A GIS integrated tool to evaluate the residual potential hydropower production at watercourse scale [*]

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ABSTRACT

The identification of the potential hydropower at river scale (within a single basin) needs a precise analysis of the water availability in terms of annual stream discharge duration curve coupled with available geodetic falls.

The paper presents a GIS integrated numerical tool that allows for the evaluation of the residual potential hydropower energy and all possible alternatives concerning the sites for hydroelectric plants along the drainage network, taking into account the relationship between the full costs of the mini-hydro power and the benefits from selling the generated power in the national market. The tool takes into account the water resources present exploitation with its geographical location and elevation (with respect to irrigation uses, drinkable water, existing hydropower plants, etc.), and the limitation that this creates regarding the potentiality for energy production. The software is based on the topographic information (Digital Elevation Model) and the isohyets maps, with a whole analysis of the catchment, together with the regional evaluation of available discharges along the river system.
Based upon a user friendly graphical interface the tool is able to split the river into a hundreds of cross sections and to calculate the available discharges and potential hydropower production, considering constrains like minimum flow, withdrawals and restitutions scheme.

The tool shows to be a quite powerful instrument to support decision makers and stakeholders, for preparing energy plans, assess potential sites and implement small scale hydropower plants.

1 Introduction

Due to the increasing attention to environmental protection issues, the role of small hydropower has gained particular attention. In fact, characteristics and operational standards of small hydroelectric plants give limited environmental impact and are compatible with multi-purpose systems (including drinking water, irrigation, etc), and usually permits to improve the management of water resources. Indeed, the construction of Italian small scale hydro electricity plants registered an important increase in the last years, near 3% in the case of the mini/micro hydropower plants (power < 1 MW) and 2% for those with power between 1 MW and 10 MW [Gestore Sistema Elettrico, 2005]. Recent studies concerning the residual potential of small scale hydropower generation in Italy show that there are conditions for increasing the current level of small hydro production [Peviani et all., 2007].

The present paper describes the developed methodology to evaluate the hydropower residual

potential in a water course taking into account the analysis of the catchment, the actual withdrawals and restitutions scheme and the application of the Minimum Instream Flow constrains [Alterach et all. RdS 2007].
A friendly user tool to evaluate the residual potential is developed based on the DEM "Digital Elevation Model", addressed mainly to the support decision makers and stakeholders.

2 Available, natural and hydropower flow

In order to analyse the potential small-hydro sites at a river scale, the knowledge of the water availability is an essential data. Two inputs are required to develop the calculation:

- at least one point with available flow (mean annual discharge) data, otherwise a regionalization method can be applied [Alterach et al, 2005, 2006];
- water exploitation annual volumes with its precise location, i.e. withdrawal flows and restitutions flows along the analysed river stream.

It is possible to estimate the potential discharge to be used in a possible hydropower exploitation following computation and interpolation steps. The interpolation process uses a double transformation of the river flow data, first the "naturalization process" of the river measured point flows, interpolation of the natural values and then a final transformation of available flows for every cross section.

- evaluation of the *Point Natural Flow (Qnat)* in a particular section, equals to the *"Point Available Flow" (Qav)* , cancelling the effect of the upstream withdrawal/restitution scheme;
- estimation of the *Natural Flow (Qnat(x))* in every river section "x", as a result of interpolations and proportions based on the Qnat data;
- evaluation of the *Available Flow (Qav(x))*, in every river section "x", equals to the calculated Natural Flow minus the upstream withdrawal/restitution flows;
- calculation of the *Hydropower Withdrawal Flow (Qhp(x))* in every river cross section "x", that represents the design value (mean annual discharge) for hydropower generation plants. It takes into consideration also the downstream withdrawal/restitution flows and the Minimum Instream Flow.

The Figure 1 shows the conceptual scheme followed to calculate the Hydropower Withdrawal Flow in a given cross section.

