenciais remanescentes de forma eficiente e rápida sendo esta ferramenta um importante instrumento para auxiliar a prospecção de potenciais hidroenergéticos.
Palavras Chaves: SIG; Hidroenergia; Recursos hídricos

1 Introduction

Together with other renewable sources of energy, small hydroelectric exploitation represent a good alternative to large hydroelectric, thermoelectric and nuclear power stations due to economic, social and environmental factors, as well as market price guarantees, governmental articulation and well defined public policies (Larentis *et al.*, 2010). A small hydropower plant has some advantages over thermal generation, such as lower installation costs, smaller investments for generation and the life cycle of hydroelectric energy is greater than in thermal power station (Abbasi & Abbasi, 2011).

Punys *et al.* (2011) evaluated tools and methodologies for planning small hydropower plants in Canada, Germany, France, the Netherlands and the in United States. They concluded that the main advances in the last decades occurred due to the integration with geographic information systems, as well as the improvement of topographic and precipitation data.

Sachdev *et al.* (2015) presented a review on the main sources of renewable energy and they commented that the small hydropower plants are cost-effective to be implemented in remote communities that have waterfalls. The greatest difficulty of a model is to be able to describe the minimum parameters for assessment of technical viability, such as safety in the supply, sizing of pumps and turbines and scope of changes in the hydrological regime.

The expansion of the hydroelectric system within the sustainability assumptions should be in line with public policies on water resources and the environment, social development plans, international agreements and conventions (e.g. Climate convention). The largest hydroelectric potential in Brazil is found in the Amazon region, some parts in protected areas, Environmental Conservation Units and indigenous lands, which makes the licensing of those large generating units very difficult (Brazil, 2007). Thus, the prospections of small generating units represent an alternative to guarantee and assure the demands for energy.

In the preliminary studies for the prospection of electric energy, the terrain morphology and the flow of the watercourse are relevant. They determine whether the power plant will be high or low, as well as the energy potential and the surface area that will be flooded and will affect directly on the implementation costs of the enterprise due to environmental and land demands.

In a conventional manner, the hydro-energetic potential is identified from the flow duration curve - FDC (Gustard *et al.*, 1992). That methodology was used by Salford Civil Engineering (1989) to identify small-scale energy potential in Scotland (<100 kW), to estimate the base flow index (BFI) and the annual flow from the combination of the use of the soil, average evapotranspiration and standard average annual rainfall.

Hydrobot is a geographic information system to identify hydropower potential in Scotland. The algorithm performs the search from a location and extends up to 1.5 km with increments of 20 meters. Criteria for legal, environmental, and financial constraints were added to the algorithm and the results could be compared with existing schemes (Forrest & Wallace, 2009; Sample *et al.*, 2015).

Simulated hydrological data in the WatBal software were applied to the HEC-5 package (Hydrologic Engineer Center of USACE) to assess the impacts of climate change on the power supply of the Batoka George power plant (1.6 GW) in the United States. The study suggests significant reductions in river outflows that will lead to a decline in the production and sale of electricity as well as impacts on long-term investment projections (Harrison & Whittington, 2002).

Tools for the evaluation of remaining electric power should detect the variability of flow and precipitation due to long-term climate change to support investment projection and in the short-term to ensure stability in the supply and management of resources. Simulations conducted in the Colorado Basin in the United States have shown that the decrease in summer flow was offset by increased winter precipitation, so robust tools for uncertainty analysis are needed (Christensen *et al.*, 2004; Christensen & Lettenmaier, 2007)

The products delivered by geographic information systems (GIS) allow the analyst to evaluate the locations to advance the electric energy expansion projects. However, the uncertainties are associated with the spatial resolution of the images for the construction of the digital elevation model (DEM) that will influence the estimation of the amount of energy to be generated and flooded areas.

The objective of this study was to develop and apply a tool in a GIS environment capable of pointing out sites for the remaining hydro-energy use in three Brazilian river basins. The results were verified by comparing hydro-energetic potentials identified with previously inventoried sites.

2 Materials and Methods

Three hydrographic basins were selected as a study area for the application of the tool. The Hydrographic Basin of Rio Preto located in Minas Gerais State, where there are three electric power generation units: Hydropower Plant (HPP) Queimado, Small Hydropower Plant (SHP) Mata Velha andSmall Hydropower Plant (SHP) Unaí Baixo. The Hydrographic Basin of Alto Teles Pires River located in the Amazonas State, where there is an inventory point (Salto do Magessi) and the SHP Canoa Quebrada; and the Açungui River Basin, between the states of São Paulo and Paraná, with several inventory points.

