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Gis-based procedures for hydropower potential spotting

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ABSTRACT

The increasing demand for energy, especially from renewable and sustainable sources, spurs the development of small hydropower plants and encourages investment in new survey studies. Preliminary hydropower survey studies usually carry huge uncertainties about the technical, economic and environmental feasibility of the undeveloped potential. This paper presents a methodology for large-scale survey of hydropower potential sites to be applied in the inception phase of hydroelectric development planning. The sequence of procedures to identify hydropower sites is based on remote sensing and regional streamflow data and was automated within a GIS-based computational program: *Hydrospot*. The program allows spotting more potential sites along the drainage network than it would be possible in a traditional survey study, providing different types of dam-powerhouse layouts and two types (operating modes) of projects: run-of-the-river and storage projects. Preliminary results from its applications in a hydropower-developed basin in Brazil have shown *Hydrospot's* limitations and potentialities in giving support to the mid-to-long-term planning of the electricity sector.

1. Introduction

Unlike the assessment of single hydropower projects, in which the site is defined and other boundary conditions are set, a river basin survey poses a type of problem where the location of projects is unknown and the energy output in each site depends on the other reservoirs planned in the same basin and their flow regulation capacity. Besides, the integrated environmental and technical assessment involves the evaluation of multiple criteria and spatially-distributed data [1–4].

Even though a preliminary indoor selection of potential sites that relies on existing geographical and hydrological data does not dispense fieldwork, it might significantly reduce costs and efforts in further analysis and investigations [4]. A thorough conduction of the site survey phase will give decision-makers the suitable grounds to reach the final set of alternatives with the least impact of the hydropower development over other activities, existing infrastructure facilities and the environment [5].

This paper concerns the research about hydropower survey in large-scale. The hydropower potential survey methodology – *Hydrospot* – comprises from the earliest identification of promising sites in the river basin to the multi-criteria pre-feasibility assessment and selection of the final set of projects. The methodology is intended to be applied in a stage of planning in which the integrated assessment of energy aspects and technical, economic and environmental fragilities could be effectively taken into account in the definitive solution of the river segmentation.

In this paper we describe in detail the GIS-based procedures for hydropower potential sites spotting and selection, and present the preliminary results we found, comparing them with those obtained from an existing hydropower survey study in Brazil.

1.1. Opportunities for small hydropower development in Brazil

The Brazilian electricity grid is predominantly hydro powered, with the hydroelectricity share corresponding to approximately 90% of the production in the country [6]. Brazilian hydropower capacity is estimated in 260 GW, from which approximately 75 GW (30%) corresponded to the installed capacity in 2006. Only about 2% of this amount refers to small hydro plants, a total of 253 units with capacity between 1 and 30 MW. The largest share comprehends 105 large plants with capacity ranging from 30 MW to 14 GW, connected to the national electric grid [7].

In general, as in other countries with hydropower endowment, in Brazil large hydropower projects have been already developed or, at least, spotted and well documented. On the other hand, during the recent, long period of restructuring of the Brazilian electricity sector, new large-scale hydropower survey studies experienced very few investments. Nowadays, those studies are being resumed with the focus on small hydro projects [8].

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The national scenario of economic prosperity and the uncertainties about the feasibility of the undeveloped potential to be explored in the long-term (2030 as the planning horizon) [7] suggest that there are opportunities to study and develop procedures to locate small to mid-size potentials (up to 50 MW). These studies could be used as a basis for feasibility and selection studies currently practiced in Brazil [9].

1.2. GIS technologies for hydropower survey studies

Increasing availability of satellite imagery information and easiness of data processing in computational-GIS environments have allowed the development of a number of methodologies for the extraction of terrain characteristics from DEM (Digital Elevation Models), as drainage network position, length and slope [10–14]. For large-scale hydropower estimation purposes, water head may be extracted from DEMs using GIS tools in a quick and reliable fashion, suitable for preliminary studies [1–3,15–19].