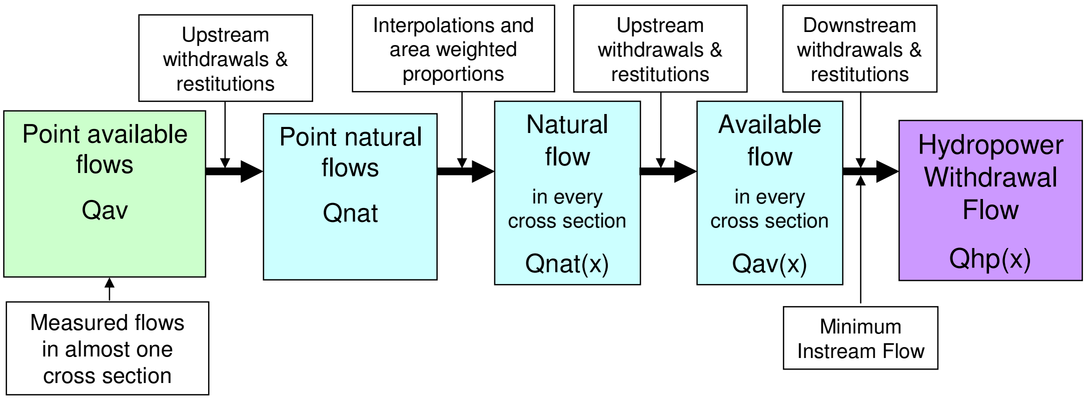

Figure 1 – Computation/interpolation process to calculate the hydropower withdrawal flow

The Qnat for each measure point, is obtained summing the upstream withdrawal/restitution flows as in the following formula:

$$Qnat = Qav + \sum_{j=1}^{N} q_j$$

where:

Qav	measured flow in the section (Point Anthropic Flow);
Qnat	natural flow in the measuring section (Point Natural Flow);
q_j	withdrawal (+) or restitution (-) upstream points.

The Figure 2 shows an schematic representation of the measure section (Available Flow) and the withdrawal/restitution upstream scheme:

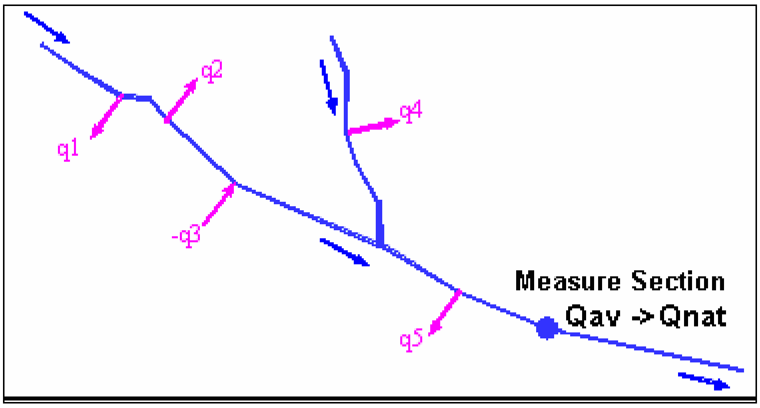

Figure 2 – Flow measure cross section and upstream withdrawal/ restitution scheme

As a second step, Qnat(x) is calculated in every cross section “x”, using the area weighted interpolation (between two measured points) or a simple area weighted proportion (in case of having only one measured point). For example, in picture below in branches B and C interpolation is applied, on the other hand the area weighted proportion is applied in branches A and D.

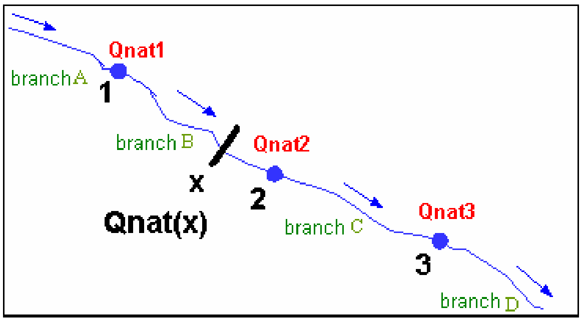

Figure 3 – Watercourse scheme with 3 flow measure sections

The third step concerns the evaluation of the available flow Qav(x) in every cross section, calculated as follows:

$$Qav(x) = Qnat(x) - \sum_{j=1}^{N} q_{xj}$$

where:

Qav(x)	the available flow calculated in each cross section “x”;
Qnat(x)	the natural flow calculated in the cross section x using the interpolation/proportion method;

q_{xj} withdrawal (+) or restitution (-) flow in the upstream j-sections, upstream of the "x" section.