The methodology for prospecting remaining potentials from digital elevation models by automated GIS procedures initially consisted of obtaining Digital Elevation Models (DEM) from study areas from the Shuttle Radar Topography Mission (SRTM) of February 2000 with a spatial resolution of 1 arc of a second (approximately 30 meters) made available to the region of Brazil from the year 2014. The regions studied include areas where hydro-energetic studies or inventories already existed or where hydraulic works were built for energy utilization after the year 2000, date of the SRTM mission.

The DEMs initially underwent the procedure of removal of areas of depression and small imperfections through the Fill Sinks tool, as described by Taborton *et al.* (1991). That procedure has the purpose of improving the hydrological consistency of the model for the next stage in the definition of flow directions of the DEM. The flow directions were determined, pixel by pixel, taking into account the eight neighbors adjacent to the pixel studied in the direction of greater slope. That procedure is known as FD8 and it was presented by Jenson & Domingue (1988).

Using the topology defined by the calculated flow directions, the cells that contribute upstream to each pixel were counted, generating a raster of accumulated flows. A threshold of 0.5% of the cumulative value in the mouth of the study basin was used for the selection of the synthetic drainage network pixel. The gaps between the upstream and downstream pixel were then analyzed only along this drainage network.

By means of a map algebra operation, the dimension value (corrected by the Fill Sink) was assigned along the drainage. In order to calculate the difference, it was necessary to define the pixel dimension values immediately downstream. When analyzing a single pixel along the drainage network between its eight possible neighbors, necessarily the neighboring pixel of lower dimension value corresponds to the downstream pixel. In order to identify that pixel, it was used a spatial analysis function called Focal Statistics, in which the 3x3 pixel area was defined as the analysis window and the minimum function to identify the downstream dimension value. That methodology was presented by Carvalho Jr. *et al.* (2008).

The calculated slope value (H), for the subsequent evaluation of the hydro-energetic potential, it is the result of a map algebra operation consisting of the subtraction of the dimension raster and the upstream dimension plus a constant value, which is a parameter defined by the analyst and it corresponds to the maximum height allowed for the dam.

For the calculation of the flow, the regionalized flow value was used as reference value for the area of the hydrographic basin of interest according to the respective areas of contribution.

From the spatial resolution of the DEM, the corresponding area of one is calculated. By multiplying the value of the pixel area by the raster of accumulated flows of the drainage network, by means of a map algebra operation, the contribution areas for each pixel of the drainage network are calculated. Applying the regionalization coefficients, the flow values are obtained at each pixel of the drainage.

With the rasters referring to the unevenness and the flow, the equation 1 can be applied to establish the potential.

$$P = \rho.Q.H.\eta \qquad (1)$$

P is the hydro-energetic potential [MW]; ρ = specific weight of water [$Kg.m^{-3}$]; Q = flow [$m^3.s^{-1}$]; H = slope [m] and η = yield of the turbines.

With the established potentials, it was possible to select those that have the highest values by means of a predetermined parameter that represents a percentage on the highest calculated potential. The selected sites were then converted from raster format to a vector and their attribute table was filled with dimension values, slope, flow, flow directions and potential.

From the coordinates of the selected points, lines representing the dam at each point are constructed, perpendicular to the lines defining the drainage network, with lengths pre-established by the analyst, in number of pixels always odd (1, 3, 5, ...). Thus, each dam has as an attribute of the quota of the dam, the quota value in the drainage network and the value of the height of the dam previously defined.

Polygons that surround the dam lines are then built through buffer with one pixel distance and those are converted to raster with calculated dam quota values. With that raster, the hydrologically consisted DEM (DEM Fill) is altered so that it incorporates the dam quota values. Where there are no dams, the DEM does not change, and in the places where the dams were selected when the DEM value is lower than the raster value of the dams, the dam is the one that passes to the new modified DEM.

From the new DEM and the dam dimension values, one must then identify the cells that constitute Sinks (depressions). For those cells, the upstream areas constituting the respective watersheds (contributed hydrographic basin of each Sink) are determined. Therefore, due to the modifications incorporated to the DEM, a new map of direction flow must be constructed.

By means of raster values of dam dimensions, these values are transferred to the watershed raster and the cross between that raster and the consisted DEM (subtraction between both), it can be determined the flooded areas as a function of the dams by selecting the pixels that result in negative values when subtracting, which are the depth values. The absolute value of the depths multiplied by the pixel area results in the flooded volume in each pixel, which will later be aggregated for each reservoir resulting in its total volume. From this selection, the depth raster is converted into polygons (vector), which are aggregated as a function of the respective identifier to each dam. Thus, the attribute table may contain the area and volume values of the reservoirs of each dam.

