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GIS-based approach for assessing the energy potential and the financial feasibility of run-off-river hydro-power in Alpine valleys

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HIGHLIGHTS

- An open-source tool to plan hydropower production is proposed.
- The GIS-based model accounts for spatial changes in physical, morphological, legal and financial variables.
- In the case of hydro-power potential raster and vector data have to be combined.
- Site-specific model has been validated by comparing model output with the local knowledge and historical decisions.
- Available sites in Alpine valley are often in isolated areas and civil work engineering cost can arise.

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ABSTRACT

In the last decade, European attractive policies are favoring the construction of new run-off hydro-power plants. The realization cost of these plants is quite low in mountain areas thanks to small water discharges and high gross heads. For this reason, small rivers have been strongly exploited without considering an optimal use of the resource. Nowadays, available sites are often in areas with low accessibility and a greater specific cost of civil engineering works. However, during the planning of new small hydro-power plants, the dependency of physical, technical, legal and financial variable on space is often not assessed. The tool presented in this paper addresses this gap to support the planning of run-off-river plants. The method improves on previous approaches by (1) integrating all the legal, technical and financial analysis in a GIS tool, and (2) trying to validate the site-specific model with local knowledge. The tool is applied to the Gesso and Vermenagna valleys in the Alps. Information and data were collected and discussed with local stakeholders in order to improve the model results.

1. Introduction

While estimating the feasibility of a renewable energy development project and plan, a first challenge is to define the availability of the natural resource. Only theoretically all the available energy in the nature could be used [1,2]. In the planning process, further restrictions to exploit the natural resource (e.g. technical, environmental, legal, social and financial constraints) should be considered [2–10].

In the case of hydro-power, defining the availability of the natural resource and its potential firstly depends on the technical installation. They can mainly be divided in two kinds, reservoir and run-off hydro-power plants (i.e. just a weir and no water storage). Dams and reservoir plants, hence big hydro-power plants, have already covered more than the 50% of European hydro-power potential [11]. They have a significant role, along with other renewable energy, since they can deliver valuable peak-load power. More favorable and convenient sites for big hydro-power plants have been already utilized and future increases could be provided only by small hydro-power projects as highlighted by the Word Energy Council for the Italian case. Nowadays, European attractive policies are in fact favoring small hydro-power supply that in most cases correspond to run-off plants. The estimation of their energy potential is then relevant for a sustainable planning.

In mountain areas, usually, run-off hydro-power plants primary use the head to generate power and the flowing water is channeled from a river through a canal or penstock to spin a turbine. Consequently, in order to estimate the energy potential, elevation and discharge data have to be combined. Palomino Cuya et al. [1] evaluate the energy potential in function of the mean annual discharge of each river section and the mean elevation calculated from the hypsographic curve. They obtain the hydro-power potential at river scale. Kusre et al. [12]

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Nomenclature

List of symbols

Δh	gross head
ϵ	roughness height
η	global efficiency
Φ_{inst}	installed power
ψ	life of the hydro-power plant
ρ	water density
ς	progressive coordinate along the pipelines
A	cross sectional area of flow
A_c	area with planning constraints
A_v	view-shed or visibility area
C	yearly cost
c	specific cost
D	diameter of the penstock
d	distance between two plants
e_{price}	price of the electricity
f	Darcy-Weisbach friction coefficient
g	gravity acceleration
h	elevation
k_s	Strickler coefficient
l	rivers exploited segment
n	number of full-load hours equivalent
P	energy potential indicator
p	value between 0 and 1
Q	yearly discharge
R	yearly revenue
r	interest rate
R_h	hydraulic radius
Re	Reynolds number
s	progressive coordinate along the river
v	velocity

List of subscripts

b	sub-basin
$comp$	compensation costs
d	derivation channel
em	electro-mechanical costs
$excv$	excavation cost
fin	financial evaluation
fix	fix costs
grd	grid connection
i	i-th plant
j	j-th bank of the river
l	supply and installation cost
loc	singular losses
lu	land use
net	net value accounting for losses
o	operating costs
p	penstock
pl	power line
$plan$	planning evaluation
st	power station costs
tec	technical evaluation
$theo$	theoretical evaluation
tr	tributes for expropriation
vup	tributes for wooded areas

pinpoint three criteria for identification of sites: order of stream, bottom gradient and minimum hydro-power site interval. They deepen the hydrological model to assess the flow rate, but they do not deal with spatial planning and site-specific financial aspects. Yah et al. [13] summarize the steps for assessing small hydro-power projects by underlying the importance of site identification and of preliminary analysis to evaluate the technical, environmental and economic (with an accuracy of circa 30%) feasibility of the project. These considerations are still not integrated in the hydro-power potential assessment and GIS analysis.

Müller et al. [14] present a webGIS tool to siting hydro-power infrastructures based on topography. Their algorithm mainly maximizes the product between the gross head and the catchment area without accounting for the spatial variability of the discharge due to existing water diversion. However, the spatial energy planning mechanisms should take into account environmental criteria as well as socio-economic aspects, including other water uses [15]. In the WebGIS tool, they introduce a financial assessment of hydro-power projects but their analysis neglects the cost factors related to hydraulic head, geometry of the infrastructure and site accessibility. Müller et al. [14] and Basso and Botter [16] simplify the cost as a power law of the electrical capacity. Ogayar and Vidal [17] highlight that most of the authors use an analytical expression for the calculation of the cost of electro-mechanical equipment depending on electrical capacity and net head. The power law coefficients are, however, related to the geographical, space or time field in which they are used and this spatial dependency should be introduced in the site-specific financial assessment. This cost of the equipment is a high percentage of the investments on hydro-power plants. Despite, the cost for civil works is around 40% of the total budget of the plant. Kaldellis et al. [18] underline as the specific cost of civil engineering works, including infrastructure, land purchase, dam construction, weir and intake, water canal, forebay tank, penstock depends on the local situation of every specific site. More specifically, the characteristics of topography, geology, road access and local electricity grid of each site have such an influence that each project becomes a prototype.

Table 1 summarizes the main works on energy potential assessment and on feasibility analysis of new hydro-power plants. It can be noticed as the two research topics are not integrated in a unique tool able to deal with the main advantages of GIS analysis and accounting for feasibility and site-specific financial aspects. However, the site specificity and the integration of this analysis in GIS tools become particularly important for planning new run-off plants at network scale but it has been scarcely investigated by the scientific literature and by policy makers.

This gap is particularly evident in Italian Alpine valleys where subsidies are favoring the construction of new run-off plants also in areas with low accessibility. A wrong planning of hydro-power exploitation can rise environmental, social and financial issues.

This study investigates a new model able to consider the spatial variability of energy potential, legal and planning constraints, and above all site-specific financial variables. All the input data are spatially explicit and the algorithm, to siting hydro-power infrastructures, includes the spatial variability of the flow rate. The model comprehensively estimates direct and indirect costs accounting for their spatial variability rarely undertaken in other studies as shown in Table 1. The GIS tool was developed within the recharge.green project co-financed by the European Regional Development Fund in the Alpine Space Programme.

As reported by Refsgaard and Henriksen [20], a model is a simplified representation of the natural system it attempts to describe. They define the following terminology:

- *Conceptual model*, i.e. mathematical description and flow processes.

Table 1
Energy potential versus feasibility studies: main features of existing works.

		GIS integration	Hydrology	Optimal siting	Spatial contexts	Technical aspects	Financial aspects	Site specificity
Energy Potential	Gollessi and Collevecchio [15]	x	x		x			
	Kusre et al. [12]	x	x	x	x			
	Müller et al. [14]	x		x			x	
	Palomino Cuya et al. [1]	x	x		x			
	Yah et al. [13]					x	x	
Feasibility	Basso and Botter [16]		x			x	x	
	Kaldellis et al. [18]					x	x	x
	Ogayar and Vidal [17]					x	x	
	Aggidis et al. [19]					x	x	

- *Model code*, a computer program that can be used for different study areas.
- *Site-specific model*, established for a specific study area.

The proposed conceptual model, Section 2, starts from the availability of the resources and goes through the different definitions (theoretical, legal and planning, technical and financial levels) of energy potential. Accounting for easily combining both vector and raster information, the model code is developed in the free and open source GRASS GIS software [21] by using the PyGrass library [22]. Each module in which the conceptual model is divided represents a GRASS add-on and is directly integrated in the GIS environment. The model code structure is reported in Section 3. Finally, the article describes the potentiality of the tool by applying it to a case study in the Italian Alps: the Gesso and Vermenagna valleys. The technical and financial parameters have been calibrated on the base of existing hydro-power plants and projects. The validation of this kind of spatial site-specific model is a big challenge. During the validation, the relationship between computation and the real world (experimental data) is the issue [23]. The reliability of the model results for decision makers is especially critical if the system cannot be tested in a fully representative environment. Due to the lack of experimental data for the validation of GIS-based computer model, it is relevant to compare model results with the local knowledge or the historical decisions. For this reason, results about energy potential have been compared with information collected thorough two round tables with local stakeholders and with previous concessions for hydro-power plants, as reported in Section 4. This comparison between model results and local knowledge increases the possibility to have realistic and reliable results. Studies that do not involve local knowledge have lower possibilities to be useful and thus to be implemented in the concrete decision-making process [24]. The validation of GIS results also passes through the information and the following participation of citizens in the implementation of decisions [25].