The intake cross section of a hypothetical small hydro power plant must be designed for the available withdrawal mean annual flow. The method considers two constrains:

- the Minimum Instream Flow (MIF) calculated in the hypothetical intake section;
- the downstream withdrawals affected by the hypothetical small hydro itself (i.e. between the intake and the restitution points).

The Figure 4 shows the hypothetical power plant, i.e. the intake point and the restitution point (from the powerhouse), and the withdrawals P1, P2 and P3 in the sections s1, s2 and s3, between them.

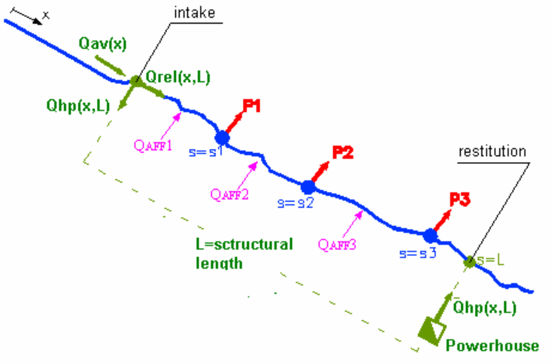

Figure 4 – Withdrawal scheme between the intake and restitution points

Let us define the *Maximum Withdrawal Flow* (Q_{max}) in a given cross section "s" as the mean annual discharge that is possible to withdraw compatibly with the environmental constrains in the section "s":

$$Qmax(s) = Qav\ (s) - MIF\ (s)$$

where Qav represents the available flow in a cross section "s" as defined above and MIF is the Minimum Instream Flow considering river environmental quality, which can be assumed equal to the 10% of the natural flow in each cross section "s" [Regione Lombardia, 2006]:

$$MIF\ (s) = 0{,}1 \cdot Qnat(s)\ .$$

In order to calculate the *Hydropower Withdrawal Flow (Qhp)* for each "x" cross section, one of the parameters that determine the potential hydropower production, it is necessary to refer to the critical section "s", with the lowest Qmax value in the "L" domain. The so called "structural length" (L) is defined as the distance between the intake and the restitution points, measured along the river thalweg (see Figure 4).

The released discharge in the power plant cross section is the following:

$$Qrel\ (x,L) = Qav\ (x) - \min|_{[s=0,L]}\ (\ Qmax\ (s)\ )\ .$$

and the mean annual discharge that can be withdrawal for hydropower purposes is:

$$Qhp\ (x,L) = \min|_{[s=0,L]}\ (\ Qmax\ (s)\ )\ .$$

It is possible to demonstrate that this methodology can ever satisfy the two constrains: the "Minimum Instream Flow" in the hypothetical intake section and the water availability at the downstream exploitation points.

3 Potential hydropower production calculation

The Digital Elevation Model coupled with GIS tools, permits to obtain the ground elevation pattern and consequently the geodetic heads, related to a particular "structural length" (L), for any cross section "x" along the river stream. The geodetic head corresponds to the "Gross Head", while the "Net Head" is obtained considering the hydraulic losses:

$$\text{Hnet}\,(x,L) = \text{Hgross}(x,L) - \Delta H(L)$$

where:

Hgross(x,L)	Gross Head (m), depending on x and L;
Hnet (x,L)	Net Head (m), depending on x and L;
ΔH(L)	hydraulic losses in the channel and in the penstock, depending on L.