In order to automate the procedures, to allow better efficiency and to minimize the processing time, a tool was built in the ArcGis software through a functionality that allows creating models from flows that join a sequence of tools, necessarily present in the ArcToolbox, and the database. Model Builder allows creating workflow routines and new tools, and even integrates scripts into the flowchart. The complete flowchart of the developed tool involves 39 spatial analysis operations between map algebra and attribute selections and GIS format conversions. It also includes a Python language script that was written specifically to generate the dam lines at each selected site, operating directly from the coordinates of the start vertices and the end of the dam, starting from the coordinates of the site and the number of cells established for the dams, as well as their spatial resolution.

3 Results and Discussion

The Rio Preto watershed is part of the Area of the Plateaus in Concordant Sedimentary Structures that covers the Goiás Minas Plateau, with altitudes ranging from 400 to 1400 meters (Brazil, 1982). The geomorphological compartmentalization is subdivided into five classes: Upstream Plateau, Dissected Plateau, Peak of the Unaí, Terraces and Fluvial Plain downstream where it flows into the Paracatu River, Minas Gerais (Borges, 2007).

Figure 1 shows the regionalization for the flow with permanence of 90% (Q_{90}%) of the data from the monitoring stations of the Rio Preto Basin in the state of Minas Gerais. In addition, Figure 2 displays the map with the places where there is the potential energy.

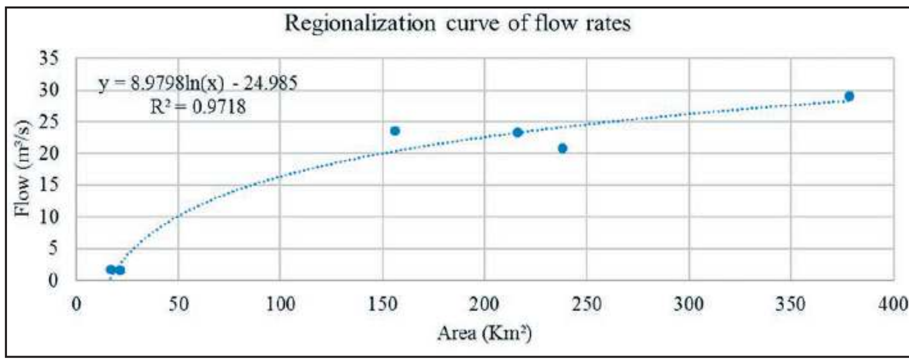

Figure 1 Regionalization curve of flow rates of Rio Preto, MG.