2. A spatial conceptual model for energy potential definition

The spatial information about the energy potential can support planners and decision makers to understand potential conflicts in the use of the natural resource and solve questions in the energy-economy domain [26].

Different levels of hydro-power potential can be defined by introducing cluster of constraints and new variables in the analysis:

Theoretical potential, P_{theo}. No constraints are taking into account. Starting from Resch et al. [2], the theoretical limit is the maximum power computed, in the ideal case, accounting only for physical laws. Then, theoretical limits cannot be reached in practice.

Planning potential, P_{plan}. Adding spatial, legal, social and environmental constraints decreases the theoretical potential. In this cluster of constraints we mainly consider the minimum flow discharge (MFD), already existing water uses and the protected or not available areas. The optimal siting of new plants is based on the availability of the natural resource accounting for these variables. This level of potential does not include technical information about the infrastructures of the plants and their financial feasibility.

Technical potential, P_{tech}. The technology is well-advanced and the energy conversion process is very efficient but, energy losses and the global efficiency of the plant reduce the hydro-power potential. The technical potential combine spatial features with technical information. The estimation of energy losses depends on the geometrical features of the system such as pipeline and channel length. A site-specific evaluation of these variables is needed in order to assess this potential.

Financial potential, P_{fin}. The feasibility issue is very significant in mountain areas where available sites can be in isolated areas with higher transmission cost. In the estimation of the energy potential, only economically feasible plants should be included. For this reason, an evaluation of the cost, depending on the site specificity, should be carried on and, finally, the financial assessment should account only for plants with Net Present Value (NPV) greater than zero [27].

2.1. Theoretical potential

In the case of hydro-power, a methodology to define the theoretical potential $P_{b,theo}$ can be derived from Palomino Cuya et al. [1] accounting for the up-stream sub-basin $P_{b,up}$ and the own lower sub-basin $P_{b,own}$ potential, as shown in Fig. 1:

$$P_{b,theo} = P_{b,own} + P_{b,up} = conv\ g\ \rho \left[Q_{b,aff}(h_{b,mean} - h_{b,closure}) + \sum_{u=1}^{n} Q_{b-u,closure}(h_{b,up} - h_{b,closure}) \right] \quad (1)$$

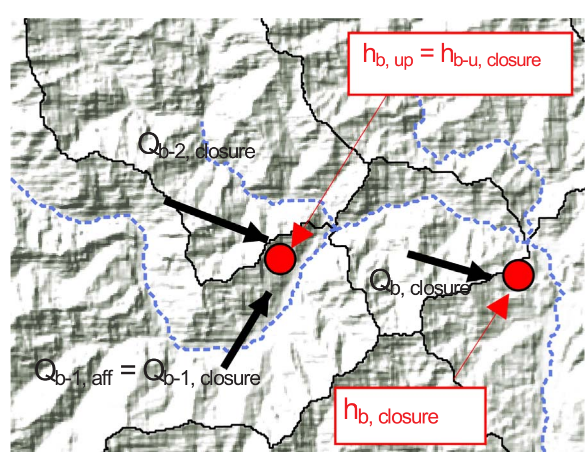

Fig. 1. Sketch of variables to compute the theoretical potential [1].

where b is the sub-basin, g is the gravity acceleration, ρ the water density, $Q_{b,aff}$ is the afferent discharge (own lower sub-basin discharge), $h_{b,mean}$, $h_{b,closure}$ and $h_{b,up}$ are respectively the mean elevation, the elevation at the closure point and the elevation at the upstream closure point of the b-th sub-basin, $\sum_{u=1}^{n} Q_{b-u,closure}$ is the sum of the flow coming from upstream sub-basins $(b-u)$, $conv$ equal to 8760 h [1].

Therefore, this theoretical potential does not depend on the kind of installation and does not account for current plants (the already exploited river segments), the planning and environmental constraints, the technical limits and the financial feasibility, but it defines the upper limit of hydro-power exploitation.

2.2. Planning potential

The first step before computing technical potential and financial feasibility, in the case of only run-off plants, is to define the potential position of new plants by neglecting the river segments already exploited by existing plants and accounting for planning constraints. As objective function to optimally place a new plant i, we assume the maximization of the potential. The power depends on the product between the maximum water flow through the turbine, diverted at the intake, $Q_{i,intake}$ and the gross head Δh_i, i.e. the difference between the elevation respectively at the intake and the water return $(h_{i,intake}-h_{i,restitution})$, Fig. 2.

Therefore, the flow $Q_{i,intake}$ is a function of the position of the intake $s_{i,intake}$ while the gross head Δh_i depends on the length l_i of the exploited segment equal to:

$$l_i = s_{i,intake} - s_{i,restitution} \tag{2}$$

with s progressive coordinate along the river. Consequently, the planning potential $P_{i,plan}$ is a function of the progressive coordinate at the intake $s_{i,intake}$ and the length l_i:

$$P_{i,plan} = n\,\rho\,g\,Q(s_{i,intake})\Delta h_i(s_{i,intake},l_i). \tag{3}$$

with n number full-load hours equivalent. Notice that the water restitution coincides with the turbine position since the gross head is the difference between $h(s_{i,intake})$ and $h(s_{i,intake}+l_i)$. This is obviously not always true but the aim of the algorithm is to analyze and evaluate the potential and not to really design a plant. Of course, several combinations of length l_i and distance between plants d_i can occur (Fig. 2) with the distance d_i equal to:

$$d_i = s_{i-1,restitution} - s_{i,intake} \tag{4}$$

In order to locate a new i-th plant, a minimum distances d_{min} between plants and a maximum length of exploited river segments l_{max} are setting depending on legal limits, stakeholders' suggestions and general planning constraints. The following optimization problem is then defined:

$$\begin{aligned} &\underset{s_{i,intake},l_i}{\text{maximize}} \quad P_{i,plan}[Q(s_{i,intake}),\Delta h_i(s_{i,intake},l_i)],\\ &\text{subject to} \quad l_i < l_{max} \text{ and } d_i,\ d_{i+1} > d_{min} \end{aligned} \tag{5}$$

where $P_{i,plan}$ is the planning potential. The position of the new plants then depends mainly on the resource availability and the spatial constraints. The technical and financial parameters are not included in the optimization problem since the aim of this module is to maximize the energy production accounting for planning constraints and not to deal with plant dimensioning of a specific project.

Other planning and legal restrictions (e.g. minimum flow discharge, environmental flow, protected and recreational area) can reduce the potential. Social, cultural and political information influences the energy exploitation. Data collected through participatory approach cannot be ignored in the planning process [24]. Rojanamon et al. [28] underlines the importance to bring social preferences at the beginning of the planning phase by means of public participation method. In this module, all the collected information, transformed in spatial data, can be considered as constraints for the hydro-power potential evaluation and creation of alternatives scenarios. The model deals with two kinds of spatial limits:

1. the area with legal, social and environmental constraints for building new run-off plants A_c;
2. the view-shed or visibility area of a set of viewpoints on the terrain [29], for example tourist or scenic points A_v.

To exclude these areas, the following constraint is added to the maximization problem, Eq. (5):

$$s \notin (A_c \cup A_v) \tag{6}$$

with $s \in [s_{i,intake}, s_{i,intake} + l_i]$.

Besides, according to the European directive 2000/60/EC [30], the issue of quantity and quality of water must be taken into account. The environmental impact of hydro-power plants can be relevant [31,32]. It is not the aim of this study to deal with the assessment of hydrological, sediment and ecological connectivity. However, the model consider, in the hydro-power potential evaluation, the minimum flow discharge (MFD) needed to achieve the environmental goals of the directive as a spatial input in order to include this information from site-specific study. In this case the discharge $Q_{i,intake}$ is reduced:

$$Q_{i,reduced} = Q_{i,intake} - MFD = Q_{i,intake}(1-p) \tag{7}$$

with p between 0 and 1. To locate potential new-plants accounting for the increasing of minimum flow discharge, the power $P_{i,plan}$ in the maximization problem (5) is computed in function of the reduced discharge $Q_{i,reduced}$.

In the optimization problem, other objective functions can be considered, e.g. the minimization of the exploited river length l_i for a given

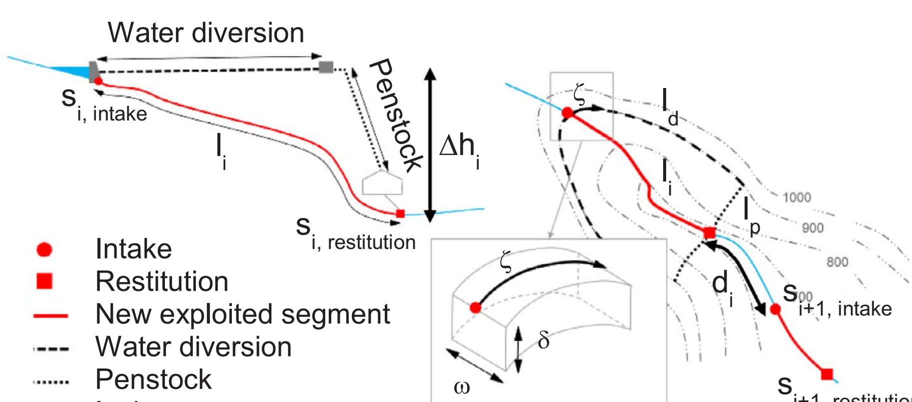

Fig. 2. Sketch of the variables for the location of new run-off plants.

power. Both the objective functions, the maximization of the potential and the minimization of the exploited river length, are implemented in the model code. This work concerns only the maximization of the potential since there is a strict dependence of the financial feasibility with the power. Besides, we deal with the mean annual value of discharge and we do not include the time variability. For this reason, seasonal changes of the minimum flow discharge cannot be currently considered in the optimization problem.