The most suitable river branches for the hydropower purposes consider the best couple [Hnet;Qhp]. Then the Maximum potential hydropower production is given from:

$$\mathrm{E}(\mathrm{x},\mathrm{L}) = \eta_{\mathrm{T}} \cdot 9{,}81 \cdot Qhp(\mathrm{x},\mathrm{L}) \cdot \mathrm{Hnet}\,(\mathrm{x},\mathrm{L}) \cdot 8760$$

where:

E(x,L)	yearly Maximum Available Energy (kWh/year), in function of x and L;
η_T	electric global efficiency;

The above mentioned energy is the maximum potential available, considering the total exploitation of Available Withdrawal Flow during the entire year (8760 hours), taking into consideration withdrawals and MIF.

To calculate the potential installable power, the following relation is used:

$$\mathrm{P}(\mathrm{x},\mathrm{L}) = E(x,l)\,/\,Kh$$

where

P (x,L)	is the installable power in a given section "x" for a structural length "L" (kW)
Kh	yearly continuous hours at a maximum equivalent power to produce the potential energy (h/year)

4 Economic feasibility

The choice of the most appropriate sites for the hydropower exploitation depends upon the relationship between the construction and maintenance costs of the full system and the income from energy selling plus the additional grants, such as the Green Certificates. The economic parameters to be considered are the following:

- the hydropower plant cost (civil and electrical), for different structural lengths equal to 50, 100, 200, 500, 1000 and 2000 meters;
- the energy income
- the income/cost ratio.

The cost of each plant is evaluated by means of parametric relations as follows:

- cost of the powerhouse function of the installed power P(x,L);
- cost of the penstock function of the pipe diameter and the structural length;
- cost of the weir and intake basin depending on the design flow;
- maintenance and exercise costs, proportional to the total work cost.

Therefore the cost can be expressed as follow:

$$\mathrm{C(x,L)} = fn(L, P, Diam, Qhp)$$

On the other hand, the income is represented by the produced energy selling during the plant lifetime and the benefits of the Green Certificates for the first 12 years (Italy):

The formula that expresses the total updated income is:

$$\mathrm{I(x,L) = p \cdot E(x,L) \cdot \frac{(1+i)^{n} - 1}{i \cdot (1+i)^{n}} + pgc \cdot E(x,L) \cdot \frac{(1+i)^{nCV} - 1}{i \cdot (1+i)^{nCV}}}$$

where

I(x,L)	total updated income (€);
p	energy selling price (€/kWh);
E	annual produced energy (kWh/year);
i	up-to-date interest (5%);
n	plant's lifetime, equals to 30 years;
pgc	Green Certificates price (€/kWh);
nCV	Green Certificates lifetime, 12 years.

The above mentioned formulas permit to calculate the Income/Cost ratio for every combination of intake sections "x" and structural lengths "L".
The whole optimization process takes into account a chain of hydropower plants with different L and "x" (two freedom degrees optimization). The optimized configuration is obtained maximizing the energy production and the Income/Cost relation of the total chain.

5 The GIS software tool to evaluate the residual potential hydropower in a watercourse

The method illustrated in the above paragraphs is applied in a GIS integrated software (Vapidro-aste) to evaluate of the residual potential hydropower in a watercourse and aid to the optimization of the whole exploitation. The software is developed in Visual Basin language, integrated with ARCGIS 9 and it is now into a conclusion phase, with the testing over two studies areas in Italy: the Ogliolo River (Lombardia) and the Sinni river (Basilicata).