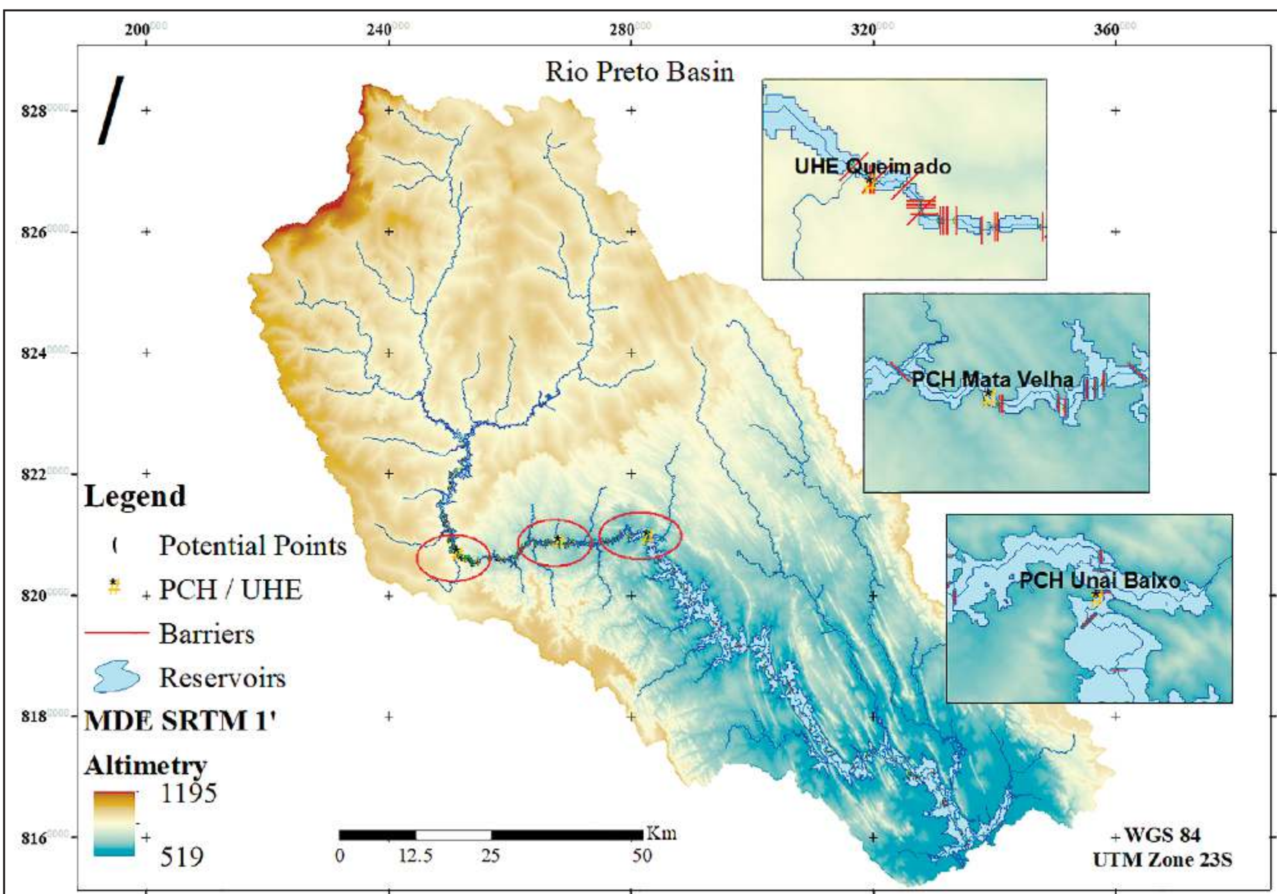

Figure 2 Map of places where there are potential energy in Rio Preto, MG.

The geomorphology of the upper basin of the Upper Teles Pires River called the Graben of the Caiabis formed by sedimentary rocks of the Caiabis Group, which in the edges form plateaus with average elevations of 500 meters and, in the interior, the plateaus formation predominates (Bias *et al.*, 2006). Figure 3 shows the regionalization of the flows ($Q_{90\%}$) of the Alto Teles Pires River stretch in the Amazonas State according to the data of the fluviometric monitoring stations of the National Water Agency (ANA, 2014).

Figure 4 displays all the potential energies of the Alto Teles Pires River identified by the tool according to the parameters provided in Configuration 1. The data processing took 26 minutes to complete all the calculations. The relief of the Teles Pires River basin is not very rugged, so even low dams generate large flooded areas and high potentials due to the high flows present in the basin. The inventory presented by the Energy Research Company 2005 already indicated the construction of UHEs in the basin with run-of-river configurations. The PCHs Canoa Quebrada (built) and Salto Magessi (inventoried) were identified by the tool. In addition, many points were identified at the mouth of this sub-basin, which is in the area covered (flooded) of the Sinop HPP.

Altering the configuration of height of dams and minimum slope (configuration 2), a new map of the potential energies of the Alto of Teles Pires River basin was obtained (Figure 5).

The Açungui River Basin is located in the geomorphological unit called First Paranaense Plateau, with a predominant declivity class of 6%, varying in altitudes from 560 to 1240 meters (Paraná, 2006a). The permanence curve of the Açungui River is shown in green in Figure 6, according to the flow studies of the surface of the Upper Iguaçu basin and the tributaries of the Upper Ribeira River (Paraná, 2006b).

The specific flow for the Açungui River is calculated by the equation 2.

$$Q_{spec\%} = -12{,}81 * \mathrm{Ln}(per\ \%) + 63{,}588 \qquad (2)$$

$Q_{spec\%}$ is the specific flow for the retention time (% PER) in $L.s^{-1} * Km^2$ and %PER is the retention time for a percentage value between 1 and 100.

Figure 7 show the results of the calculation of the potential energy for the Açungui River. After the selection of some points, new calculations were made for the formed reservoirs, as shown in Figure 8.

It noteworthy that, for the three study areas, the tool pointed to possible hydroelectric potential points close to places where there are Small Hydroelectric Plants already installed or inventoried. It demonstrates that the tool can help managers in the preliminary definition of areas that provide greater potential in the generation of energy, thus taking better advantage of the flooded area. Obviously, such a tool does not eliminate fieldwork since there is need for hydrosedimentological studies.

