



**SMALL HYDROPOWER RESOURCE ASSESSMENT USING
GEOGRAPHICAL INFORMATION SYSTEMS**

by

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Andrea Brandelli Schaan holds a Bachelor degree in Biological Sciences by the Federal University of Rio Grande do Sul, Brazil where the research interest was centered in environmental conservation and protection. Working as environmental supervisor, especially for small hydropower projects, she had a multidisciplinary teamwork and decide go deeper in her studies with the Master in Economics and Environmental Management at University of Porto for a wider knowledge. In this program, her research interest relies on renewable energy planning, and the research time spent in the Power Systems Research Laboratory at University of La Rioja in Spain results in the present dissertation.

Resumo

O progresso industrial e tecnológico está geralmente relacionado com o aumento do consumo de energia e deve ser acompanhado da ampliação da capacidade das redes de transmissão e de distribuição bem como pela construção de novas centrais de produção elétrica. Entretanto, estes aumentos devem respeitar as restrições técnicas e/ou ambientais e ainda propor a melhor solução econômica. Este trabalho desenvolve uma metodologia baseada em Sistemas de Informação Geográfica para avaliar o potencial regional e nacional para o aproveitamento de centrais mini-hídricas com exemplos em Portugal.

Palavras-chave: Metodologia, Centrais Mini-hídricas, Sistemas de Informação Geográfica.

Abstract

The industrial and technological progress is usually related to the increase of energy consumption and must be accompanied by capacity expansion of transmission and distribution network as well as by construction of new electric generating plants. However, this increase must comply with the technical and/or environmental restrictions and propose the best economical solution. This study develops a methodology based on Geographic Information Systems to assess the potential for regional and national exploitation of small hydroelectric plants with examples in Portugal.

Key-words: Methodology, Small Hydropower Plants, Geographical Information Systems.

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1. Introduction

1.1. General Framework

Nowadays, the scarcity of natural non-renewable resources, the growing contamination of the environment and the maintenance of high oil prices in the international market have been responsible by an incessant search for alternative energy sources (Gomes, 2008). Regarding environmental issues, the point of greatest emphasis is on the amount of greenhouse gases emitted by the use of fossil fuels (oil and coal) for energy production and, as we can see in the figure below (Fig. 1), the world energy-related carbon emission will probably keep rising until 2035 (EIA, 2010).

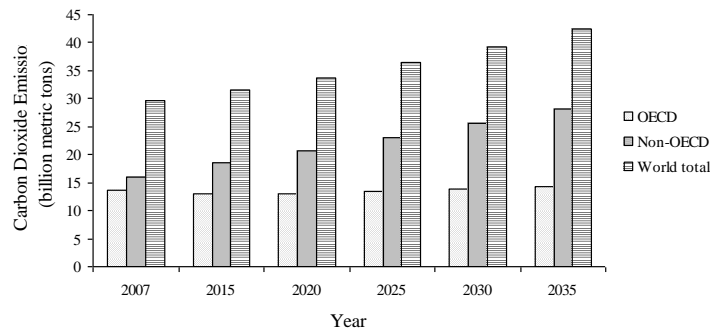


Figure 1: World energy-related carbon dioxide emissions by region^a (EIA, 2010).

Therefore, energy and environment policies should be coordinated, based on existing synergies and considering implicit contradictions of their impacts. An integrated strategy should seek for a balance between technical and economic feasibility and environmental constraints, regarding the promotion of sustainable development^b, security of supply and competitiveness.

^a The 32 member countries of OECD (Organization for Economic Co-operation Development) are: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

^b The concept of Sustainable Development was published for the first time in the Bruntland Report "Our Common Future", in 1987. According to the report, the Sustainable Development is "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

The implementation of renewable energy acquire a global relevance and interest after the assignment of the Kyoto Protocol (UN, 1998) consisting in a commitment to limit the CO₂ emissions. Portugal, as one of the adherent countries, aims to limit the increase in 27% of GHG emissions in the period 2008-2012, compared to the values in 1990 (EU, 2006).