2.3. Technical potential

Given the position of the i-th plants, in order to compute energy losses and the technical potential, both the water diversion and the penstock paths have to be traced. The penstock corresponds to the line l_p of steepest gradient traced starting from the water restitution, Fig. 2. Both the sides, left ($l_{p,1}$) and right ($l_{p,2}$) bank, have to be considered. Consequently, the water diversion corresponds to the two segments of isohypse, $l_{d,1}$ and $l_{d,2}$, from the intake to the intersection with the penstock. The following equations, defining the technical potential, concern the j-th bank (left or right) of the i-th plant. In the derivation channel, the friction losses Δh_d are computed through the Chèzy formula under the assumption of uniform flow [33]:

$$\Delta h_d = l_d\left(\frac{Q}{k_s A R^{2/3}}\right)^2 \tag{8}$$

where R_h is the hydraulic radius, A the cross sectional area of flow, l_d is the derivation channel length, k_s the Strickler coefficient. The geometry of the channel is mandatory to compute R_h and A.

The Darcy-Weisbach formula [34] is used for the friction losses Δh_p of the penstock under the assumption of circular section with diameter D known:

$$\Delta h_p = \frac{f 8 Q^2}{\pi^2 D^5 g} l_p \tag{9}$$

where l_p is penstock length, D is the diameter, f is Darcy–Weisbach friction coefficient, which can be determined by iteratively solving the Colebrooke-White formula [35]:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\frac{\epsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}} \tag{10}$$

where ϵ is the roughness height and Re the Reynolds number.

The singular losses Δh_{loc} are related to the enlargement and narrowing respectively at the entrance and the exit of the forebay tank and to the bend at the beginning of the penstock. This local losses are linked with the motion of the fluid and can be neglected comparatively to that due to the friction for long pipes. They are defined as [36]:

$$\Delta h_{loc} = \xi\frac{v_i^2}{2g} \tag{11}$$

with v_i reference velocity.

By accounting for all the energy losses, the net head Δh_{net} is equal to:

$$\Delta h_{net} = \Delta h - (\Delta h_d + \Delta h_p + \sum \Delta h_{loc}). \tag{12}$$

The global efficiency of the plant includes the efficiency of the shaft, the alternator, the transformer and the turbine. The choice of the turbine depends on the head and discharge. Therefore, the technical potential of the i-th plant for the two left and right banks j is defined as:

$$P_{i,j,tec} = n\,\eta\,\Phi_{i,j,inst} = n\,\eta\,g\,\rho Q_{i,reduced}\,\Delta h_{i,j,net}. \tag{13}$$

with n number of full-load hours equivalent, η global efficiency and Φ_{inst} installed power.

2.4. Financial potential

Technical information such as channel and penstock paths, diameters and technical potentials are useful to derive the financial potential, i.e which are the technical solutions with a positive net present value (NPV). Notice that all the geographical constraints (steepest area, distance from electricity grid, etc.) increase the cost of new plants. The Net Present Value of investments for the i-th plant and for the bank j is defined as:

$$NPV_{i,j} = \left(1 - \frac{1-(1+r)^{\psi}}{r(1+r)^{\psi}}\right)(R_{i,j} - C_{i,j,o}) - C_{i,j,fix} \tag{14}$$

with $R_{i,j}$ the yearly revenue, $C_{i,j,o}$ the yearly operating costs, $C_{i,j,fix}$ the fixed costs, r interest rate and ψ the life of the hydro-power plant.

The yearly revenue R is calculated as the product of the electric energy times the price of the electricity e_{price}:

$$R = \eta\Phi_{inst} n \cdot e_{price} + c \tag{15}$$

where n are the number of full-load hours equivalent and c is a constant to consider potential additional subsidies.

The yearly operating cost C_o consists of two parts, size-dependent cost and size-independent cost [37]. The size-independent cost is related to maintenance of plant and pipelines, supervision and control of the plant. In the size-dependent cost there are charges for using the power grid and costs in connection with sales. The total yearly operating cost is then a function of the installed power. A general formula, according to the regression of several operational costs [38], is:

$$C_o = \alpha_o \cdot \Phi_{inst}^{1-\beta_o} + \gamma_o \tag{16}$$

with α_o, $0 < \beta_o < 1$ and γ_o regression coefficients. The regression shows a decrease of the unitary cost with respect to the power P_{inst} due to the scale economics.

The fixed costs C_{fix}, according to [27], include grid connection cost C_{grd}, compensation C_{comp}, electro-mechanical costs C_{em}, supply and installation cost C_l and excavation cost C_{excv} for derivation channel, penstock and power transmission lines, costs for power station C_{st} and intake C_{in}:

$$C_{fix} = (C_{grd} + C_{comp} + C_{em} + C_l + C_{excv} + C_{st} + C_{in})(1 + \alpha + \beta) \tag{17}$$

with α and β factors respectively to consider general and hindrances expenses.

The grid connection cost C_{grd} is the easement indemnity and it is assumed constant. It does not include cost of excavation and construction costs for the power transmission line that depend on the topography and on the distance.

The compensation cost C_{comp} represents the value to compensate owners for the construction of the hydro-power plant. It depends on the land use value c_{lu}, the yearly tributes paid by land owners also in case of expropriation c_{tr} and the upper part of the soil for wooded area c_{vup} [39]. These specific costs per unit of area depend on the kind of terrain and, therefore, on the spatial coordinate ς along the pipelines as shown in Fig. 2.

The compensation cost C_{comp} is computed by integrating these specific costs along the coordinate ς:

$$C_{comp} = \sum_l \int_0^l \left(c_{lu}(\varsigma) + c_{tr}(\varsigma)\cdot\frac{(1+r)^n}{r\cdot(1+r)}\cdot\gamma_c + c_{vup}(\varsigma)\right) w\varsigma d\varsigma \tag{18}$$

with w width of the terrain considered for the compensation, γ_c coefficient to consider buffer zones and $l = l_p, l_d, l_{pl}$ respectively length of derivation channel, penstock and power transmission line. The cost c_{vup} is computed with the formula:

$$c_{vup}(\varsigma) = \frac{c_{sv} + c_{lu}}{(1+r)^{(rot-y)}} - c_{lu} \tag{19}$$

with $c_{sv}(\varsigma)$ is the cost per unit of area related to the stumpage value of forest, $rot(\varsigma)$ rotation period per land use type and $y(\varsigma)$ the current age of forest.

The excavation costs C_{excv} is the digging cost for derivation channel, penstock and power transmission line. The cost depends on the kind of terrain and the slope s, steeper slope has an higher excavation cost than lower slope. The minimum specific excavation cost per unit of volume is $c_{excv,min}(\varsigma)$, the maximum specific cost for steepest slope, greater than s_{max}, is $c_{excv,max}(\varsigma)$. The excavation cost per unit of volume is consequently varying along the coordinate ς in function of the slope s and between $c_{excv,min}(\varsigma)$ and $c_{excv,max}(\varsigma)$:

$$C_{excv} = \sum_{l} \int_0^l \left[c_{excv,min}(\varsigma) + \frac{c_{excv,max}(\varsigma) - c_{excv,min}(\varsigma)}{s_{max}} \min(s(\varsigma), s_{max}) \right] w\delta\varsigma d\varsigma \tag{20}$$

with w and δ respectively the width and the depth of the excavation, $w\delta\varsigma$ is the volume of excavation.

The Electro-mechanical cost includes the turbine, the alternator and the regulator costs [19]:

$$C_{em} = \gamma_{em} \Phi_{inst}^{\alpha_{em}} \Delta h_n^{\beta_{em}} + c_{em} \tag{21}$$

with α_{em}, β_{em}, γ_{em} and c_{em} empirical coefficients.

Supply and installation costs for derivation channel l_d, penstock l_p and power transmission line l_{pl}, which links the transformer near the turbine to the existing grid, are assumed linear to the lines:

$$C_l = \sum_{l} c_l \cdot l \tag{22}$$

with $l = l_p$, l_d, l_{pl} and c_l specific costs per unit of length respectively of derivation channel, penstock and power transmission line, and C_l total supply and installation cost.

The power station costs C_{st} concerns the construction cost of the power station while C_{in} is the cost of the water intake structure. These costs are generally a percentage of the electro-mechanical cost C_{em}:

$$\begin{aligned} C_{st} &= \alpha_{st} C_{em} \\ C_{in} &= \alpha_{in} C_{em} \end{aligned} \tag{23}$$

with α_{st} and α_{in} percentage of the electromechanical cost derived from statistical computation based on technical manuals and existent mini-hydro plant projects.

Table 2 summarizes all the indicators of the different levels of hydro-power potential.