4 Conclusion

The proposed tool for the location and the calculation of the hydro-energy potentials proved

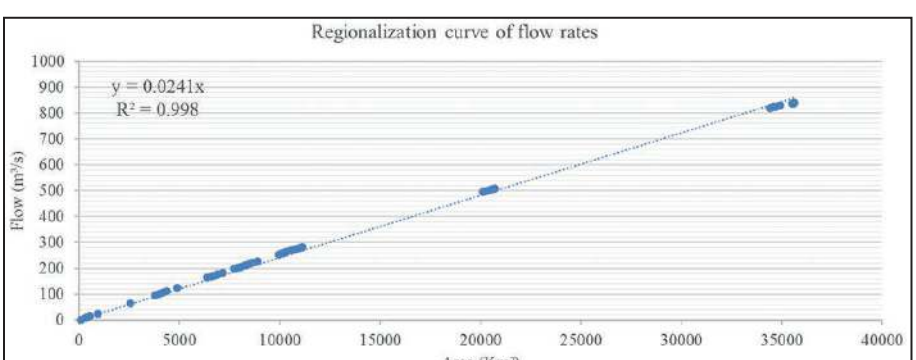

Figure 3 Regionalization curve of flow rates of Upper Teles Pires River

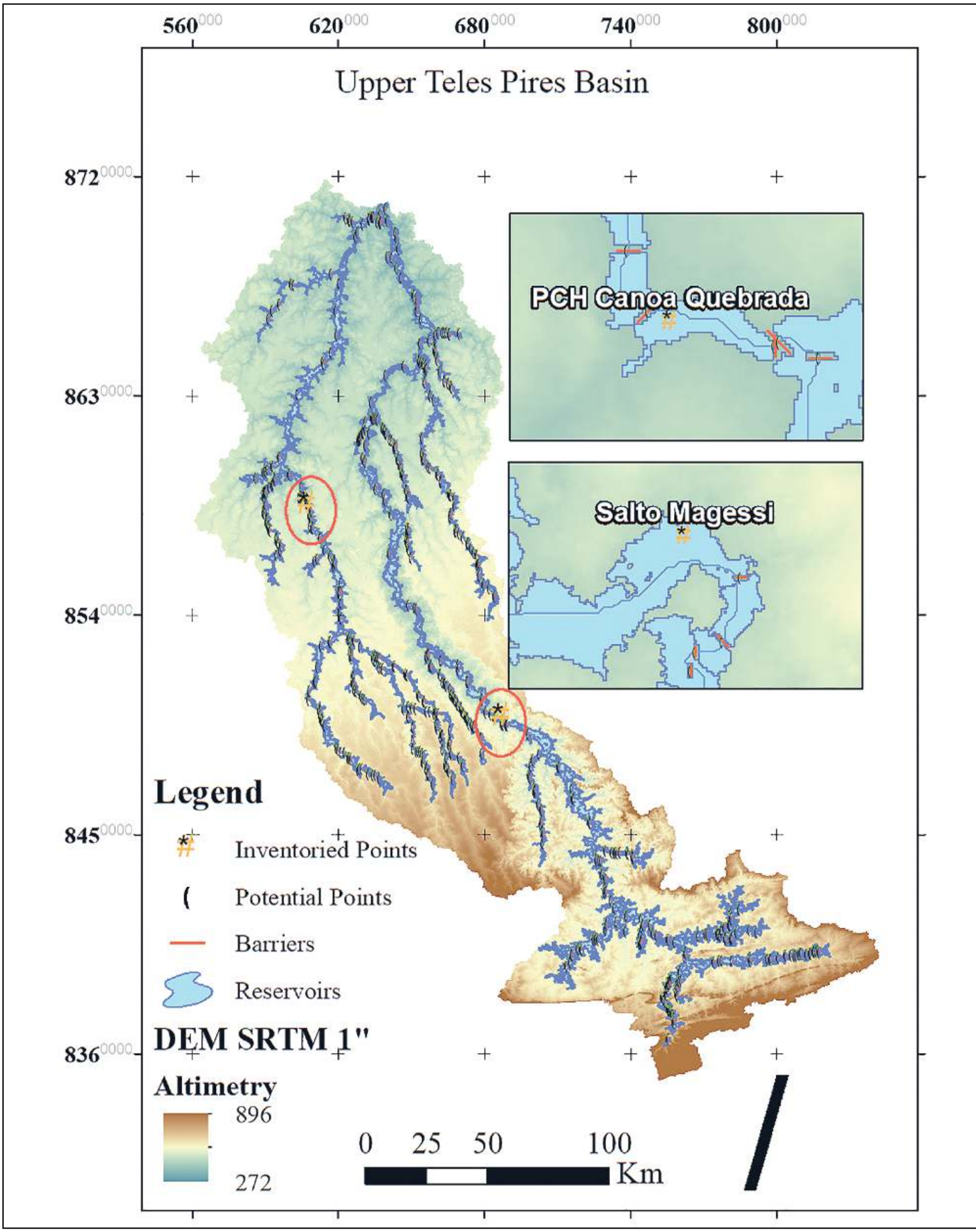

Figure 4 Map of the hydro-energetic potentials of the Upper Teles Pires River, AM in configuration 1