At European Union (EU) level the concern with the integration of energy and climate policies is included in the "Energy Policy for Europe" (EU, 2007), with the objective to promote a highly efficient energy economy with low CO₂ emissions, complying with the energy and environmental requirements to fulfilling the EU targets (knew as 20-20-20). Also, the Community Directive 2001/77/CE (EU, 2001) establish the percentage of energy supplied to consumers that should be originated from renewable sources. In respect to the directive, Portugal has pledged in 2010 to provide 39% of the total energy supplied to consumers from renewable sources. However this goal was increased to 45% (Governo de Portugal, 2008).

Hence, the Portuguese Government through the National Energy Strategy^c (ENE 2020) is now engaged in reduce the external dependence, increase the energy efficiency, reduce CO₂ emissions and improving service quality. Another goal of this strategy are to guarantee the security of energy supply during the diversification of the primary resources and to ensure that all the energy process are environmentally developed through the reduction of their impacts at local, regional and global scales.

Taking into account the legal requirements, it is essential to enhance and strengthen the electricity production from indigenous resources. According to REN (2006), the production of electricity in Portugal from renewable sources is only feasible by using the hydroelectric or wind power. This is justifiable, since other sources of renewable energy still have a state of technologic in development and in the short and medium term do not allow them to achieve the desired quota, and cannot provides competitiveness.

Over the past 15 years, the growth of hydropower in Portugal was lower than other European reference countries, especially when we analyze the national untapped water potential. So, with the "National Program of Hydroelectric Dams with High

^c Governo de Portugal "National Energy Strategy - ENE 2020", Cabinet Resolution nº 29/2010.

Potential”, Portugal intends to increase the potential explored from 46% to 70% in 2020 which represents a final amount of 7000 MW (DGEG, 2010) and double the installed potential from small hydropower - more 250MW (Governo de Portugal, 2010).

Electricity generated from hydro resources is characterized by extremely low operating costs and essentially zero fuel costs, which do not escalate over time, as is the case with fossil-fuel resources. With negligible greenhouse gas emissions, hydroelectric power offers an attractive solution to address global climate change. However, a number of barriers, including ecological impact and front-loaded investment in developing transmission and reservoir infrastructure, must be overcome for the full potential of the resource to be realized (Araújo *et al.*, 2010). For various reasons, which includes the water management, flood control and the ability to respond instantly to changes in electricity demand, this technology is the most popular renewable source of electricity generation.

Nevertheless, in the last years there has been a growth in RES (Renewable Energy Source) installed capacity for electricity production in Portugal, having been reached in 2010, 9321 MW as we can see in the table below (Tab. 1) being the large hydro^d (with 4234 MW) and the wind (with 3802 MW) resources responsible for the biggest share.

Table 1: Historic evolution of installed power from renewable energy (MW) in Portugal from 2002 to 2010. Source: DGEG (2010).

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | AAGR* |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| Total Hydro | 4288 | 4292 | 4561 | 4752 | 4784 | 4787 | 4792 | 4821 | 4829 | 1.7% |
| Large Hydro (>30MW) | 3783 | 3783 | 4043 | 4234 | 4234 | 4234 | 4234 | 4234 | 4234 | 1.6% |
| SHP (>10 e <=30 MW) | 251 | 251 | 251 | 232 | 263 | 263 | 263 | 263 | 263 | 0.7% |
| SHP(<10 MW) | 254 | 258 | 267 | 286 | 287 | 290 | 295 | 324 | 332 | 3.5% |
| Wind | 175 | 253 | 537 | 1047 | 1681 | 2446 | 3012 | 3566 | 3802 | 53.8% |
| Biomass (with cogeneration) | 372 | 352 | 357 | 357 | 357 | 357 | 357 | 359 | 360 | -0.5% |
| Biomass (without cogeneration) | 8 | 8 | 12 | 12 | 24 | 24 | 24 | 101 | 106 | 43.7% |
| USW | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 0% |
| Biogas | 1 | 1 | 7 | 8.2 | 8.2 | 12.4 | 12.4 | 20 | 21 | 53.4% |
| Photovoltaic | 1.5 | 2.1 | 2.7 | 2.9 | 3.4 | 14.5 | 58.5 | 106.1 | 111.1 | 83.8% |
| Waves | | | | | | | 4.2 | 4.2 | 4.2 | |
| Total | 4933.5 | 4996.1 | 5564.7 | 6267.1 | 6945.6 | 7728.9 | 8348.1 | 9065.3 | 9321.3 | 9.1% |

*AAGR – Average Annual Growth Rate.

