On the Large Scale Assessment of Small Hydroelectric Potential: Application to the Province of New Brunswick (Canada)

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Abstract: The mapping of the small hydropower (SHP) resource over a given territory is indispensable to identify suitable sites for the development of SHP renewable energy projects. In this study, a straightforward method to map the SHP potential over a large territory is presented. The methodology uses a synthetic hydro network (SHN) created from digital elevation models (DEM) to ensure precise hydro head estimations. From the SHN, hydro heads are calculated by subtracting the minimum from the maximum elevation of synthetic stream segments. Subsequently, stream segments with low hydro heads over a specified maximum distance are removed. Finally, the method uses regional regression models to estimate the annual baseflow for all drainage areas in the study area. The technical SHP potential can then be estimated as a function of the hydro head and maximum penstock length. An application of the method is made to the province of New Brunswick, Canada, where SHP maps have been developed to promote the development of the SHP energy sector in the province. In terms of the SHP opportunity, it is shown that the province of New Brunswick (71,450 km^2) has a good SHP resource. Using a representative hydro head (10 m) and penstock length (3,000 m) for the region, 696 potential sites have been identified over the territory. Results show that the technical SHP potential for New Brunswick is 368 MW for the conventional hydroelectric reservoir SHP configuration.

Keywords: *Small hydropower (SHP), Resource assessment, Hydroelectric power potential, Mapping*

1. Introduction

The definition of small hydropower (SHP) varies according to jurisdictions; in some instances, hydroelectric generating stations having installed capacities of up to 15 MW are generally characterized as SHP [1], while in Canada, hydroelectric generating facilities with installed capacities of up to 50 MW are considered as SHP [2]. Similarly to other renewable energy sources, such as wind power, the mapping of the SHP resource over a given territory is indispensable to identify suitable sites for the development of SHP renewable energy projects.

Large scale SHP assessments for pre-feasibility studies have been done in the United States [3], where data from hydrological regions were used to estimate the annual average streamflow for ungauged drainage areas; the estimated annual average streamflow was then used in conjunction with digital elevation models (DEM) to determine the hydropower potential for sites situated in ungauged natural streams in the corresponding regions. In Canada, even though the province of British Columbia is the only province to have developed an official map of the SHP resource [4], many Canadian SHP sites have been mapped in the International Small-Hydro Atlas [5]. However, the latter was developed with information from ref. [6-10] which are generally based on a combination of historical data and observations from field research; modern mapping techniques have only been implemented in a few of these studies.

In this paper, a methodology for the large scale assessment of small hydroelectric potential is presented along with an application to the province of New Brunswick, Canada. In the first instance, a method is described to find the available hydro head on the hydrographic network of a study area. Secondly, the annual streamflow is calculated, as a function of the hydro head and maximum penstock length, for each available hydro head sites. The technical hydropower potential is then calculated and the study results are presented in the form of a SHP map.

2. Hydropower Potential Modeling

At a given site, the hydropower potential, *P*, can be calculated as

$$P = \rho Q g h \eta \tag{1}$$

where ρ is the density of water (kg/m^3), Q is the volumetric fluid flow rate (m^3/s), g is the gravity constant (9.81 m/s^2), h is the height (m) of the drop (gross hydro head), and η is the efficiency coefficient. In this study, the density of water is assumed constant at 1,000 kg/m^3, the efficiency coefficient is set to 0.8 while the hydro head is defined as the height difference between the intake and the generating station. Thus, with these assumptions, only two remaining parameters, Q and h, are needed to determine the hydropower potential for any site in a given study area. A third indirect parameter, the penstock length, can also be used in the determination of the gross hydro head.