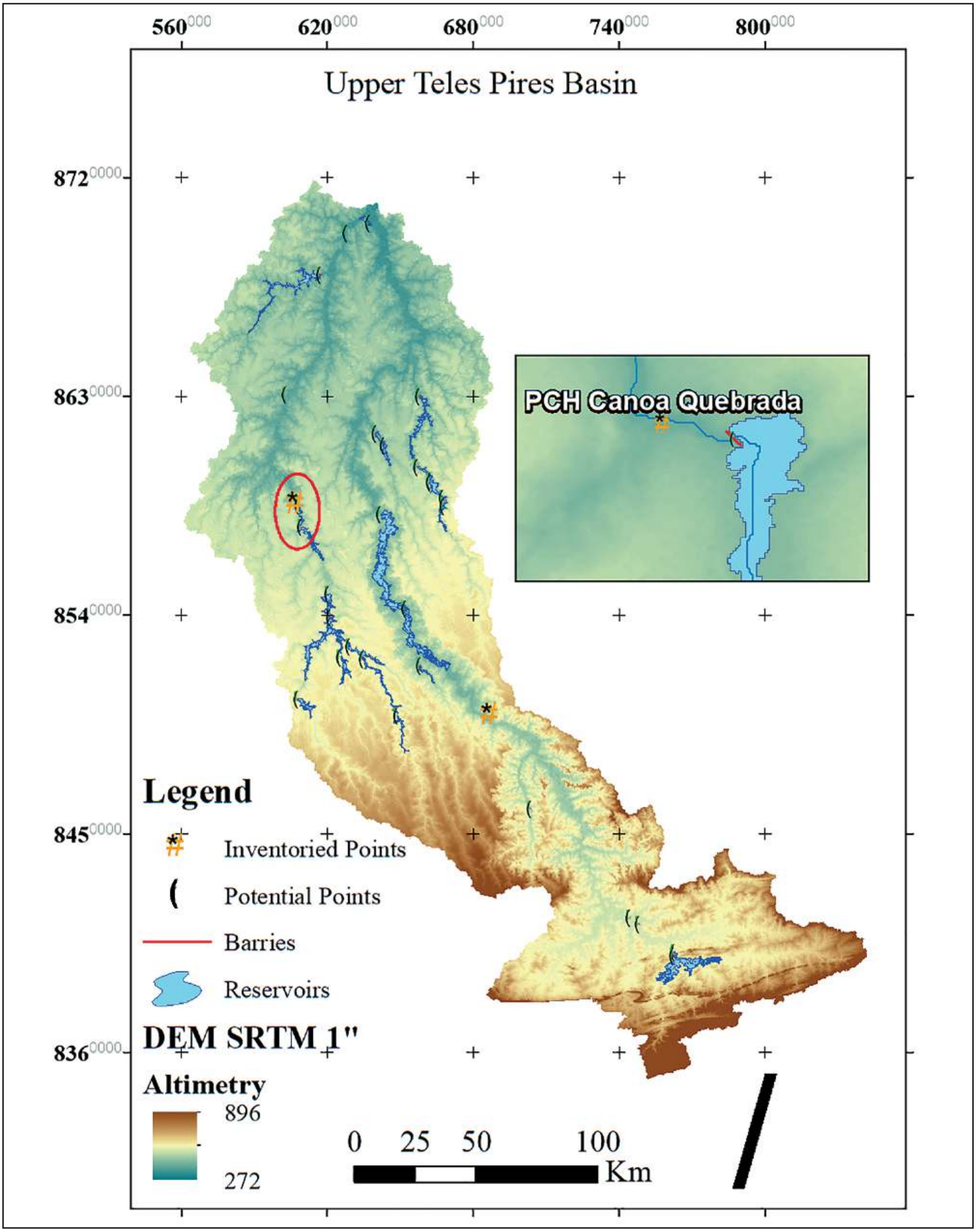

Figure 5 Map of the hydro-energetic potential of the Upper Teles Pires River, AM in configuration 2