GIS-based tools and remote sensing data applied to hydropower survey studies have found room in a sector that has been very orthodox in the assessment tools and source of information. Those technologies have been employed in different countries in order to locate and select hydropower opportunities of different types, such as pumped hydroelectric energy storages in Ireland [18], small run-of-the-river projects in Thailand [2], US [17] and Brazil [15], and storage capacity dams in India [1], Brazil [19], South Korea [3] and South Africa [5].

2. Methodology and tools

Hydrospot consists of a series of FORTRAN routines with input and output maps in ArcGIS' ASCII format. Besides DEM pre-processing, we automated into the program both main modules that compose the methodology:

- *Survey*: a large number of project alternatives are spotted in the river basin through DEM automated assessment, with regional streamflow and excluded-zones maps;
- *Selection*: all alternatives of hydroelectric power plants that were raised are ordered for test and selection, resulting in a set of plants in the basin and its respective total potential.

The program supports:

- all combinations of potential (small to large), head and power (high and low);
- different plant layouts (derivation either by tunnel or through the riverbank or generation at the toe), varying dam height and longitudinal length and headrace length and path;
- two types of operation (run-of-the-river and storage). Statistical values of streamflow derived from the long-term average and the flow-duration curve are used, so operation rules of storage projects are not able to be represented.

2.1. Survey procedures

As shown in Fig. 1, the steps in the survey phase are:

- Finding the site of the dam (weir);
- Locating the site of the powerhouse;
- Checking the gross natural potential;
- Developing a dam and reservoir lake.

2.1.1. Dam axis spotting

The algorithm runs a search along the drainage network pixel by pixel, or within a distance defined as one of the methodology parameters, as shown in Fig. 2.

The system is spatially represented by sub-basins, which is accomplished in a previous step (pre-processing), according to the Otto Pfastetter method [20]. This method provides a logical and hierarchical codification of river reaches so that the drainage network will be queried by each algorithm from upstream to downstream, according to the sub-basins Otto-ID number, avoiding double processing.

2.1.2. Powerhouse spotting

Each pixel defined as dam axis has its DEM neighborhood queried in order to identify the powerhouse site, which is found with the best relation between head (vertical distance between dam axis and powerhouse) and slope, defined by the greater value of their product (Fig. 3, Case B). This assumption prevents the algorithm from seeking the highest head (usually the farthest point) at any cost (Fig. 3, Case C).

The lookup neighborhood is defined by a circular area around the axis of the dam, as adopted by Rojanamon et al. [2] and Yi et al. [3]. Its radius is one of the parameters of the methodology and can be interpreted as the maximum headrace length admitted in the basin.

The idea of setting a maximum headrace length was used in other methodologies [1,5,17]. Nevertheless, the assumption that the headrace runs along the river (Fig. 3, Case A) does not allow the representation of cut-off schemes (Fig. 3, Cases B and C), which is possible with the round buffer approach.

The headrace length parameter might vary between different sub-basins depending on geographical characteristics, such as how much a river meanders, and practical engineering issues, such as head losses, and costs. The combination of headrace length and downstream step parameters is determinant in order to spot cut-off alternatives.

2.1.3. Gross potential threshold check

The gross potential due to the terrain head is only calculated for the dam-powerhouse alternative. This test allows the exclusion of sites where the terrain characteristics are not favorable at all.

2.1.4. Dam development and reservoir inundation

The dam vertical development procedure is iterative with the reservoir inundation rule. For every raise of the water level, a raster mask equivalent to the projection of the lake and obtained by filling the DEM up to the current elevation, is obtained. Each water level in a given site configures a project alternative.

A dam expansion is performed when the addition of an incremental head to the water level of the reservoir causes it to exceed the lowest terrain elevation on the dam abutment projection. When the dam is raised above the water level it also has to be extended laterally, getting projected beyond the farthest pixel of its axis to both sides.