Notice that the conceptual model considers the progressive coordinate along the river, the derivation channel, the penstock and the power transmission line. Therefore, the morphology, the current land use and generally the spatial dimension have a significant role in the computation of the hydro-power potential. For this reason, in the next session, we deal with the development of a model code able to integrate the spatial information.

3. GIS-based model code

In the literature there are several studies dealing with the computation of the energy potential from wind [40–46], solar [47–49], biomass [50,51,6,52–54] and geothermal [55] sources by means of GIS. These tools are based on raster computation since the energy production depends only on one variable related to the natural source, e.g. wind velocity, irradiation and ton of biomass. In the case of hydro-power two variables, i.e. the water amount and the gross head, have to be combined. The resulting algorithm can be quite complex and GIS-based models are scarcely present in the literature. Bódis et al. [4], Palomino Cuya et al. [1], Kusre et al. [12], Lehner et al. [56], Rojanamon et al. [28] are the main examples on how these variables can be considered in GIS tools. Most of these models are still based on raster data manipulation although some information regarding hydro-power are better represented by vector formats. Punys et al. [57] review other

Table 2
Definition of indicators for the different level of hydro-power potential.

Level of potential	Indicator
Theoretical	$P_{b,theo} = P_{b,own} + P_{b,up}$
Planning	$\underset{s_{i,intake}, l_i}{\text{maximize}}\ P_{i,plan}$ subject to $l_i < l_{max}$, d_i, $d_{i+1} > d_{min}$ and $s \notin (A_c \cup A_v)$
Technical	$P_{i,j,tech} = n\eta g\rho Q_{intake}\ \Delta h_{net,j}$ with $j = 1,2$
Financial	$P_{i,j,fin} \mid NPV(i,j) > 0$ with $j = 1,2$

tools for small hydro-power resource planning based on GIS. They underline as some models operate as a standalone and integrate only the results into the GIS environment. Therefore, the challenge is to model the energy potential by integrating all the different levels of information such as legal, environmental, social, technical and financial constraints in a GIS environment. The model code has been developed as GRASS GIS extension, *r.green.hydro* and it is available on the GRASS community site [21].

The code is divided into four main modules: (1) *r.green.hydro.theoretical*, (2) *r.green.hydro.planning*, (3) *r.green.hydro.technical*, (4) *r.green.hydro.financial*. Each main module defines a level of potential according to Table 2. Fig. 3 reports the structure of the model code with mandatory and optional inputs for all the modules. Vector data input (i.e. points, lines and polygons) are represented in light blue,[1] raster data (cells with associated values) in blue, while scalar values in dark blue. Vector data are used when the topological information is relevant, raster data whether this model choice is more efficient. The Pygrass library [22] allows to combine directly both the information. Each grey box represents a GRASS add-on, i.e. an extension of the GRASS GIS software, light grey for the main modules and dark grey for the auxiliary modules. Notice that each module does not depend on the output of the previous one and it can be independently used or combined.

For the evaluation of the theoretical potential, the module *r.green.hydro.theoretical* is based on Eq. (1). Input of the module are two raster maps with elevation and discharge data. On the base of the elevation map, the study area is divided into several sub-basins by means of the GRASS module *r.watershed* [58,59]. Each sub-basin label is a unique positive even integer, the same label is assigned to the stream segment corresponding to the watershed basin. On the base of the *r.watershed* stream network, Eq. (1) is solved for each sub-basin.

The core of the module *r.green.hydro.planning* is the optimization problem, (5). The mandatory input data are the stream segments (vector format), the discharge and elevation raster map, the maximum distance l_{max} and the minimum distance d_{min}. To solve Eq. (5) and locate the plants, in the auxiliary module *r.green.hydro.optimal* a recursive algorithm has been developed.

In Fig. 4, the pixels represent the cells of the raster data (discharge and elevation) along the stream lines (vector format). A brute force algorithm (i.e. it computes the function's value at each point of a multidimensional grid of points, to find the global minimum of the function [60]) is used to determine the unknowns $s_{i,intake}$ and l_i that maximize the function $P_i(s_{i,intake}, l_i)$, grey pixels in Fig. 4. The next step is considering the remaining exploitable segments on the left and right side of the i–plant. A tree is then recursively built until the length of all the remaining segments, black pixels in each branch of Fig. 4, is less then d_{min}, i.e. the minimum distance between a water restitution and the intake of the closest plant. The final output is a vector data, named potential plants in Fig. 3, with lines representing the exploited river segments. In the case of additional constraints in the main module

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

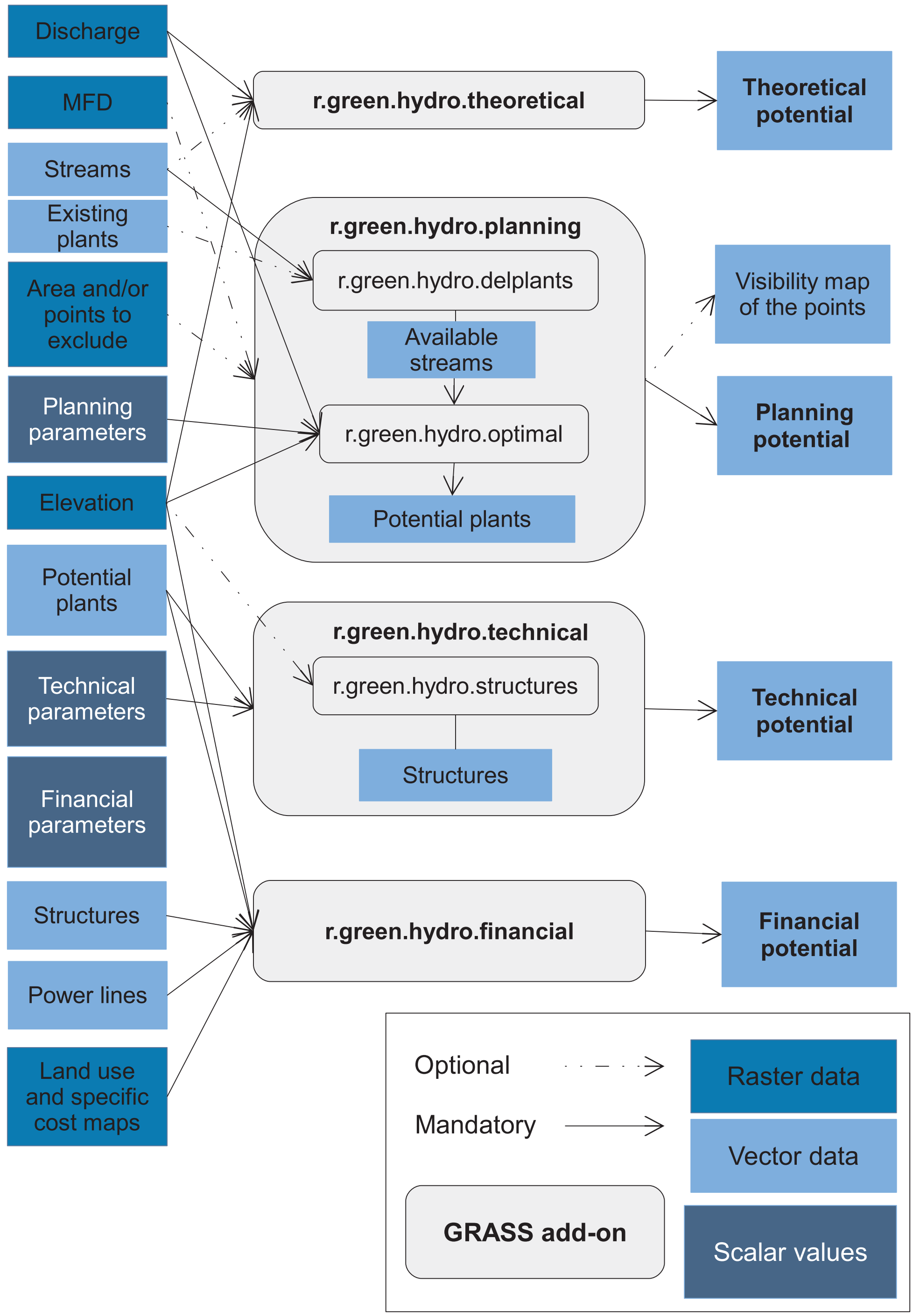

Fig. 3. Sketch of r.green.hydro GRASS add-on with sub-modules, input and output data.

r.green.hydro.planning, Eq. (6), the view-shed or visibility area A_v is computed through the GRASS add-on *r.viewshed* starting from the vector data containing the set of viewpoints [29]. The raster data defining the area A_c and the vector data with the viewpoints are optional input for the module *r.green.hydro.planning* in order to exclude the corresponding areas from the computational domain in the optimization problem. Besides, river segments that are already exploited by existing plants can be deleted through the auxiliary module *r.green.hydro.delplants*.