2.1. Hydro head modeling

Assuming that a drainage area generates enough streamflow to be considered as a potential site, the first phase of large scale SHP mapping is to locate every potential hydro head on all stream segments of the hydrographic network. To this end, a synthetic hydro network (SHN) using DEM is created to ensure relatively precise hydro head estimations. This is done because spatial entities in the National Hydro Network (NHN) are based on existing data of different agencies [11] and do not perfectly match with the DEM. Since the SHN perfectly matches the DEM, the interoperability between information layers is assured. GIS software tools such as the TauDem tools [12], along with algorithms based on the previous works [13-15] are used to create the SHN from the DEM. The SHN is then validated with the NHN and all stream segments present in the SHN that does not correspond to a NHN stream segment are excluded. From the SHN, hydro heads are calculated by subtracting the minimum from the maximum elevation of the synthetic stream segment. Subsequently, because the penstock length represents an important capital cost of the total civil work costs for SHP projects, a limit is imposed on the Euclidian distance between the highest and lowest node of a SHN stream segment, which is used to represent the penstock length. In this work, the maximum penstock length is established at 3,000 m and all stream segments up to the maximum penstock length having hydro heads of less than 10 m are removed from the model, due to the altitudinal precision of the DEM (± 5 m, 90 % of the time).

2.2. Streamflow modeling

A regional regression model based on the work of Vogel et al. [16] is used to estimate the annual streamflow for all drainage areas in the study area, namely:

$$Q = e^{C_0} X_1^{C_1} X_2^{C_2} \ldots X_n^{C_n} e^{\varepsilon} \tag{2}$$

where Q is the observed annual streamflow or baseflow in a gauged basin (m^3/s), X_i are the various drainage area characteristics (climatic and physical attributes such as average annual temperature, average annual precipitation, elevation and drainage area), C_i are the ordinary least square regression coefficients and ε is the residual of the model.

In order to evaluate the efficiency of the regional regression model between the estimation results and the observation data, a goodness of fit statistical model, known as the Nash and Sutcliff efficiency index [17], *E*, is used and is given by:

$$E = 1 - \left[\sum_{t=1}^{T} \left(Q_0^t - Q_m^t \right)^2 / \sum_{t=1}^{T} \left(Q_0^t - \overline{Q_0} \right)^2 \right] \quad (3)$$

where Q_o is the observed streamflow at a given time t and Q_m the modeled streamflow. The Nash and Sutcliff efficiency index ranges from $-\infty$ to 1, where 1 represents a perfect match between the model results and the observed data.

2.3. A case study: Province of New Brunswick, Canada

As an application of the methodology proposed, and in order to promote the development of the small hydropower energy sector in the province, the large scale SHP assessment methodology for the conventional hydroelectric reservoir SHP configurations is applied to the province of New Brunswick (NB), Canada. The province of New Brunswick, one of the smallest of the Canadian provinces, both in size (71,450 km^2) and population (748,319), is part of the Maritime provinces on the eastern coast of Canada. The topography of New Brunswick consists in three major geographic regions. The north-west region is characterized by the Appalachian Mountains, which are dominated by Mount Carleton (820 m above sea level). The center of the province is composed of small rounded hills delineated by river valleys. Finally, the southern part of New Brunswick is composed of small hills sloping down to the Bay of Fundy, with the exception of the south-eastern part of the province which is composed of the Caledonia Highlands. In terms of climate, the province of New Brunswick is located within the Atlantic Ecozone, which is characterized by a continental climate due to eastward moving air masses. Although the moist climate provides an annual runoff varying from 600 to 1,000 mm, the annual runoff is more important in the southern region of the province, near the Bay of Fundy, due to higher precipitation events. The province's hydrographic network is composed of three major rivers: the St. John River, which drains the western part of New Brunswick, takes its source in the state of Maine, U.S.A. and discharges into the Bay of Fundy; the Restigouche River, which discharges into the Baie des Chaleurs, drains the northern part of New Brunswick; finally, the Miramichi River, which drains the eastern part of New Brunswick, discharges into the Gulf of Saint Lawrence.

2.3.1. Hydro head modeling input data

The DEM's used to generate the SHN are retrieved from the Canadian Digital Elevation Data (CDED) [11]. The raster dataset, at a 1:50,000 scale, has a minimum cell resolution of 0.75 arc seconds, which represents approximately 32 m^2 for the province of New Brunswick. The altitudinal precision of the dataset is ±5 m, 90% of the time. Furthermore, because some watershed areas are contiguous to the state of Maine, DEM covering corresponding sections of the state are also used. The dataset used to cover the corresponding watersheds are taken from the National Elevation Dataset (NED) 1 Arc Second of the United States Geological Survey (USGS) [18]. The NED dataset has a resolution of approximately 30 m^2 and is resized to match the CDED resolution. Finally, due to computing limitations, the DEM for the entire region is divided into 9 sub-regions, as shown in Fig. 1. These sub-regions are defined by using aggregates of sub-sub-drainage areas as delimited by the Water Survey of Canada (WSC) dataset [19], thus maintaining the topology of the SHN within each sub-region.