^d Large hydro, due to environmental impacts, is not considered a renewable energy.

However, despite this growth, the hydropower had not a great AAGR (Average Annual Growth Rate). So, increase the national hydroelectric production is one of the solutions in order to achieve the objectives outlined to the country (DGEG, 2010).

Electricity production (Tab. 2) from RES reached 24325 GWh in 2010 (DGEG, 2010). The renewable sources that have been more implemented are the wind, biomass without cogeneration, biogas and photovoltaic technologies, the last 3 with the lower electricity production in 2010.

Table 2: Historic evolution of electric power produced from renewable sources (GWh) in Portugal from 2002 to 2010 (DGEG, 2010).

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Total Hydro | 8096 | 15894 | 10053 | 5000 | 11323 | 10351 | 7102 | 8717 | 15040 |
| Large Hydro (>30MW) | 6896 | 14303 | 9065 | 4454 | 9897 | 9406 | 6190 | 7547 | 13241 |
| SHP (>10 e <=30 MW) | 615 | 822 | 587 | 265 | 702 | 504 | 478 | 618 | 945 |
| SHP(<10 MW) | 585 | 769 | 501 | 281 | 724 | 441 | 434 | 552 | 854 |
| Wind | 341 | 468 | 787 | 1741 | 2892 | 4007 | 5720 | 7440 | 9008 |
| Biomass (with cogeneration) | 1166 | 1069 | 1206 | 1286 | 1302 | 1361 | 1381 | 1390 | 1465 |
| Biomass (without cogeneration) | 42 | 43 | 52 | 64 | 78 | 149 | 146 | 311 | 487 |
| USW | 518 | 523 | 475 | 545 | 532 | 498 | 441 | 458 | 485 |
| Biogas | 2.5 | 2.3 | 14 | 31 | 33 | 55 | 67 | 80 | 87 |
| Photovoltaic | 1.8 | 2.6 | 2.9 | 3.8 | 4.1 | 23.6 | 41.4 | 159.9 | 189.5 |
| Waves | | | | | | | | | |
| Total | 8441.3 | 16367 | 10857 | 6775.8 | 14252 | 14437 | 12930 | 16397 | 24325 |
| PHI (base year - 1997) | 0.623 | 1.115 | 0.68 | 0.336 | 0.8 | 0.631 | 0.562 | 0.634 | 1.024 |
| Total Hydro Corrected | 12995 | 14255 | 14784 | 14881 | 14154 | 16404 | 15406 | 13749 | 14688 |
| Total Corrected | 15066 | 16363 | 17321 | 18552 | 18995 | 22498 | 23202 | 23588 | 26409 |
| Gross Production + Imp Balance | 46652 | 48220 | 50017 | 51729 | 52749 | 52952 | 53558 | 52808 | 53970 |
| % Renewables (Real) | 21.80% | 37.30% | 25.20% | 16.80% | 30.60% | 31.10% | 27.80% | 35.10% | 49.60% |
| % Renewables (Directive) | 32.30% | 33.90% | 34.60% | 35.90% | 36.00% | 42.50% | 43.30% | 44.70% | 48.90% |

It should be noted that in March 2009 the total installed power in hydroelectric power plants up to 10 MW is 299 MW, with an estimated production of 562 GWh (DGEG, 2010). On future prospects, forecasts point to an installed capacity of about 400MW and an estimated annual production of 1600 GWh (ADENE & INETI, 2001).

As said before, one of the best solution to achieve the policies targets is from hydropower generation. Nevertheless, the greatest hydropower locations for the installation of large hydropower plants have been already exploited and because of their environmental impacts, it ceases to be the best option. Therefore, the SHP (small hydropower plants) is a good choice to provide security of supply and for meeting commitments to renewable energies, constituting a technology that benefits the characteristics of decentralized electricity generation (DG) with low impacts on the environment and still available potential in Portugal.

According to Dragu *et al.* (2005) the SHP is one of the most economic source to electricity production, since they are high reliable and flexible in operation, due to the existence of mechanisms that allows to respond immediately to rapid changes in the system. This technology can last over than 50 years and have relatively short construction period (one to two years).

Furthermore, SHP is very independent of variations in the oil price and enables the decentralized production close to consumption spots reducing losses in transmission lines. Such plants can be controlled by distance, thus relieving the human presence at the local.