The lateral development of the dam starts when the program seeks the highest pixel adjoining the dam axis, leftwards and rightwards. In order to avoid referencing problems that could occur because of the orientation of the river flow, instead of left and right, the algorithm works with clockwise and counter-clockwise riverbanks, using the flow direction map as a reference (Fig. 4.a). If there is no elevation difference among the pixels in the queried neighborhood, the pixel perpendicular to the axis is chosen. The searching procedure continues by querying the DEM in the vicinity of the dam ends (Fig. 4.b). A queried pixel is valid as long as:

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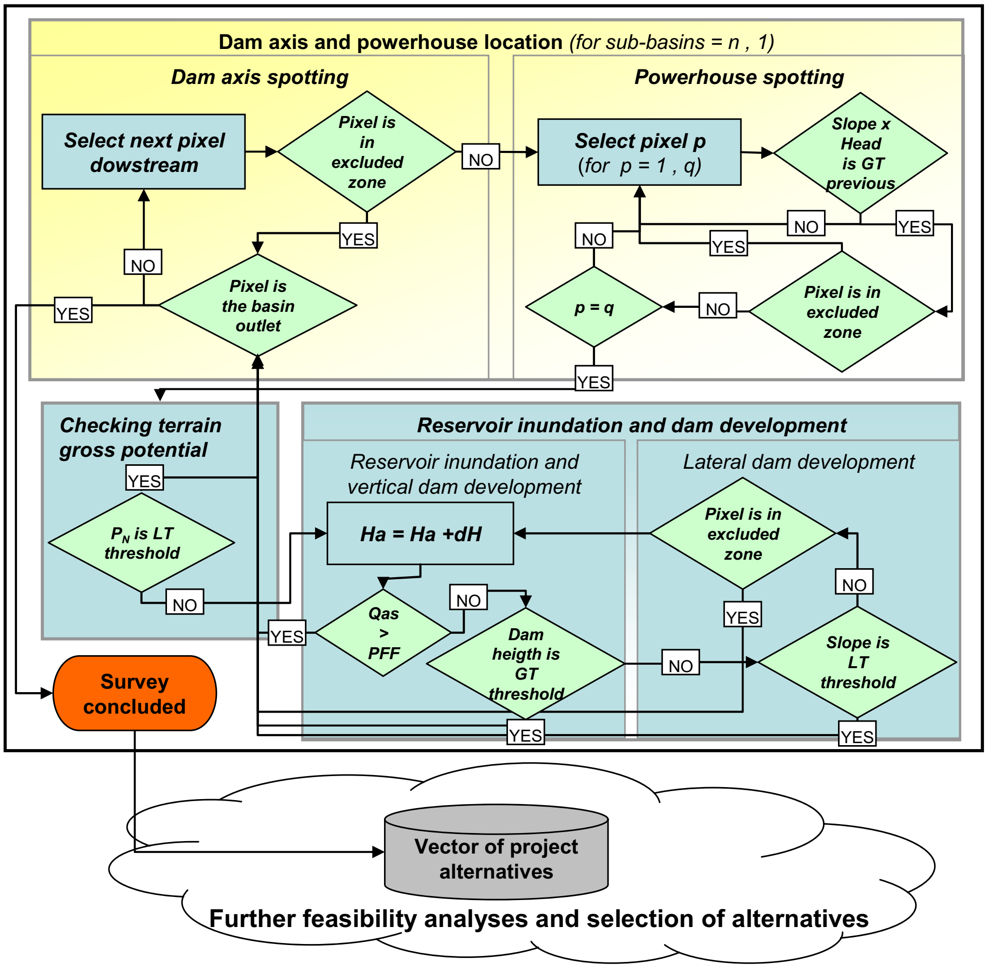

Fig. 1. Scheme of procedures and criteria in hydropower potential survey.

- It does not belong to the drainage network; this prevents the dam projection from being defined on the drainage system;
- It was not defined as a dam in a previous step; this avoids an overlapping of dams.

At any time within the whole procedure, when a stop criterion is reached, the development of the dam is interrupted and the dam projection gets defined. Stop criteria are defined by the following preset conditions:

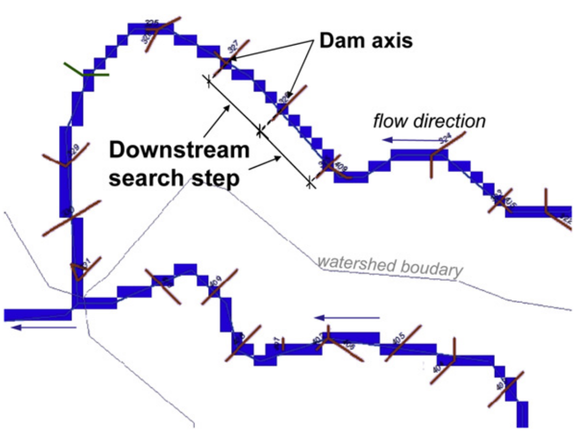

Fig. 2. Downstream search of dam axis.