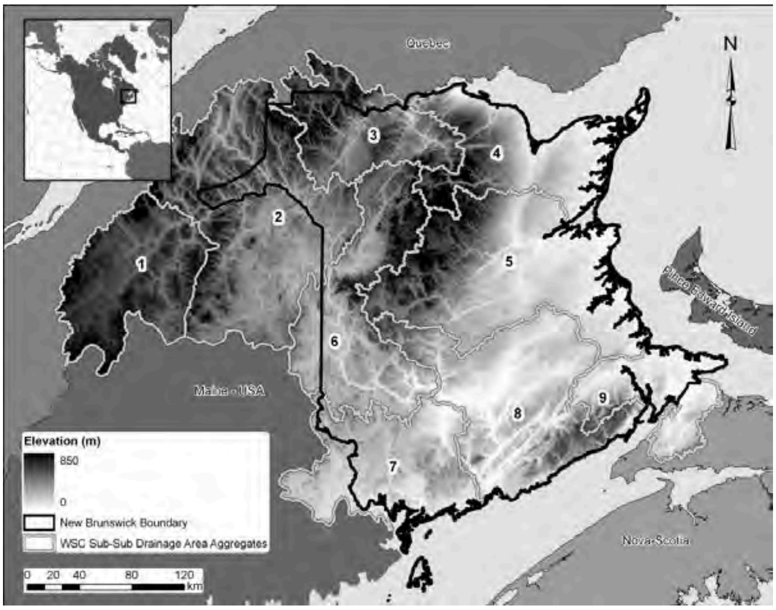

Fig. 1. Study area; sub-regions used for the extraction of the DEM.

2.3.2. Streamflow modeling input data

The climatic attributes such as average annual temperature and average annual precipitation used in several regional regression models tested in this study are taken from ref. [20-21]. In terms of the physical attributes used in the regional regression models, the majority of them, i.e. average slope, average elevation, elevation range, drainage area and eccentricity of the drainage area, are calculated from the DEM.

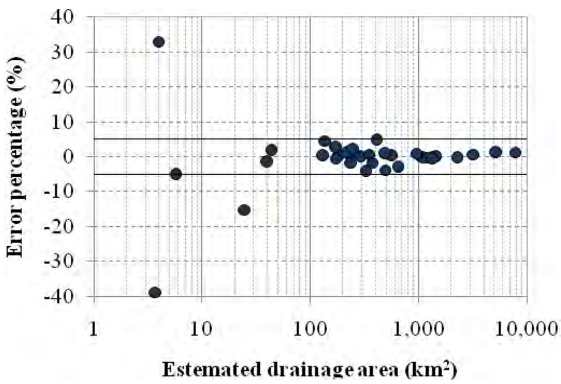

Fig. 2. Relative error between reference basin drainage areas and DEM-based basin drainage area estimation.

Previous research work in regional regression models has shown that the basin drainage areas provide good correlations in such models [16]. As is shown in Fig. 2, by comparing the DEM-based drainage area results for basins having hydrometric stations measuring natural flow to those of the Water Survey Canada as reference, it can be seen that the relative error decreases as the drainage area increases. In this work, a lower limit of 50 km^2 was imposed on drainage basins, such that hydro head having drainage areas with less than the lower limit where not considered. Finally, streamflow data from hydrometric stations [22], located across New Brunswick and having at least 30 years of continuous data, while being situated in basins with drainage areas larger than 50 km^2, are used in the various regional regression models tested.

3. Results

3.1. Hydro head modeling results

Results from the hydro head modeling showed that a total of 696 hydro heads in the province of New Brunswick satisfied the modeling constraints. In general, as in the case of other research in similar topography [23], because the topography is more variable in the upper part of a watershed area, stream segments with high hydro heads were generally located in the upper parts of a watershed area, while sites located in lower parts of a watershed area generally had lower hydro heads. Fig. 3 shows the distributions of hydro head sites by their characteristics.