VAPIDRO-ASTE - Nessun Progetto Caricato

Progetto Elaborazioni ArcGIS Calcoli Tabelle/Grafici

VAPIDRO-ASTE

Valutazione del Potenziale
di producibilità idroelettrica
per aste fluviali

CESI RICERCA RDS

12-02-2008
by A. Elli e M. Vergata
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Figura 5 –VAPIDRO-ASTE start windows

The following paragraphs relate to some relevant working aspects of the software:

- River network, sub-basin and physiographic calculation parameters
- Discharge calculations and interpolations
- Residual potential Energy and Power profiles
- Results view
- Hydropower Optimization process

The Vapidro-aste tool is able to calculate automatically the river network associated to the interesting area. The user chose the interesting river branch, where to calculate the potential hydropower production, and then a series of chained sub-basins, are generated by the model. The following figure shows a vapidro-aste window containing the map of the Ogliolo river (Lombardia – Italy) with the sub-basin generated automatically:

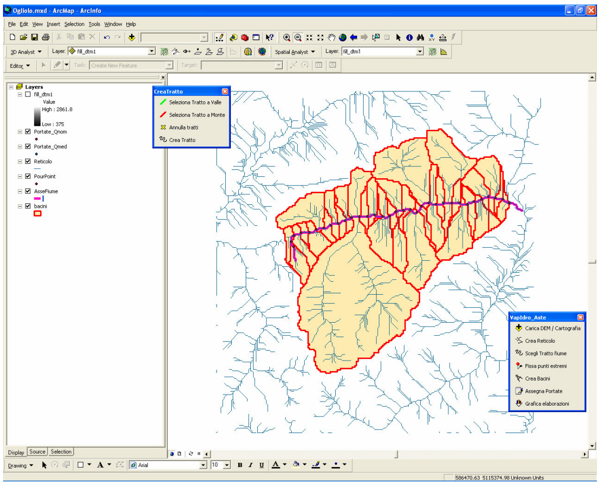

Figure 6 – River network, sub-basin and main watercourse automatic computation

The main activities performed by the model are the following:

- Split of the Digital Elevation Model (DEM) regarding the interesting area.
- Automatic creation of the river network, by means of the Arcinfo Spatial Analyst functions

  Selection of the interest watercourse; by means upstream and downstream points user aided allocation
- Automatic creation of the sub-basins used for the interpolation (**Figure 6**)

Each basin is identified by its own closure point and the software calculates automatically the necessary data to perform the flow interpolation: progressive distances x, sub-basin areas, minimum elevation.
At this step, the user inputs the measured flows (Qav) in one or more points over the selected watercourse.

The Software is able to calculate automatically the potential hydro energy and installed power for the selected watercourse, in a logarithmic scale.
As an example, the **Figure 7** shows the maximum installable power in the Ogliolo river, in Lombardia (Italy).

It is possible to observe that the software produces a set of energy and power curves which are parametric with the structural length L.

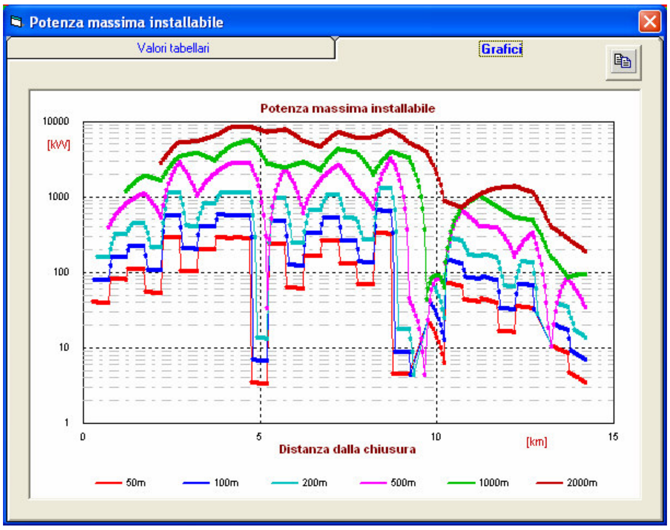

Figure 7 – Installable hydropower along the watercourse

The tool is useful to represent the hydropower potential in a map, with a color spectrum, as shown in Figure 8