- The maximum (dam) technical height, which depends on regional and geotechnical aspects, available construction technology and engineering expertise. If the dam height equals or exceeds the maximum technical height, stop condition is reached;

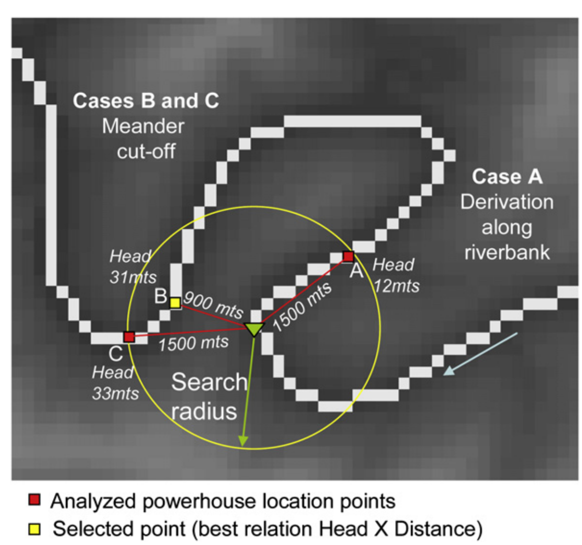

Fig. 3. Search of powerhouse location.

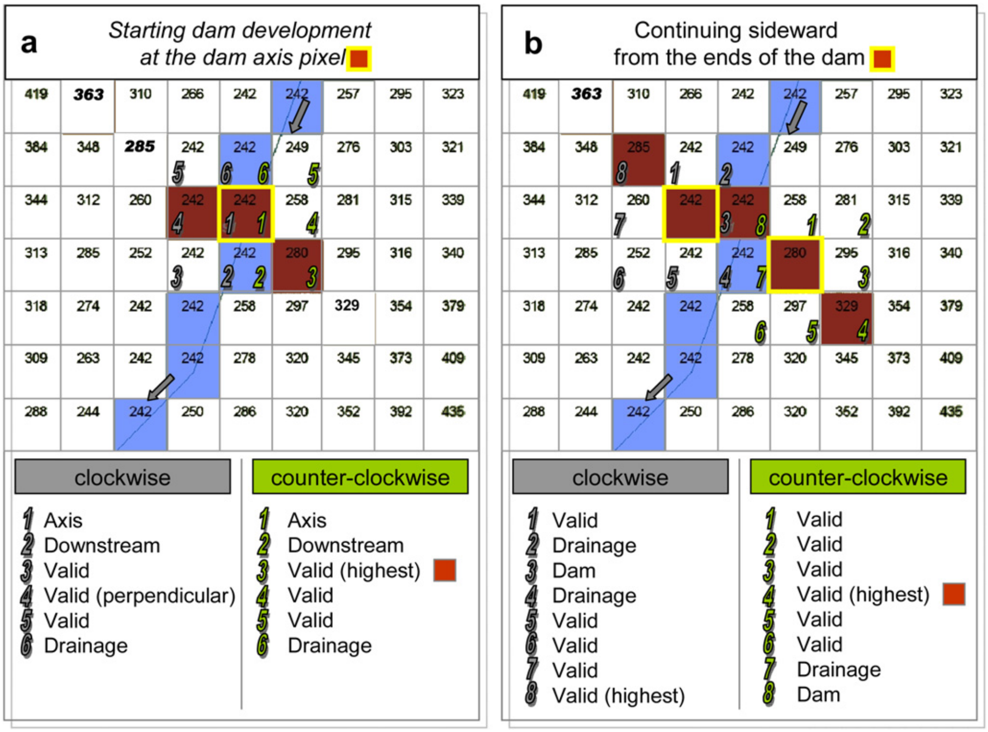

Fig. 4. Dam development procedure.