In the module *r.green.hydro.technical*, the auxiliary module *r.green.hydro.structure* is called to trace the water diversion and the penstock starting from the exploited river segments, the vector data named potential plants in Fig. 3. The algorithm computes the isohypses passing from the intake point (first point of the exploited river segment) through the GRASS module *r.contour* based on the elevation raster map. The isohypses is then split by considering the intake point position and the point that minimizes the distance between the restitution and the isohypse. This segment of isohypse represents the derivation channel. The penstock is the segment passing from closest points of the left and right side of the isohypse and the restitution point of the plant. These structures are in vector format and are mandatory to compute energy losses based on the lengths of the pipelines l_d and l_p. For the derivation channel, Eq. (8) is implemented in the model code for the case of a channel with circular section and water level equal to 2/3 of the diameter. In the penstock, if the diameter of the pipeline is unknown, the friction losses are assumed equal to a percentage of the gross losses and,

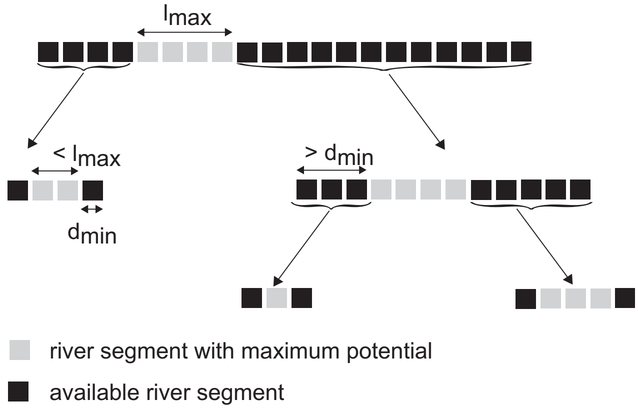

Fig. 4. Recursive function for optimal plant position.

through (9), the diameter is computed. The total efficiency of the plant is the product of shaft, alternator and transformer efficiencies, generally equal to 1, 0.96 and 0.99, times the efficiency of the turbine. A list of the most common turbines with efficiency and ranges of discharge and head is available in the model code and can be updated by the users. The algorithm selects the turbine based on the head and the discharge of the potential plant.

The net present value and the financial potential are computed in the module *r.green.hydro.financial*. The compensation and excavation costs depend on the spatial distribution of the specific costs and on the slope of the terrain as shown by Eqs. (18) and (20). These data are then raster maps and, especially, c_{lu}, c_{tr}, c_{sv}, rot and y raster data can be computed starting from the land use raster map by reclassifying the values through the GRASS module *r.reclass*. The specific costs in Eqs. (18) and (20) are computed for each cell of the raster maps along the lines of the vector map with the pipelines. Finally, the total compensation and excavation costs are obtained by calling the GRASS module *v.rasts.stats* that calculates the sum of raster values based on a vector map and solves the integrals. To determine all the other costs in Eq. (17), the operating costs, Eq. (16), and the revenues, Eq. (15), the input are scalar and not spatially dependent data. Finally, the NPV is computed for each plant by knowing the power P reported in the vector data named potential plants and the related structures.

4. A site-specific model: the Gesso and Vermenagna valleys

The software is tested in a case study located in the Italian Alps, the Gesso and Vermenagna valleys, Fig. 5.

A big portion of the case study area is a protected area, the Alpi Marittime Natural Park. Thanks to the richness of natural resources, a strong interest in hydro-power generation has been always present in the area since the first half of the 20th century. The total installed power is consequently very high, about 1140 MW. The biggest power plants are sited in Entracque (1065 MW) and in Andonno (65 MW). There are eight plants completely located within the protected area. These plants were built before the institution of the Natural Park of the Maritime Alps and the Natura 2000 sites.

4.1. Approach and parameter definition

The four modules are applied to the case study in the following order. Firstly, the theoretical potential is assessed in order to define the upper limit of energy availability. Secondly, on the base of the local water plan and by means of the optimization algorithm, the planning potential and the optimal plant position are calculated depending on

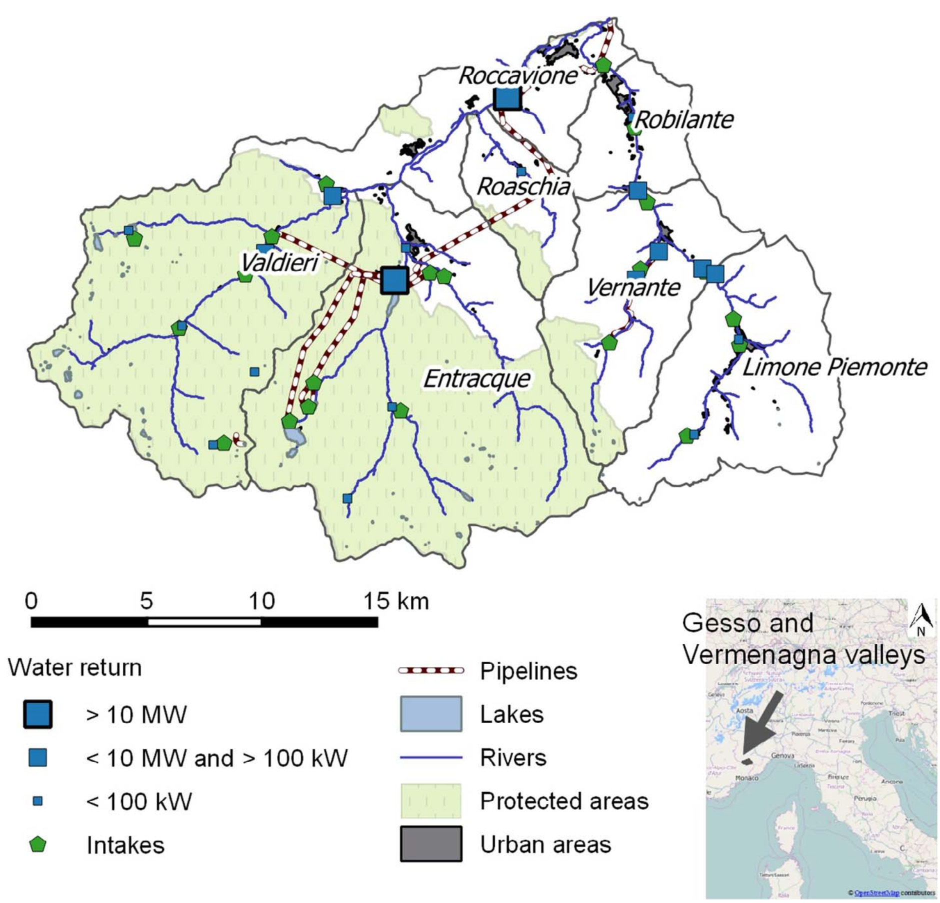

Fig. 5. Geographical setting and existing plants in the Gesso and Vermenagna Valleys.

different combinations of plant lengths and minimum water flows. The output of this module, for each considered parameter set, becomes the input of *r.green.hydro.technical*. The infrastructures and the technical potential, accounting for energy losses, are then evaluated. Finally, the financial evaluation is figured out by means of the module *r.green.hydro.financial* by considering the position of the plants and the infrastructures obtained through the previous modules in function of different energy prices.

In order to compute the specific annual mean discharge, the work refers to the local water plan [61], a transposition of the European directive 2000/60 prescriptions [30]:

$$q_m = 0.00860H + 0.03416A - 24.5694 \quad (24)$$

with H altitude of the catchment (m) equal to $0.9H_{max} + H_{min}$,H_{max} and H_{min} respectively are the maximum and minimum altitude of the corresponding catchment and A is the average annual precipitation evaluated with isohyet map (mm). Secondly, the regional water plan defines three MFD starting from morphological and hydro-geological parameters:

$$MFD = Kq_m SMA \quad (25)$$

where q_m is the specific average contribution of the natural flow; K is the experimental parameter associated with homogeneous areas; S is area of the catchment; M is morphological parameter; A is the parameter of interaction between surface and ground water. All parameters K, M, A are reported in the regional plan [61]. Due to the presence of big plants in the area existing water diversions have already changed the river flow. In the model of the Gesso and Vermenagna valleys, the flow diverted at the intake is assumed equal to the difference between the annual mean discharge $q_m \cdot S$ and the MFD that each plant must grant. In the planning module there is the possibility to exclude protected area from the computation of the hydro-power potential and to increase the MFD. Three different values of MFD are considered, MFD computed through Eq. (25) and MFD set equal to 25% and 50% of the natural discharge

Regarding the prediction of the number of full-load hours equivalent, it is conditioned on the time variability of water discharge and depends on the accuracy of the hydrological studies. This work does not deal with the assessment of the flow duration curve and the discharge data but it suggests a model for the site selection of small hydro-power plants based on technical, environment, social and financial criteria. Therefore, the number of full-load hours equivalent is set to 3392 h according to the national statistics [62].

The three chosen values of MFD are combined with different maximum lengths of exploited river segments l_{max} (100 m, 200 m, 400 m, 800, and 1000 m) while the distance between plants is set equal to 100 m. A scenario with l_{max} equal to 100 m supports the construction of small-hydro power plants exploiting small portion of the rivers while, by setting a higher values of l_{max}, also bigger run-off hydro-power plants are allowed.

In order to compute energy losses for each scenario, in the technical module, the flow velocity in the derivation channel is set equal to $1\,m\,s^{-1}$ and the Strickler coefficient equal to $75\,m^{1/3}\,s^{-1}$ (steel pipeline), while in the penstock we assume the friction losses equal to the 4% of the gross head since generally the purpose is to choose the diameter that minimizes the losses.

For the financial potential, the scalar parameter assumed in the site-specific model are reported in Table 3.