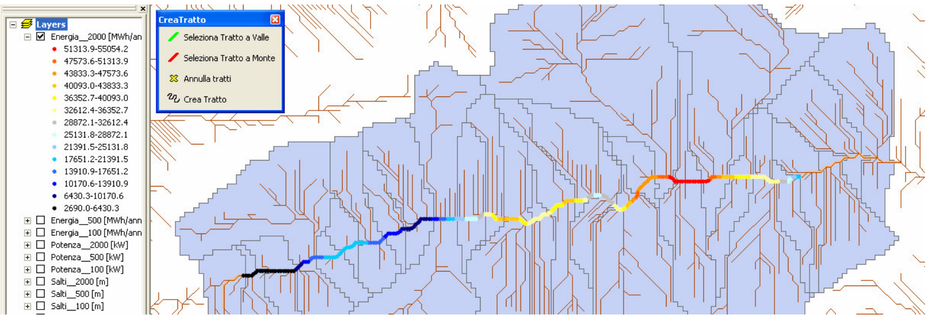

Figure 8 – Potential Hydropower production in the Ogliolo River

The whole exploitation of the river is performed maximizing the total potential energy production and global Income/Cost ratio of the hydro plants exploitation chain. The Figure 9 show seven optimized intakes position (squares), with the background of the benefit/cost ratio curves, in the Ogliolo River:

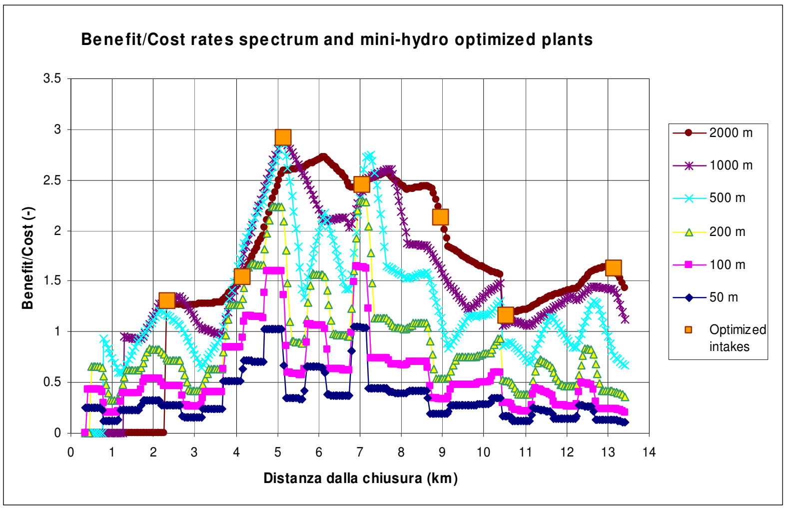

Figure 9 – The income/cost spectrum and the optimal hydropower exploitation

Other way to represent the optimized position of the hydro plants is in a mapping way, laying intake (squares) and powerhouse locations:

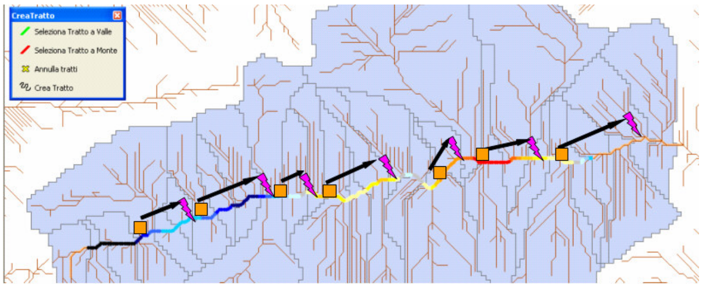

Figure 10 – Watercourse optimal hydropower exploitation

6 Conclusion

A GIS integrated numerical tool for the analysis of the mini-hydro residual potential sites at a river scale is developed. An optimization analysis considering the power generation and the benefit/cost relationship maximization is performed with the tool.
Is in progress the data acquisition regarding two case studies in Lombardia and Basilicata regions in Italy, to validate the application of the residual potential hydropower tool in watercourses.

The tool shows to be a quite powerful instrument to support decision makers and stakeholders, for the energy plan preparation, the assessment and the implementation of small scale hydropower plants.

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