- The minimum slope admitted, referring to the longitudinal development of the dam structure, consequently to the river cross section. This criterion can be used to avoid the dam to be extended in excessively plain areas, what would not be economically efficient;
- The PFF (Potential Firm Flow) that contributes to the cross section. One reservoir cannot regulate the river flow by a rate above PFF. So, when a reservoir reaches its maximum storage volume, defined by PFF integrated along the critical hydrologic period, such reservoir is complete and dam development stops.

PFF is previously calculated for every gauging cross section in the river basin and regionalized through the entire basin. PFF estimation is accomplished by optimizing the average potential at a gauged cross section, based on the sequential streamflow routing of its discharge time series. The demanded discharge is tested in different scenarios in which the average potential is calculated for the simulated period (available data). When the discharge rate is raised, there is a point where the average head in the reservoir will be too low and the average potential will start to fall. This is assumed to be the optimum discharge rate at the cross section, or the PFF. PFF values are usually found between 70 and 80% of the long-term average discharge.

2.2. Selection procedures

The hydropower potential of the whole basin is obtained through a process of selection of project alternatives. As illustrated in Fig. 5, the selection algorithm performs the following steps within each new implementation cycle:

- Site potential evaluation;
- Ranking and pre-selection;
- Interference tests;
- Flow regulation and at-site potential optimization;
- Hydropower evaluation of the river basin;
- Update of the vector of project alternatives.

2.2.1. Site potential evaluation

The net hydropower potential of a given project alternative is calculated by

$$P_N = Q_T \cdot Ha \cdot 8.85 \qquad (1)$$

where P_N is the average net potential [kWa]; Ha is the average net water head [m]; and Q_T is the average discharge passing through the turbines [m3/s], given by

$$Q_T = Qas + Qacc_U + Qf - Qreman - Qcons_U \qquad (2)$$

where Qas is the average regulated streamflow in the reservoir, $Qacc_U$ is the discharge rate due to the flow regulated by other projects upstream the site; Qf is the natural firm flow at the cross section (as a rule of thumb it may be assumed as the 95%-duration discharge); $Qreman$ is the streamflow that remains dowstream the dam (in the cut-off river reach), calculated as a fraction of Qf; $Qcons_U$ is related to the consumptive demand upstream the plant. Both Qas and $Qacum_U$ are obtained as a function of the maximum depletion of the reservoir and limited by the PFF that may be stored within a period of one year.

2.2.2. Pre-selection

While the hydropower potential for every alternative is being calculated, the alternatives are put in a sequence according to their net potential. At every new implementation cycle the alternative with the highest potential in the vector is chosen for testing. The first alternative is selected based on its stand-alone potential. The following selections will take into account a regulated flow component at each site.