To compute the compensation cost, Eq. (18), we refer to the text on expropriation for public utility D.P.R. n. 327/2001 [39], updated in 2013 with $\gamma_c = 1.25$ and $w = 0.6$ m for the power lines and 2 m for the other lines. For the excavation cost, δ is equal to 0.6 m in the case of power line and 2 m for the other lines and the maximum slope s_{max} to 50°. The specific costs to reclassify the land use raster maps are reported in Table 4. The rotation period and the current age of forest are, respectively, set to 35 and 20.

4.2. Local knowledge and historical decisions versus model results

A significant element of any simulation study should be the validation of the simulation model. The purpose of this process is to determine if the overall model provide a sufficient accurate representation of the real world. Relevant difficulties with this kind of validation is the lack of accurate real world data. Comparison against approximate real world data may not give absolute confidence in the model, but it should be help to increase confidence [63]. In this work, we compare the model results (1) with data collected during events involving local stakeholders and (2) with historical decisions related to already existing hydro-power plants.

Firstly, during the recharge.green project local stakeholders were involved in three different events. The last event included scientific and local experts' presentations with the aim to give information to citizens on the project and its results. In the final event, more or less sixty citizens participated. Instead, in the first two events, the existing potentials in the Gesso and Vermenagna valleys were discussed.

The first focus group [64] involved nineteen local experts. In this case, local experts were people or groups with both scientific and local knowledge of water resource management and energy production. This event was organized at the begin of the project for collecting local data and integrate missing information into the model.

The second focus group involved other 12 important local private and public stakeholders. One of the specific objective of this event was to confirm (or not confirm) the spatial description of the territory through the *r.green.hydro* maps. During this focus group, a geographical map of the valleys was shown to the stakeholders. The discussion focused on the identification of areas (1) with higher energy potential, (2) with lower availability of water and (3) areas that should be preserved due to their environmental or landscape value. The output of this focus group was a map with the following qualitative information:

Lower water availability areas. Currently, the hydro-power reservoir of Entracque is used to store the water not only for energy purposes but also for irrigation of the agricultural areas. Consequently, the water availability downstream the Sant'Anna weir and the energy potential are currently lower, Fig. 6(c) and (d).
Higher potential areas. Some areas inside the park are interesting from the energy perspective but, at the same time, they are not exploitable without compromising the environment in a such fragile system.

The qualitative data collected in the events were compared with the maps of energy potential provided by the different modules of *r.green.hydro*. Especially, the most interesting result concerns the area pointed out by the model with a high energy potential, Fig. 7.

This area was also indicated by local private stakeholders as suitable for the construction of new hydro-power plants. Besides, as shown in Fig. 6, the

Table 3
Financial scalar parameter for the site-specific model, based on (1) several case studies implemented for Alpine context [38], (2) price list of the Piedmont Region for public works, (3) analysis of several existing projects for mini-hydro power in Italy.

Interest rate	Life of the plant	Operating cost(1)			Fixed cost [27]	
r (–)	ψ (year)	α_o	β_o	γ_o	α (–)	β (–)
0.03	30	7000	0.45	0	0.15	0.10

Electro-mechanical cost [19]				Linear cost(2)		Percentage(3)	
α_{em}	β_{em}	γ_{em}	c_{em}	c_{lp},c_{ld} (€ m^{-1})	c_{lpl} (€ m^{-1})	α_{st} (%)	α_{in} (%)
0.56	−0.112	15,600	0	310	250	52	38

Table 4
Rules to compute raster maps with specific costs staring from the land use and based on the text on expropriation for public utility D.P.R. n. 327/2001 [39] and the price list of the Piedmont Region for public works.

Land-use value (–)	c_{lu} (€ m^{-2})	c_{tr} (€ m^{-2})	c_{sv} (€ m^{-2})	$c_{excv,max}$ (€ m^{-3})	$c_{excv,min}$ (€ m^{-3})
Rocks glacier	0	0	0	392	292
Urban areas	0	0	0	255	14
Gravel bed	0	0	0	250	100
Waters	0	0	0	250	100
Gardens	200	10	0	59	8
Mining areas	4000	100	0	255	14
Agricultural areas	2000	100	0	59	8
Meadows	1500	10	0	59	8
Pastoral land	1000	100	0	59	8
Forestry land	3000	100	5000	59	8

results of the module *r.green.hydro.optimal* demonstrate a decrease of the energy potential downstream the Sant'Anna weir. The current uses of water (Fig. 6(b) and (d)) is reducing the water availability, as suggested by stakeholders, downstream the Sant'Anna weir and, consequently, the residual energy potential is lower with respect to the scenario without existing water diversions (Fig. 6(a) and (c)). Some of the stakeholders underlines that the energy potential can be higher if the water diversion for agriculture uses is reduced. On the other hand, this water is necessary for the flat area downstream of the case study. The site-specific model is thus able to represent an existing conflict, pinpointed by local stakeholders, between different uses of the resource.

Secondly, historical decisions can be compared to the results of the site-in specific model when it is run under the same condition. In order to validate to overall behavior of the model, we verify if the model output and historical data are sufficiently similar.

In this case, we only consider the Vermenagna and the Valle Grande rivers (on the left orographic side, Fig. 8) since there are not intakes for big hydro-power plants and we can collect data about the concessions of already existing run-off hydro-power plants. The upper part of the valley is characterized by the presence of four main hydro power plants with different lengths of exploited river segments l_i (from about 500 m to 4000 m) and different capacity (from about 10 kW to almost 1 MW). With the purpose of having an overall figure of the energy potential in the selected area, we can assume as initial condition the natural discharge. In this specific case, we run the module *r.green.hydro.planning* with the maximum length l_{max} equal to 4000 m and minimum flow discharge according to the regional plan [61]. Secondly, we evaluate the financial feasibility by means of *r.green.hydro.structure* and *r.green.hydro.financial* for the already existing plants with energy the price equal to 0.20 € kWh^{-1}.

As illustrated in Fig. 8, the old concessions are placed in areas with high energy potential according to our model results, while the first part of the two rivers seems to not be suitable for the construction of hydro-power plants.

The first concession for hydro-power plants in this part of the valley concerns the intake located on Valle Grande river. This run-off river plants has a capacity of 980 kW. The plants is an area with high energy potential and, above all, the output of the model related to this plant has the highest *NPV* (3·10^6 €). The second plant is instead located in the area with highest potential, a low *NPV* (0.09·10^6 €) but also a low initial cost. As shown in Table 5, all the first three realized plants have a positive *NPV*.

The last plant (600 kW of installed capacity) is located in a part of the river with high potential. Based on model results, the plant has a high *NPV*. Its concession is later than the two smaller plants with zero *NPV* without considering local subsidies. The existing plats may not always follow the physical potential due to external factors that cannot be easily integrated into the GIS model (e.g. political decision, social pressure, etc.). Therefore it is very difficult to reproduce faithfully the

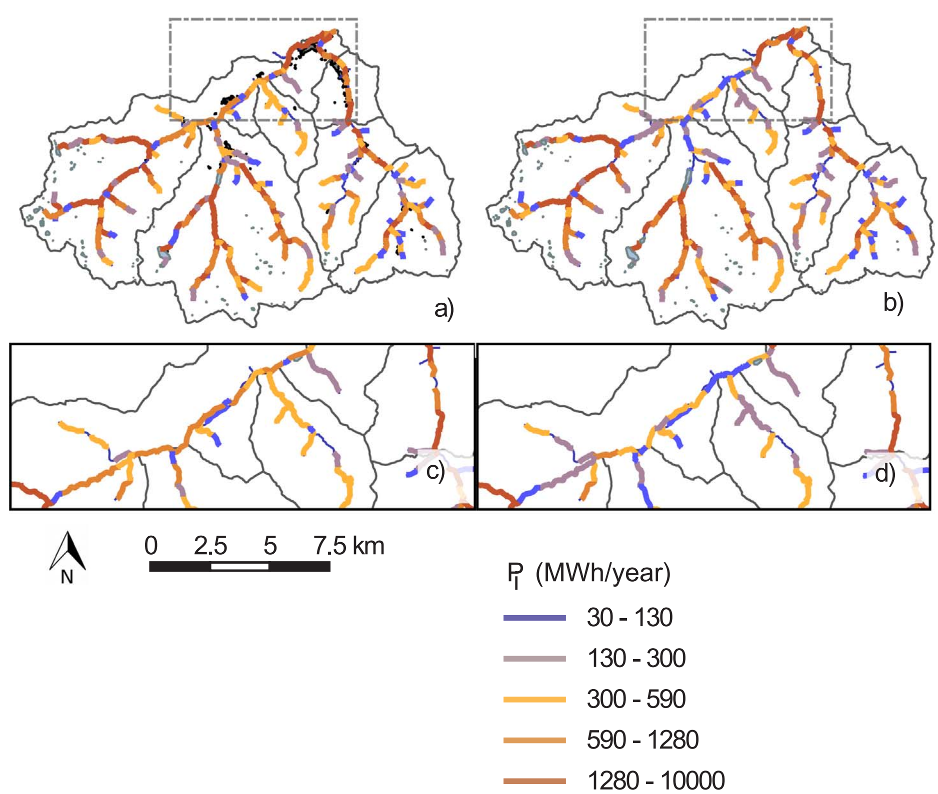

Fig. 6. Comparison of results obtained with *r.green.hydro.optimal* (maximum length l_{max} equal to 1000 m and minimum distance d_{min} equal to 100 m) with discharge map based on regional plan [61] (a) without considering existing water diversions and (b) by taking into account different current uses of water. (c) and (d) are zooms on the valley downstream the Sant'Anna weir respectively of case (a) and (b).