1.2. Motivation

The power system planning in general is subject to a process of multidisciplinary decision making under uncertainty where different considerations like technological, economic, environmental, and social aspects and/or conflicts are involved. In this context, most of the energy planning process should introduce new proposal, involving and emphasizing negotiation and promoting consensus between the groups with conflicts of interest (Gorenstin *et al.*, 1993).

The GIS is a set of tools in which is possible to pool resources and data together with a platform of geographical knowledge, allowing the results visualization on image form that enables greater safety and agility in decision-making (Carvalho *et al.*, 2007). The environmental problems of energy projects, as well as the technical and economic aspects can be also geographically mapped and modeled in GIS (Geographic Information Systems) at various levels of severity and be filtered to find areas of lower conflict of interest where the small hydropower plants can be developed.

This type of spatial assessment is based on methodologies for which there is a well-developed state of art for solar resource assessment, wind, and biomass. However, for regional assessment of small hydropower potential these methodologies are still in development (Teixeira, 2009) and potential evaluation is performed generally project to project through an exhaustive coverage held on the field.

As the hydropower is one of the priorities addressed by national energy policies, the motivation inherent in this work is to develop an easier and faster way without fieldwork surveys to access the potential power that can be developed in the Portuguese

territory. With the proposed methodology we aim to provide a tool to accelerate the decision making process once it can select the more suitable site regarding engineering, economic, and environmental factors and also the areas of minor conflict of interest between stakeholders.

1.3. Objectives

The general objective of this dissertation is to construct a comprehensive methodology based on geographical information systems to address the best sites for small hydropower plants considering energy, economic and environmental factors using Geographical Information System (GIS).

Furthermore, this dissertation seeks to fulfill the following specific objectives:

- Create models to head estimation seeking for the economic optimization;
- Create models to estimate the flow in water lines, based on the rainfall characteristics;
- Create models for assessing the energy potential and project costs;
- Create models for site selection for small hydropower plants.

The methodology of this research is based on literature review and software processing in ArcGis 9.3.

1.4. Structure of Dissertation

This dissertation is organized in 4 chapters. After this introduction, the second chapter presents the policies and technical characteristics of small hydropower plants. Chapter 3 introduces the *Geographic Information Systems* and the current methodologies used for assessment of small hydropower plants location. The chapter 4 presents the proposed methodology, followed by a conclusion.

1.5. Data and Tools

This thesis used as a basis for analysis and data processing, the program developed by ERSI, ArcGis 9.3. This software was available during the research period performed at the University of La Rioja, in Logroño, Spain.

The input basic data used were provided by National Environment Agency (APA)^e, Water Institute (INAG)^f, and University of Aveiro (CLIMAUA)^g available at their world wide web page.

^e APA - Agência Portuguesa do Ambiente (1989), "Atlas do Ambiente", available at <http://www.iambiente.pt/atlas/est/index.jsp>, accessed on 28/03/2010.

^f INAG - Instituto da Água (2010), "Sistemas de Informação de Recursos Hídricos", available at <http://www.inag.pt/>, accessed on 17/03/2010.

^g CLIMAUA - Grupo de Meteorologia e Climatologia da Universidade de Aveiro (2010), "O tempo - Precipitação total", available at <http://climetua.fis.ua.pt/fields/atlantic/precip>, accessed on 08/10/2010.

2. Technology Characterization of Small Hydropower Plants

2.1. Development Policies for Small Hydropower

2.1.1. Small Hydropower in the world

The given advantages of generating electricity from small hydropower coupled with rising interest in the sector and an increase in government support will derive in new installations in many countries in the years to come. At present, small hydropower plants accounts for about 4% of the world’s total hydro capacity and the percentage is bound to increase at a fast rate due to the restructuring of electricity sector, higher fossil fuel costs, and the move toward renewable energy sources. Cumulative installed capacity of small hydropower is expected to reach 140GW in 2015 and 201GW in 2020 (Fig. 2) (Thilak, 2009) .