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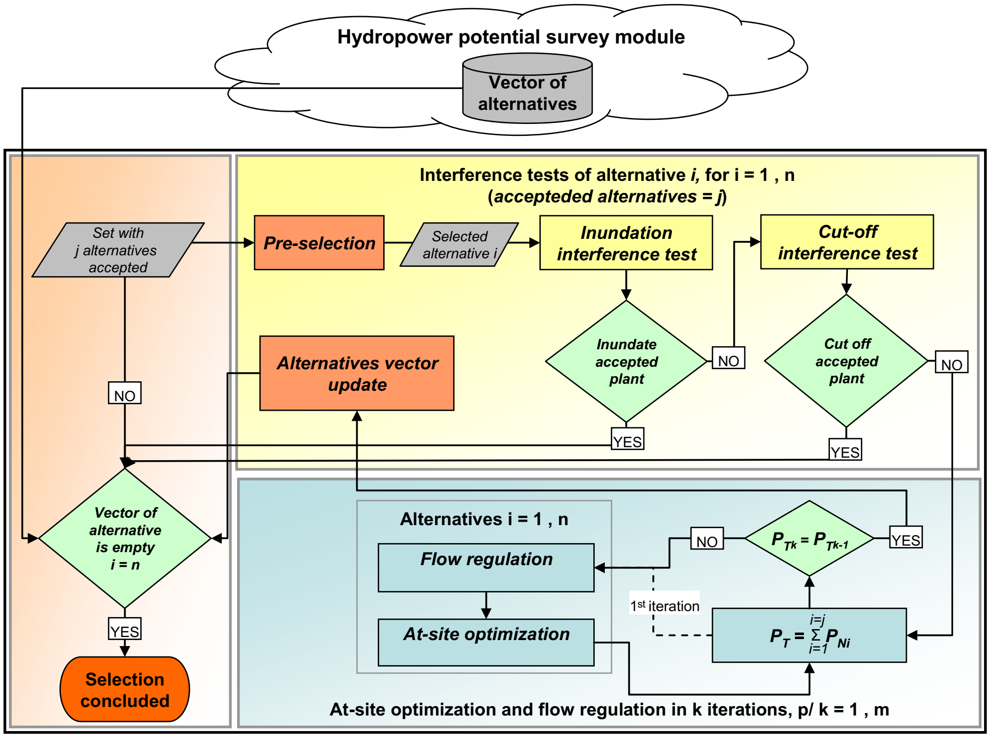

Fig. 5. Scheme of procedures and criteria in hydropower potential selection.

2.2.3. *Pre-selected project interference tests*

A pre-selected project alternative is submitted to two interference tests:

- by inundation: in which the water stage of the project exceeds the elevation of a powerhouse located upstream;
- by cutting off: in which there is a plant located in the bypassed river reach.

In case of interference, the alternative under analysis is discarded. If accepted, it gets included in the final set. Depending on the value of the downstream step, a large number of alternatives might get lined up along the drainage network during the survey phase, increasing the computational efforts with interference tests.

2.2.4. *At-site optimization*

The at-site optimization is the procedure to obtain *Qas* and *Ha* for a given project alternative. This is done by testing different maximum water depletions in the reservoir. The relation *Volume-Water Stage* for every site was obtained in the survey phase, in the dam development and reservoir inundation step, which means there is a known *Qas* for every maximum depletion.

The gross head is calculated by maximum water level minus half the depletion. If there is a cut-off scheme, the natural head is added. *Ha* is obtained by applying a 2% head-loss factor to the gross head. The maximum at-site potential is obtained for the "optimum" relation between regulated flow and water head, i.e. *Qas* and *Ha*. Finally, the plant hydropower potential is calculated through Eq. (1).

2.2.5. *Flow regulation*

The flow regulation algorithm allows us to configure one plant to influence the energy production in other ones located downstream. When a new plant is added to a system, its regulated releases will provide an opportunity for a downstream generation increase and the new dam will configure an extra head for volumes stored upstream to flow through. This means that the order of implementation is important.

Let us consider a river reach with only two possible alternatives, as illustrated in Fig. 3: if case 1 is implanted, the project located downstream (case 2) would have the regulated discharge of case 1 ($Qacc_U$) added to its Q_T, following Eq. (2). Then case 1 would have discharge regulated by other plants upstream added to its Q_T.

2.2.6. *River basin potential evaluation*

The flow regulation and at-site optimization procedures are the core of the selection algorithm. Every time a plant is accepted, stored volumes are reallocated through the basin, from upstream to downstream. The P_N of every alternative already accepted or yet to be tested is updated for the new configuration of stored volumes and heads. Within this process, the at-site optimization is lost and the P_N has to be optimized again for every site, this configuring an iterative process between at-site optimization and flow regulation procedures. The purpose of the objective function is to minimize the difference between the value of the total potential in the river basin before (trial) and after every flow regulation and at-site optimization cycle. In a scenario with n alternatives accepted and included in the final set of projects, the total potential is calculated by the simple sum of every P_N in the basin.

2.2.7. *Update of the vector of project alternatives*

Untested alternatives that interfere with the accepted plant are discarded. Interferences could happen by inundation, meander cut-off or by location in the same site as the accepted alternative (another maximum water stage).