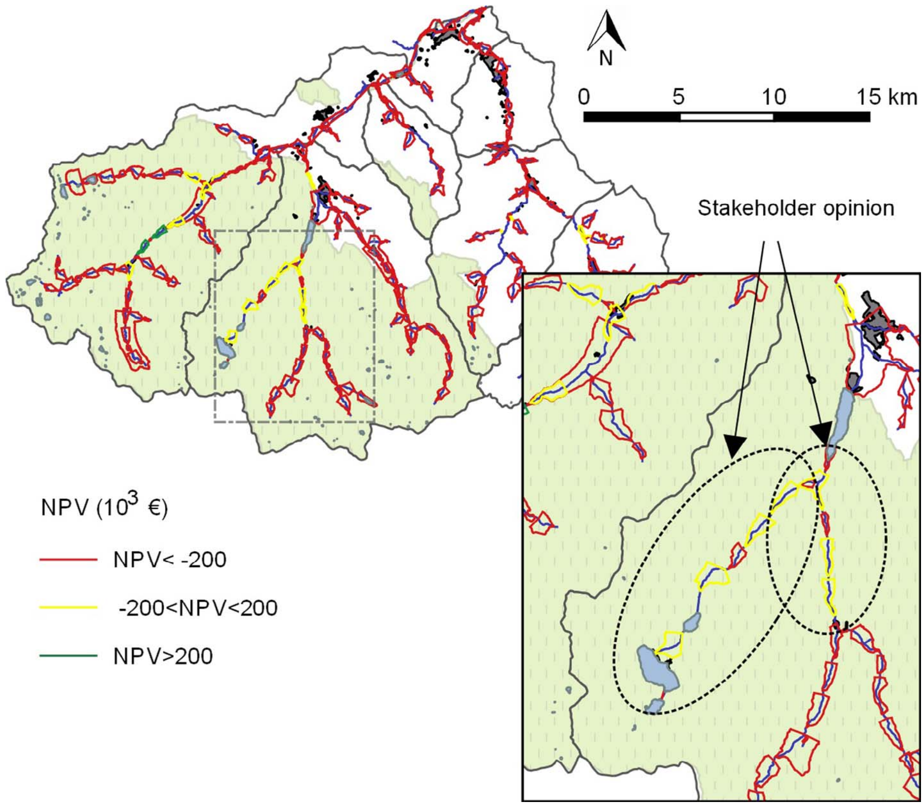

Fig. 7. Net present value for each potential new plant obtained by applying *r.green.hydro.financial* to the results of *r.green.hydro.technical* and *r.green.hydro.optimal* with energy price set to 0.15 € kW^{-1} according to Italian energy authority GSE [65].

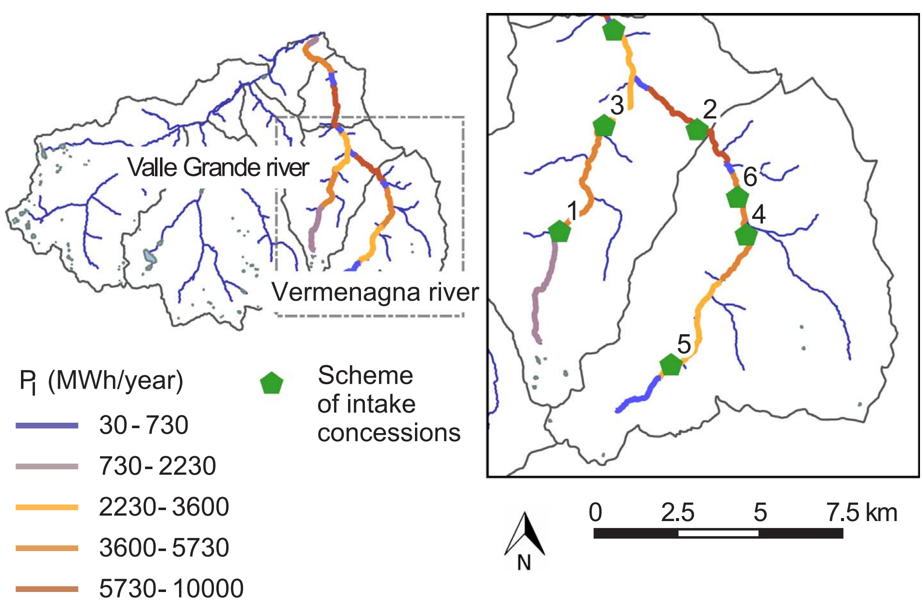

Fig. 8. Comparison between the scheme of the historical hydro-power concessions for the Vermenagna river and the model results obtained with *r.green.hydro.planning* (maximum length l_{max} equal to 4000 m and minimum distance d_{min} equal to 100 m, discharge map based on regional plan [61] without considering existing water diversions).

sequence and the order of the local decisions. Furthermore, consider that, the model is not a tool for designing new hydro-power constructions but only to support energy planning. However, the figures confirm the trend of most of the historical decisions to exploit segments with high energy potential and higher *NPV*.

Thanks to the comparison of output maps with local knowledge and historical decisions, the model of the Gesso and Vermegnana valleys is then suitable for evaluating the residual energy potential of the valley.

4.3. Results and discussion

Different scenarios with several combinations of minimum flow discharge, distance between intake and restitution l_{max}, different energy prices and interest rates have been considered since the prediction of the energy potential and the energy planning are deeply conditioned on these several parameters.

In 2016, the Italian energy authority GSE set a minimum price e_{price}

Table 5
Comparison of existing plants with model outputs.

Plant size (kW)	Order of concession (–)	Potential (GWh year^{-1})	NPV 10^6 €
980	1	4.0	3
170	2	6.0	0.09
280	3	3.0	0.5
10	4	4.0	0
50	5	2.5	0
600	6	4.0	1.5

for hydro-power energy equal to 0.15 € kWh^{-1} [65]. Accounting for an increasing of energy prices assumed as 0.20 € kWh^{-1} and 0.25 € kWh^{-1}, i.e. possible subsidies, several scenarios are obtained. Fig. 9 refers to the energy potential and the exploited discharges for different definitions of potential with the energy price set equal to 0.20 €kWh^{-1}. As expected, the total energy potential $\sum P_i$ decreases in function of different minimum flow discharge and it increases depending on the distance between intake and restitution l_{max}. Instead, the total water flow diverted at the intakes $\sum Q_{i,intake}$ grows inversely proportional to the length l_{max} for the planning and technical potential. In the case of smaller values of l_{max} the same segment of rivers is exploited with a higher number of plants. The total potential remains comparable but the total flow $\sum Q_{i,intake}$ is higher. This means that the cumulative energy production generated by smaller run-of-river power plants is not relevant compared to the hydro-power energy produced by plant with greater power. However, the water quantity is strongly decreasing and, consequently, the quality of river ecosystems can be affected. Instead, in the case of greater values of l_{max} the same segment of river is exploited by a low number of plants with higher gross heads and smaller discharges. Despite, in the case of financial potential, greater lengths l_{max} lead to an increasing of the energy potential and of the total water flow through the turbines. In fact, smaller hydro-power plants become financially unsuitable, consequently a decreasing of the number of plants reduces the potential and total water flow through the turbine. Therefore, planning the construction of hydro-power plants by considering financial and technical aspects can support a better exploitation of energy potential with lower values of diverted discharge.

As shown in Fig. 10, in the Gesso and Vermenagna valleys, the plants with higher energy potential are sited in protected areas (points with ∘ symbol). The energy potential P_i of the plants and the NPV_i are strictly correlated and they rise with the distance from urban areas where higher gross head are available. In fact, the plants with the highest financial potential are located in protected areas at a significant distance from urban areas (7 km). Instead, plants outside the protected areas (points with △ symbol) have lower potential and they are closer to urban areas. The graph in Fig. 10(c) shows that few plants remain feasible by increasing the interest rate to 0.05 and decreasing the l_{max}. Under these assumptions, only one plant is still feasible in not protected area.

By considering all the plants, as reported in Fig. 11, the feasibility falls in the case of distances from urban areas greater than 7 km and the number of plants with negative NPV becomes relevant. Notice that a order of magnitude increase occurs in the costs for installation and excavation of the power line C_{pl}. If the cost for civil engineering works is not balanced by revenues, namely plants with high values of energy potential P_i, the NPV becomes negative.

Consequently, only small hydro-power plants close to the urban areas and outside the protected areas seem to have residual potential. Nevertheless, these plants are very sensitive to interest rate.

Furthermore, changes in energy cost strongly influence the feasibility of small hydro-power plants. In Fig. 12, in all the scenarios, the number of hydro-power plants with power lower than 100 kW escalates by changing the energy price from 0.20 € kWh^{-1} to 0.25 € kWh^{-1}. In the scenarios with lower l_{max}, namely only with small hydro-power plants, the price sensitivity affects a higher number of plants as shown in the graph on the right of Fig. 12.

Finally, the model results show the availability of high energy potential only in protected area or far from the infrastructures and a high influence of financial variables on the feasibility of small hydro-power plants. A limited opportunity to exploit new sites is then foreseen by the model in the Gesso and Vermenagna valleys.