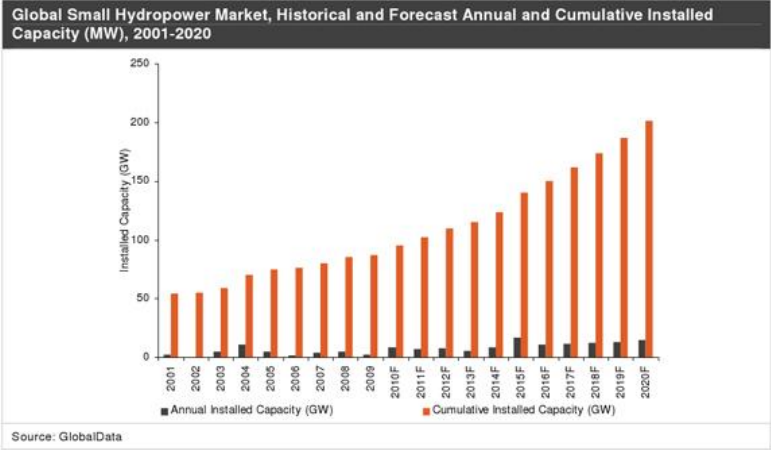


Figure 2: Global small hydropower market, historical and forecast annual and cumulative installed capacity (MW), from 2001 to 2020.

Today, small hydropower is a proven technology that provides reliable renewable electrical power and has large benefits at the local level. Lately, small hydro has gained popularity as a clean energy source and as an effective distributed power generation resource that supplies remote and grid-connected load centers. So small hydropower can strengthen both locally unstable and remote electrical systems. Developing, maintaining, and operating these units can provide jobs to the local community, and the solution of local environmental issues can actually provide enhancements to the local environment all around the world (Schwartz and Shahidehpour, 2006).

2.1.2. Small Hydropower in EU-25

According to ESHA (2004), in the former EU-15^h about 14000 SHP plants are in operation with an average size of 0.7MW and 10828MW of total installed power. For the EU-10ⁱ, this number is 2800 and for CC^j is 400 SHP plants installed and together the amount of 1430MW installed. The average plant size of these categories is 0.3MW and 1.6 MW respectively (Fig. 3).

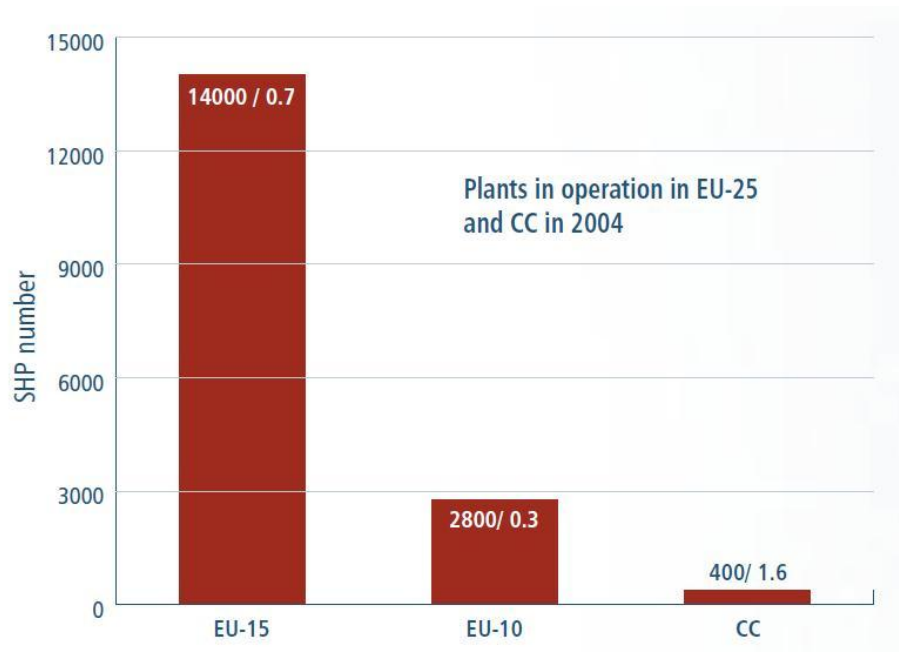


Figure 3: Plants in operation in EU-25 and CC in 2004 (ESHA, 2004).

According to Eurostat records for 2004, Italy accounted for about 21% of the total SHP installed capacity in the EU-25, followed by France (17%) and Spain (16%) (Fig. 4).

^h EU-15 consists of the following countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the UK.