3. Case study, results and discussion

Preliminary tests of *Hydrospot* were carried out in the Taquari-Antas river basin, located in the south of Brazil as shown in Fig. 6.

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Fig. 6. Taquari-Antas river basin location.

The basin has a drainage area of 26,500 km^2, presenting in its middle third narrow and steep valleys and a sinuous drainage network where the discharge and water levels can vary abruptly during the whole year. The long-term average discharge is 633 m^3/s.

The hydropower potential of Taquari-Antas has been studied since the first half of the 20th century. In 1993, a comprehensive inventory covering the upper two thirds of the basin (18,600 km^2), which the local energy company – CEEE – considered as having potential for hydropower production [21], was performed.

A basin spatial discretization equivalent to a level 2 Otto Pfafstetter division was adopted. The used DEM was an SRTM 3" acquired in January 4, 2000, before any plant had been constructed. The parameters for the survey phase were set as follows:

- Downstream step: 450 mts
- Headrace length: 1800 mts
- Gross potential threshold: 10 kWa
- Incremental water stage: 4 mts
- Maximum (dam) technical height: 50 mts
- Minimum cross section slope: 10%

The PFF was calculated as 70% of the long-term average discharge at three gauge stations. The natural firm flow was considered the Q_{95}. In order to estimate the gross theoretical hydropower potential in the river basin – i.e. the maximum potential despite environmental, economic and technical constraints – *Qreman* was set equal to zero.

The hydropower potential spotting process resulted in 31,266 project alternatives distributed in 1933 sites, from which:

- 997 developed the dam until the maximum technical height;

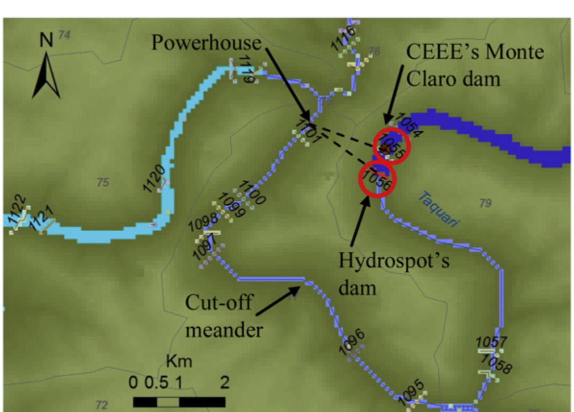

Fig. 7. Monte Claro hydropower plant location.

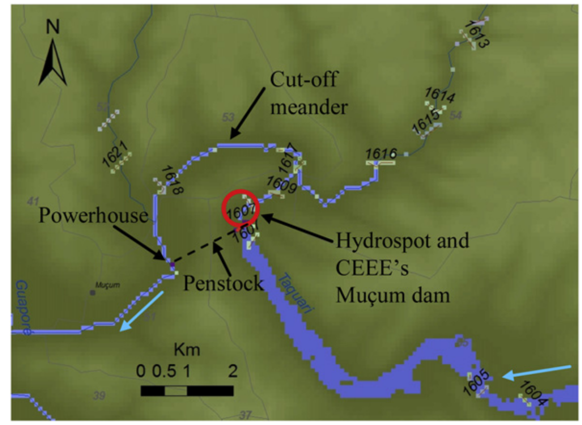

Fig. 8. Muçum hydropower plant location.

- 39 stopped the development because PFF was exceeded;
- 16 stopped the development due to confinement in a confluence;
- 881 stopped the development because the minimum slope was exceeded.

Other 2344 sites were queried and discarded due to low potential (<10 kWa) and 55 due to interference with restricted areas.

The gross theoretical potential was estimated as 736 MWa distributed in 274 plants, with power potential varying from 10 kWa to 58 MWa. In relation to the type of project, 199 out of 274 were run-of-the-river operations and 75 had storage capacity. In concordance with CEEE's findings, most part of the plants (246) had cut-off or riverbank derivation schemes, and only 28 generated at the toe of the dam.