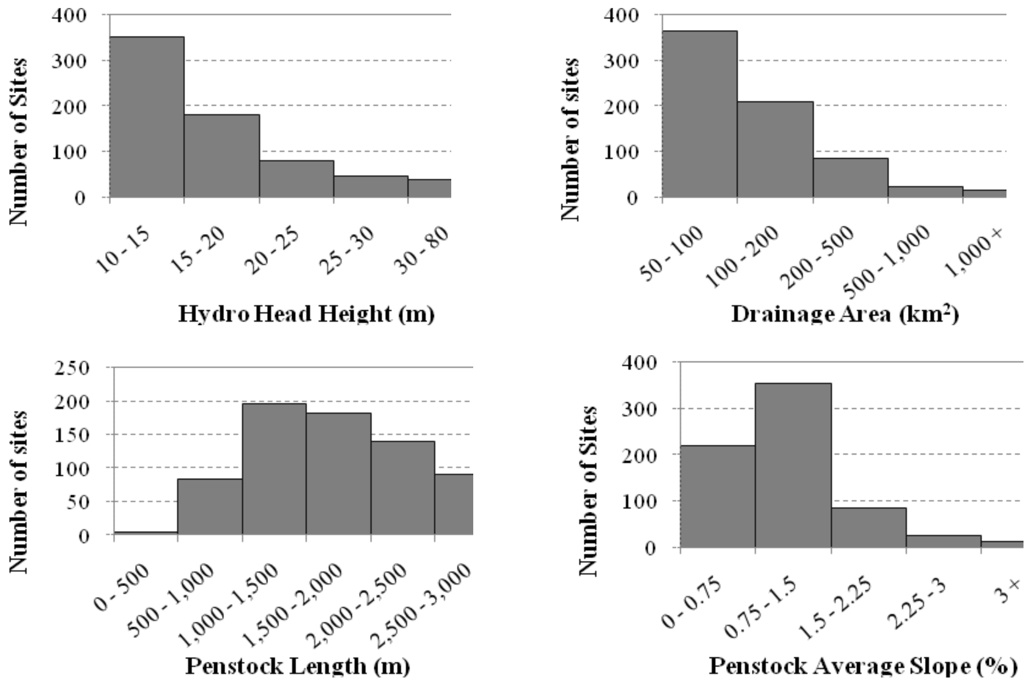

Fig. 3. Distribution of the hydro head sites.

3.2. Streamflow modeling results

In order to estimate the average annual streamflow for all basins in the study region, multiple regional regression models have been attempted in this work; the regional regression model having both the lowest average relative error (6.5%) and the highest Nash and Sutcliffe efficiency index (0.993) was chosen:

$$Q_m = e^{-16.552} A^{0.977} P^{1.733} D^{0.133} \tag{4}$$

where Q_m is the modeled streamflow (m^3/s), A is the drainage area (km^2), P is the average annual precipitation (mm) and D is the average elevation (m) of the drainage area.

3.3. Mapping results

While the methodology described in this paper can be used to estimate the SHP resource potential for both conventional hydroelectric reservoir and run-of-river SHP configurations, only results for the conventional hydroelectric reservoir SHP configuration are presented. Fig. 4 shows the mapping results of the SHP resource potential, for the conventional hydroelectric reservoir SHP configuration, in the province of New Brunswick. For this SHP configuration, the technical SHP potential for New Brunswick is 368 MW. The sites range in

SHP potential from 92 kW to 16.1 MW; the average potential for the 696 sites is 528 kW per site, while the median power potential is 303 kW.