ⁱ EU-10 consists of the following countries: Czech Republic, Hungary, Poland, Slovakia, Slovenia, Latvia, Lithuania, Estonia, Cyprus and Malta.

^j The Candidate Countries (CC) are: Romania, Bulgaria and Turkey.

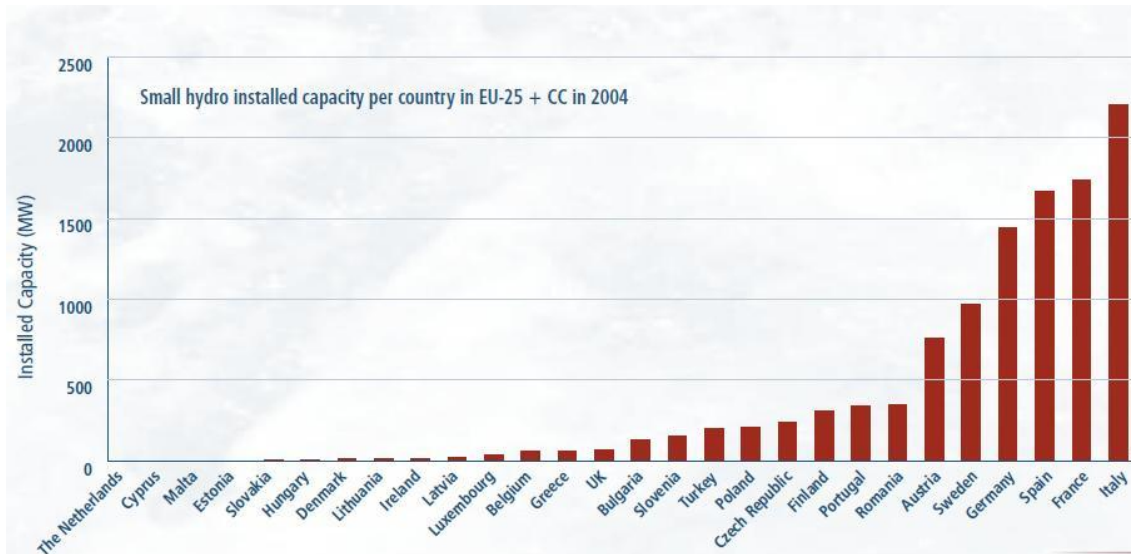


Figure 4: Small hydro installed capacity per country in EU-25 + CC in 2004.

In the New Member States, Poland and the Czech Republic both with 2% of the total EU-25 SHP capacity, are the lions of the New EU Member States. From the Accession Countries, Romania and Turkey represent about 25% and 15% respectively of the total SHP installed capacity in 2002 in EU-10 +CC.

At present, in almost all countries, hydropower is a dominant source of energy in RES-E (Renewable Energy Source for Electricity) production. Small hydropower accounts for approximately 4.6% of total hydro generation in the new EU Member States and CC. None of the other renewable energy sources (wind, biomass, PV etc) is able to compete with small hydropower in these countries.

It is important to note that from January 2007 the EU is composed for 27 member-states, joining the 25 Romania and Bulgaria, and now Turkey, Croatia, and Macedonia are candidate member states.

2.1.3. Small Hydropower in Portugal

Since the creation of Decree-Law No. 189/88 there was an awakening interest in SHP due to advantages granted by the legislation and financial incentives available. Historically, until 1994, 120 projects were licensed to use water for energy production, but in 2001 only 44 were in operation, representing a total of 170MW of installed capacity and annual production of 550GWh. Regarding the previous concessions, data indicates the existence of more 54 SHP, 20 of which belong to the

Non-Binding Electricity System (SENV)^k - EDP group - with 56MW of installed power and 165GWh/year. The remaining 34 SHP make up a total of 30MW and 100GWh/year. Thus, at the end of 2001 there were 98 SHP with 256MW of installed power and an output of 815GWh/year (ADENE & INETI, 2001, PER), of which 78 (200MW) in Special Regime Producers (PRE)^l and 20 (56MW) in SENV.

In March 2009 there were 299MW of installed power provided by SHP and a total of 562GWh of electricity produced (this being calculated from April 2008 to March 2009). In terms of outlook, although it is difficult to estimate the potential for exploitation of SHP, point to values between 500 and 600MW of total installed power with an average production between 1500 and 1800GWh/year (ADENE & INETI, 2001).