5. Conclusion

In this study, we developed a model for evaluating the hydro-power potential with the purpose of support decision makers and energy planning. The open-source model is suitable for assessing energy potential by considering combinations of gross head and discharge. Thanks to the modular structure of the model, other information can be added to this first energy potential evaluation and, above all, financial indicators can be considered In fact, the design of the model, as a set of different and independent tools, supports the development of different scenarios. This model feature is essential in order to analyze the influence of technical, planning and financial variables on the energy potential. Secondly, the use of vector and raster data allows to directly consider all variables in a GIS environment accounting for their spatial variability and by including information such as the distance from urban areas or the dependency of civil engineering works costs on land use.

Another important step to have a suitable model is the validation of the site-in model. Since a GIS model generally describes a complex territory, the accuracy of the model has been verified by comparing model output with stakeholder knowledge and existing concessions for hydro-power plants. Three events, involving stakeholders and citizens, verify the capability of the model to describe the territory and its spatial heterogeneity. Information collected during the three events are in agreement with model results obtained under the same assumptions. Secondly, we compare model output with real world historical decisions. Generally, historical decisions on the realization of hydro-power plants depend on local conditions and choices that cannot be strictly reproduced by this kind of models. However, the model confirms that river segments with higher technical and financial potential are firstly exploited.

In this valley with a very relevant hydro-power exploitation, segments with low potential are the only ones without plants. For this reason, decision makers can use the model also in order to evaluate the dependency of the prediction to input variables, above all the financial and territorial parameters. In the case study of Gesso and Vermenagna valleys, the energy price strongly influences the feasibility of smaller plants while the cost of civil engineering works becomes relevant far from the urban areas. Only few sites in protected area have a high

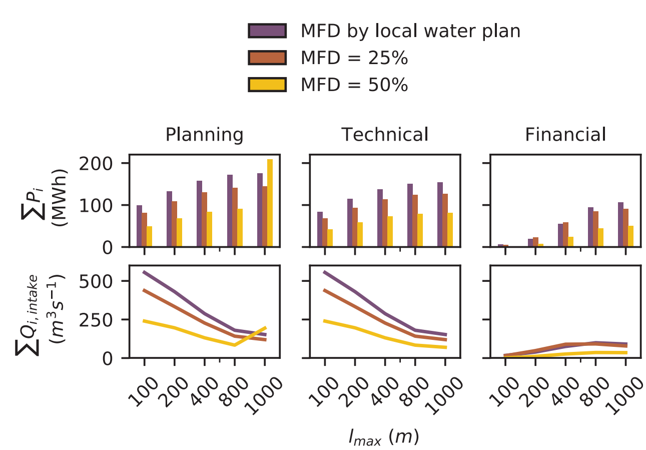

Fig. 9. Total energy potential (Planning, technical and financial with energy cost set to 0.20 € kWh^{-1}) and total water flow diverted at the intakes with different minimum flow discharges and different l_{max}.

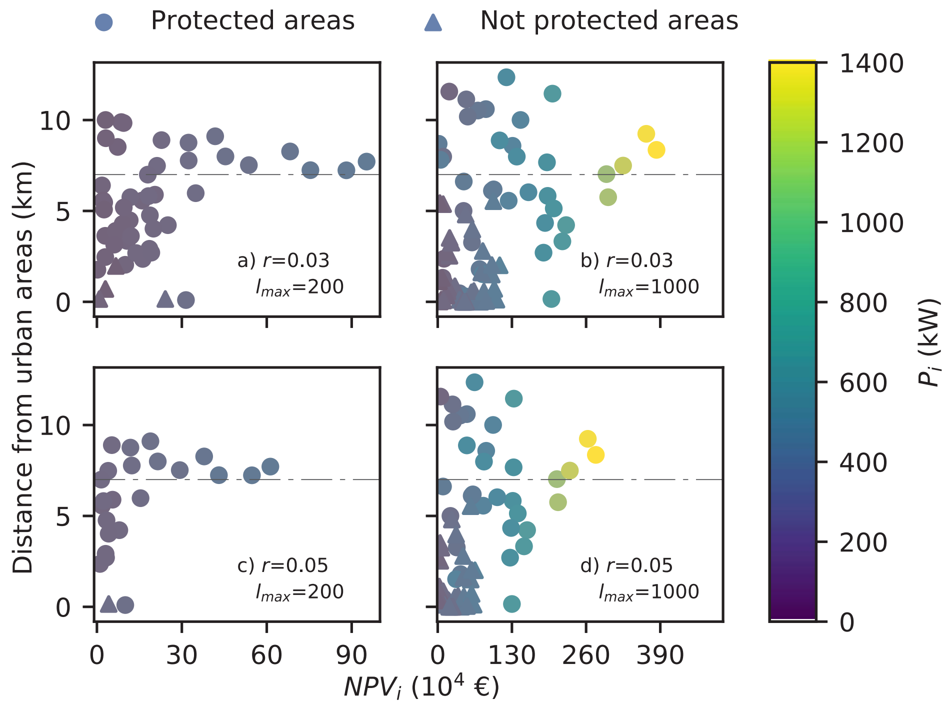

Fig. 10. Distance from urban areas of each plant in function of NPV and energy potential P_i in the case of energy price equal to 0.20 € kWh^{-1}, l_{max} and *r* respectively set to (a) 200 m and 0.03, (b) 1000 m and 0.03, (c) 200 m and 0.05 and (d) 1000 m and 0.05 and for positive *NPV*.

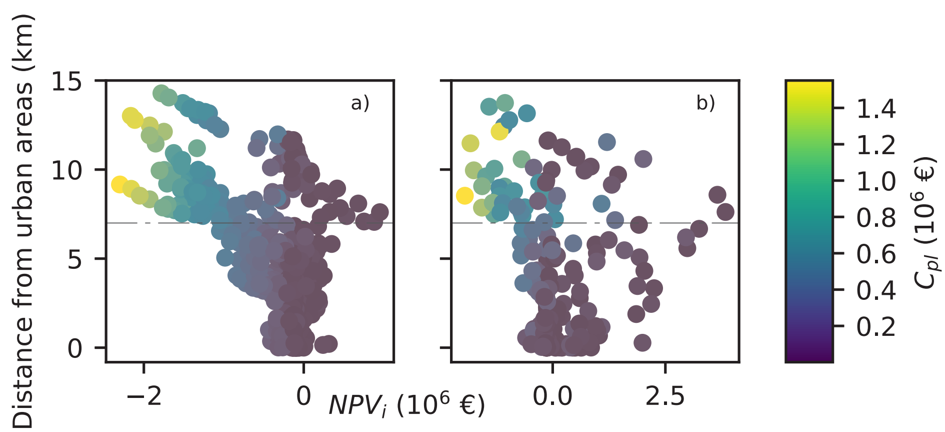

Fig. 11. Distance from urban areas of each plant in function of *NPV* and costs for installation and excavation of the power line C_{pl} in the case of energy price equal to 0.20 € kWh^{-1}, l_{max} and *r* respectively set to (a) 200 m and (b) 1000 m.

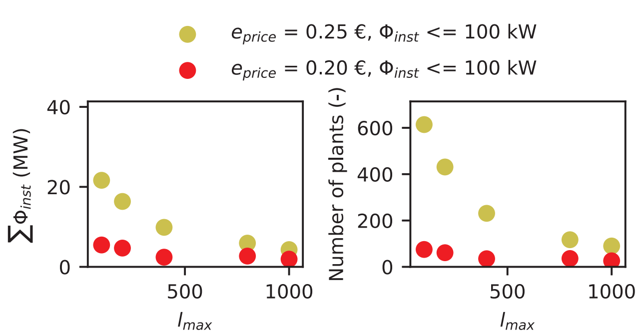

Fig. 12. Total power and number of plants with net present values greater then zero.

energy potential also accounting for the financial variables. In conclusion, the high sensitivity to energy price and interest rate of smaller hydro-power plants and the presence of residual potential only far from urban areas or, above all, in protected areas make the valleys not attractive for the realization of new hydro-power plants.

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Appendix A. Software and data availability

Name of software: r.green.hydro.
Developers: Giulia Garegnani and Pietro Zambelli.

Contact: giulia.garegnani@eurac.edu

Year First Available: 2015.

Hardware required: A personal computer.

Software Required: Microsoft Windows, Mac OSX, or Linux operating system. GRASS 7.0, Python and the following libraries, numpy, scipy, numexpr.

Software Availability:

https://trac.osgeo.org/grass/browser/grass-addons/grass7/raster/r.green/r.green.hydro

Cost: All software elements are open source and freely available. GRASS GIS add-ons are offered under the GNU General Public License. The GRASS community site for the ADD-on is https://grasswiki.osgeo.org/wiki/AddOns/GRASS_7

The data are freely available as open data through:

- Geographic data and existent hydro intakes, Piedmont Region Geographic database http://www.regione.piemonte.it/geopiemonte/
- Land use, Territorial Forestry Plans (PFT) of Piedmont Region http://www.sistemapiemonte.it/montagna/sifor/.

A complete and pre-elaborated GRASS GIS project mapset is available for testing and for further analysis through: https://gitlab.inf.unibz.it/URS/Gesso_Vermenagna

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.02.043.

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