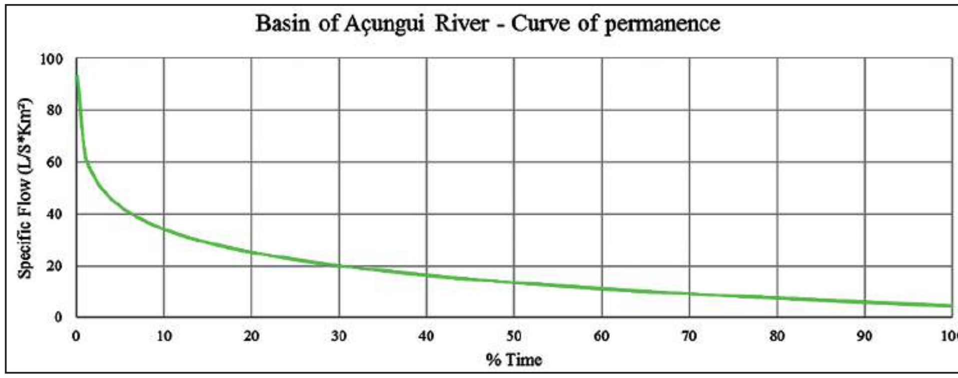

Figure 6 Curve of permanence of specific flows of the Açungui River (in green).