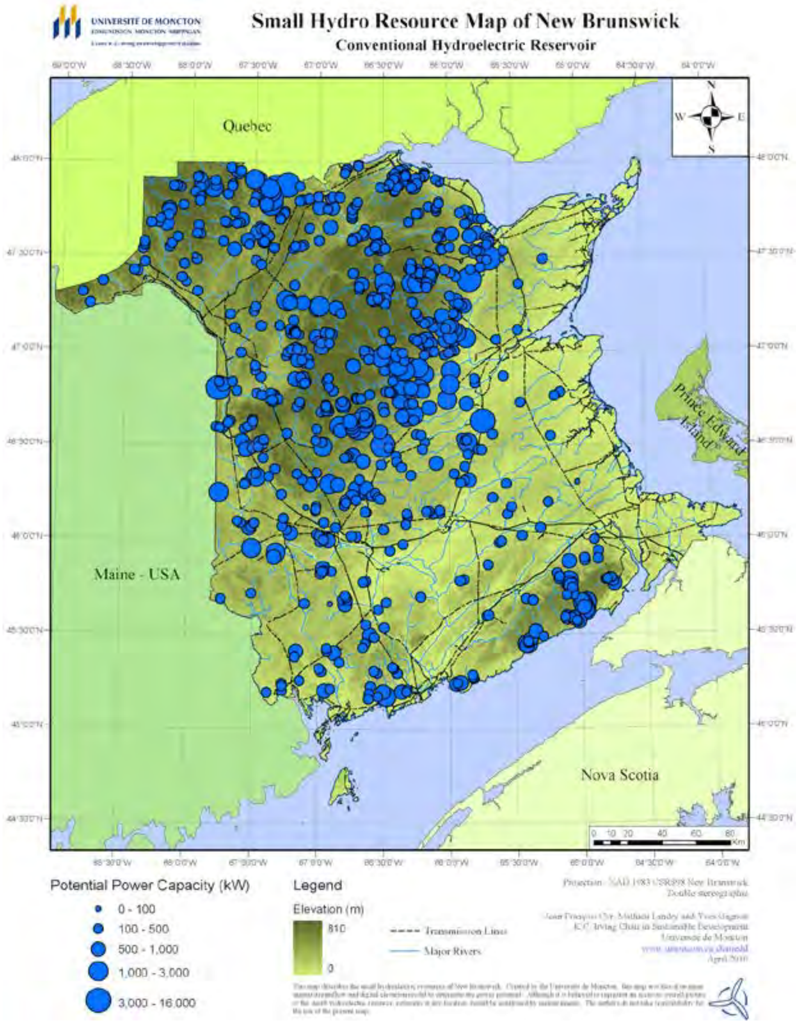

Fig. 4. SHP resource map of New Brunswick for conventional hydroelectric reservoirs.

4. Discussion and Conclusion

In this work, a straightforward method to map the small hydropower (SHP) potential over a large territory was presented. While the methodology presented in this paper is based on previous research work in this field of study, it contains several advantages which are not exclusive to this work but where their combination as a whole represents a significant advancement in this field. First, the methodology is general such that few variables are needed to perform a SHP study. Furthermore, the variables needed in the methodology are readily available at large scale for SHP studies in Canada or in other countries having publicly available GIS data. Secondly, the methodology can simultaneously evaluate and compare the SHP for both conventional and run-of-river configurations over a given area; this point represents a significant advancement in the field of study. Third, the methodology uses the gross hydro head, which significantly reduces the computational efforts of site selection. Fourth, the methodology is extremely fast and cost-effective when implemented using GIS-based software. However, the methodology introduces uncertainties in the estimation of the SHP resource potential which are due to the estimation of the efficiency of the SHP systems, the neglecting of SHP system head losses due to friction, and the use of yearly baseflow data instead of monthly baseflow data. Finally, field measurements of terrain could be used to increase the accuracy of potential site locations.

An application of the method was made to the province of New Brunswick, Canada, where SHP maps were developed to validate the methodology and to promote the development of the small hydropower energy sector in the province. In terms of the SHP opportunity, it was shown that the province of New Brunswick has a good SHP resource. In comparison to the neighbouring state of Maine[1], a previous study [24] identified that there were over 5,883 sites in the state of Maine having a technical SHP potential capacity of 2,780 MW, thus giving an average SHP of 472 kW/site. In New Brunswick, results from this study have shown that there is a technical SHP potential capacity of 368 MW distributed on 696 sites; thus giving an average SHP of 528 kW/site.

Future work should focus on the elimination of potential sites that are not sustainable economically, environmentally or socially. To this end, potential sites that are located within federal and provincial park boundaries should be notably excluded. In addition, drainage basins having issues such as water supply, tourism, sport fishing, and the presence of species at risk should also be eliminated from the model.

Finally, the New Brunswick SHP map results have shown that the province of New Brunswick has a good small hydropower (SHP) resource which should be developed not only for its environmental benefits and attributes, but also for the social and economic benefits of its residents.

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