In the studies carried out by CEEE, 79 potential sites were raised, encompassing 94 alternatives in the range of 600 kWa and 57 MWa. The river basin potential was estimated as 552 MWa. Since the study considered only pre-selected sites at least technically viable, these numbers suggest that a feasibility assessment applied to *Hydrospot* results would lead to a mass discarding of lower-potential projects, equalizing the minimum potential thresholds found by CEEE and *Hydrospot*.

Some important projects included in CEEE's study had their dams and powerhouses spotted with reasonable accuracy. Figs. 7 and 8 show the location of the plants of Monte Claro (operating since 2004) and Muçum in comparison with the results obtained by *Hydrospot*.

In Figs. 7 and 8 it is possible to see the dam and the lake projection over the DEM of the selected alternatives and several other dam alternatives that appeared in the survey phase. Although the site of Monte Claro dam was spotted at CEEE's study, the selected alternative was located downstream the original project

Table 1
Comparison of key design characteristics between *Hydrospot* (in parenthesis) and CEEE power plants.

Site	*Ha* (m)	Q_T (m^3/s)	P_N (MWa)
Castro Alves	90 (32)	75.8 (50.3)	47.6 (13.4)
Monte Claro	43.8 (68)	126.1 (83.9)	45.4 (45.2)
Muçum	28.8 (13)	176.8 (109.2)	40.2 (12.4)
Linha Emília	36 (37)	26.9 (31.4)	7.7 (9.6)
Cotiporã	33.6 (78)	27 (30.5)	7.5 (19.5)

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because of a slightly higher discharge rate at that site. Both Monte Claro and Muçum powerhouses were precisely located, attesting the ability of the algorithm to represent cut-off schemes.

Hydrospot missed the cut-off possibility of Castro Alves, an important plant operating since 2008. This plant was originally conceived and constructed with a diversion tunnel approximately 8 km long, while the algorithm was set to a maximum headrace length of 1.8 km. Nevertheless, the site had spotted a plant alternative with a shorter head in comparison to the original project. Another important plant, 14 de Julho, in operation since 2008, was not represented by *Hydrospot* within the final set. This happened because a higher-potential alternative was first implanted downstream, flooding the site. The main characteristics of some power plants included in CEEE's study and represented by *Hydrospot* are presented in Table 1.

As shown in Table 1 regarding CEEE results, the average discharge was underestimated for large projects located at the main stem and overestimated in tributaries. In general, the power potential of a plant estimated by *Hydrospot* did not match its counterpart in CEEE's survey. This happened because of divergent discharges (CEEE used a critical period approach) or heads (projects with different dam height or headrace length).

4. Conclusions

Preliminary results have shown that the hydropower spotting algorithm performs robustly to locate the main hydropower plants planned in the basin. It has provided reasonable estimates of the main features of the projects for planning purposes. The automation of the head and the discharge calculation process allow raising a larger number of potential sites in basin than in a traditional hydropower prospection study. On the other hand, while the inundation and dam development algorithm permitted testing the different water stage alternatives in each site, it also assigned some parsimony to the survey phase by restricting dam development in flat areas.

The selection algorithm is not based on an optimization procedure. Therefore, the gross theoretical hydropower potential in the river basin might not be the maximum. During the methodology development, different approaches were tested in order to optimize hydropower potential in the river basin. However, all of them bypassed a real optimization approach because of the size of the sample and the interdependence of its elements (project alternatives), due to flow regulation effects, cut-off conflicts and physical overlapping (many alternatives at the same site and lakes that inundate upstream projects).

In this paper, in the hydropower potential survey problem, we have considered only Boolean constraints, all imposed by the topologic, hydrologic and legal (exclusion zones map) characteristics, and employed in the survey phase.

5. Ongoing and future works

The total feasible potential in the river basin has been recently calculated using the survey and selection modules coupled to a comprehensive multi-criteria methodology, taking into account legal, social, environmental, economic and technical aspects. In the new application, an integrated sustainability index has been tested, as in Larson and Larson [22], and calculated based on multi-attribute maps, as in Begić and Afgan [23]. However, differently from a ranking kind of problem, the feasibility assessment of *Hydrospot* is applied at a stage in the planning process when it is able to affect the arrangement of the final set of plants in the river basin.

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