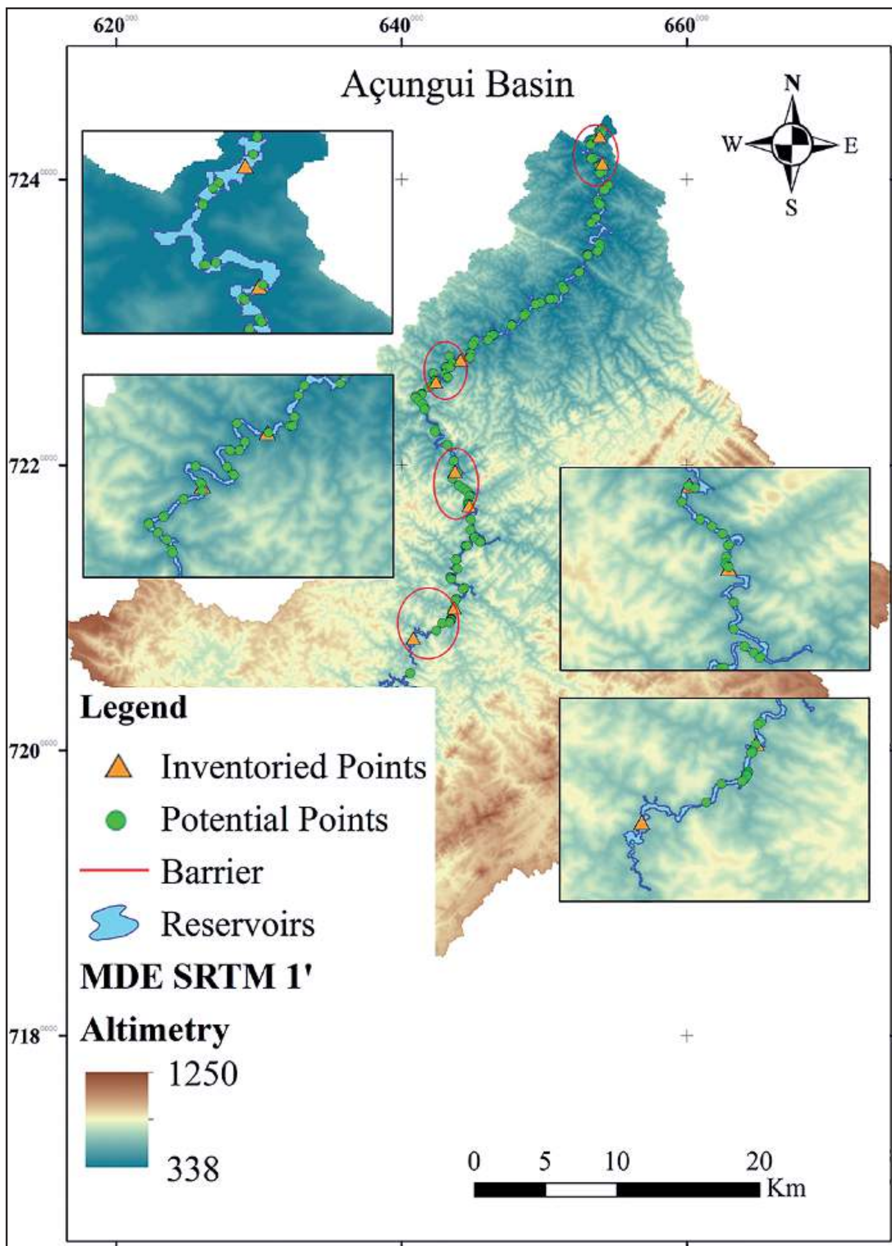

Figure 7 Map of all of the hydropower potential of the Açungui River

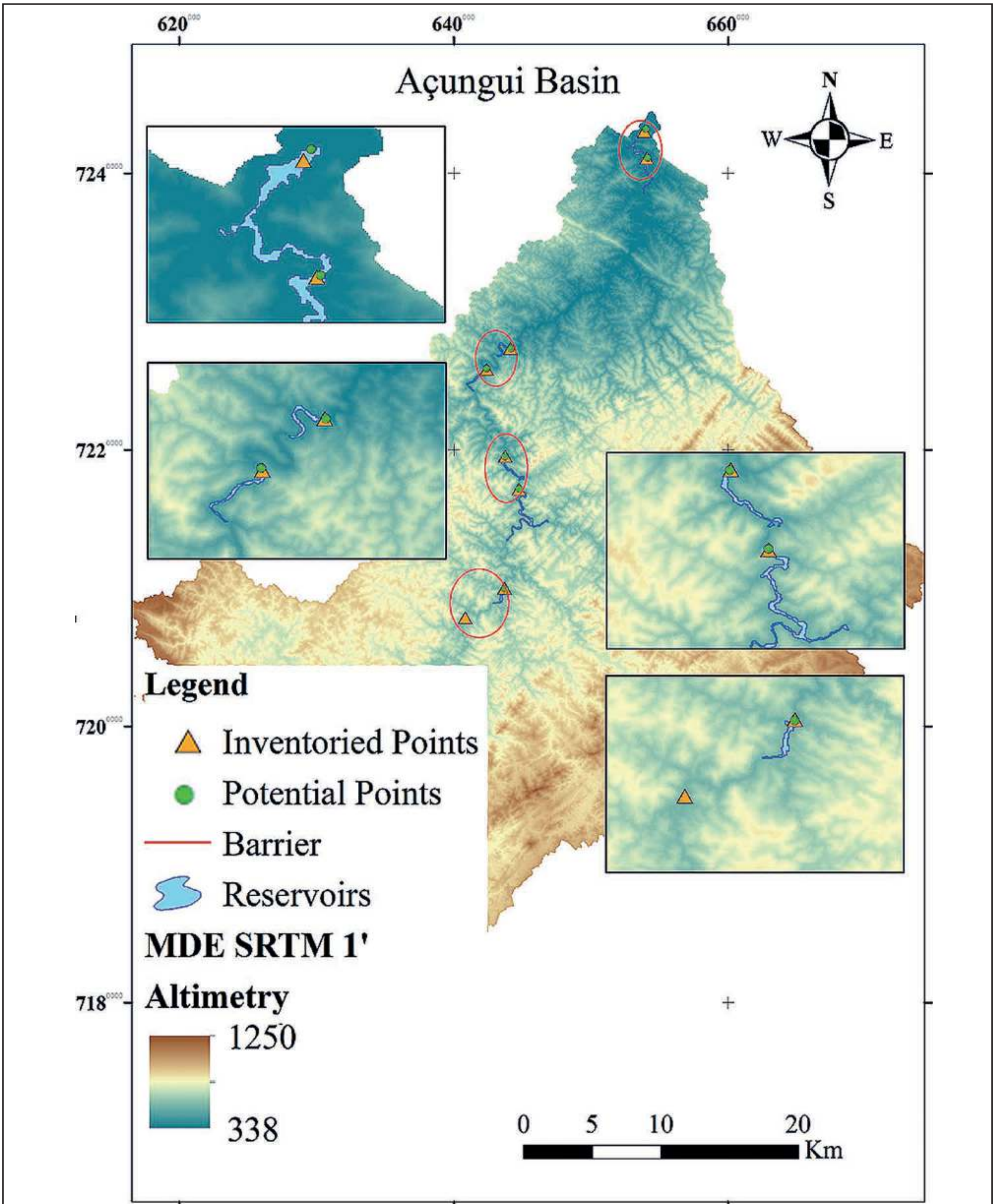

Figure 8 Map of the hydropower potential after recalculation

to be very effective, since it was able to identify, in the studied basins, the points where inventories were already carried out and the power plants were installed in a fast and automated manner.

The spatial resolution of the digital terrain models and the consistency of the flow data influence the accuracy of site identification and estimation of potentials, as well as the configurations in terms of height and size of the dams. The obtained results showed that this tool assists in the preliminary evaluation of the hydropower potential for any basin of interest.

Once the locations of the largest remaining hydroelectric potential have been identified, efforts can be made to investigate other variables such as environmental impacts, climate change effects on pluviometric indices, flow, sediment production, costs and amortization of investments.

5 Acknowledgments

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