2.2. Technical Characteristics of Small Hydropower Plants

2.2.1. Differences between Large and Small Hydropower

Apart from the scale of development, the philosophies behind large hydropower and small hydropower are different. Large hydropower plants are generally designed to connect into a bigger grid thereby exploiting the economic benefits of scale (Ballance *et al.*, 2000). The advantages of small plants are manifested particularly in saving in transmission network for remote users, as the typical small-hydro plant is designed just to serve a local community; thus long, high voltage lines and associated energy losses are avoided.

Small hydropower generation plants have shorter construction period. Large hydropower plants usually have a construction period of about seven years, whereas it is about two to five years for smaller plants. Additionally, SHP gives a higher return on investment due to the low capital investment and operational and maintenance costs and being easier to construct by the simpler designs. Other infrastructure development costs can sometimes be ameliorated on small schemes. Seasonal dam storage costs can be avoided if the required flow is less than the low river flow. If the water source does dry

^k The SENV operates under market logic, in that clients are allowed to choose their electricity supplier. In SENV, the access is free to the production and distribution in Medium Voltage and High Voltage.

^l The Special Regime Producers (PRE) includes wind farms, small hydro (up to 10MW), cogeneration and other producers that generate electricity from renewable energy sources.

up, an alternative power source would be necessary. Low set efficiencies may be tolerable if there is surplus of river flow for the wanted energy. Transformer costs can be reduced by reticulating at low voltage, which also enhances safety.

Small hydropower plants allow community participation and capitalize on local skills for plant construction; large hydropower plants require rigorous surveys, investigations, and designs. Furthermore, it does not require a large flood area and can be constructed in small or medium rivers. Small hydropower provides an excellent distributed and abundant source for power generation and does not have any fuel costs as it uses water.

During the electric production, the hydropower does not emit almost any GHG, but, in large hydropower plants, that require a large dam, the reservoirs produce greenhouse gas emissions because of decaying vegetation from flooded lands. This typically results in higher levels of naturally occurring mercury in water resources, which is released from land that is flooded. For small-hydro power, diversion and damming of rivers may not be necessary, and the water passing through the generator is directed back into the stream, therefore there are few of the environmental impacts associated with large dams. Damage to fish in turbines is thus reduced, and barriers to migration of aquatic organisms are less significant than those caused by large hydropower generation (Kubečka *et al.*, 1997).

Besides the environmental impacts, larger hydro plants, especially those that involve the construction of dams, can have serious impacts on local communities. There are many examples of hydropower plants around the world where whole communities have been moved, lost their livelihood or had their health compromised. This may not happened with small hydropower plants.

Apart of the benefits compared with large hydro plants, many advantages can be addressed to small hydropower when comparing with others small-scale renewable technologies. This kind of production can be a reliable electricity source considering that produces a continuous supply of electrical energy with the peak energy season during the winter months^m when large quantities of electricity are required. If the site

^m The Portugal case presents a *Csa* in the South and *Csb* in the North accordingly with the Köppen climate classification. Meteorologia, I. d. (1960-1990), "Clima de Portugal Continental - Instituto de

produces a large amount of excess energy, there is the possibility of integrate with the local power grid and some power companies can buy back the electricity overflow

At the same time, some weakness can be deliberate to this kind of project. They are:

- Small hydropower units using run-of-river configuration cannot always meet the required load demand due to the seasonal water flow variations;
- Floods during rainy seasons may cause break down of the small hydro system;
- Small hydropower plants can only be sited where the potential exists;
- Expansion of a small hydropower plant unit to serve additional load is frequently limited by available flow.

The overall impact of small-scale hydro schemes on the environment is likely to be extremely small and heavily localized. However, it is important to understand and be aware of existence of such impacts so that the impact can be easily reduced.

Hence, in order to take full advantage of the electrical potential of small streams, a suitable site is needed; to better understand the methodology proposed, the next section explain the basic elements that must be taken in consideration when selecting the installation site.

2.2.2. Classification of Small Hydropower Plants

In general, SHP can be classified according to their regularization capacity, the system of water supply, and the installed power, head design and flow.

Regularization Capacity

Regarding the regulate capacity, SHP can be classified as:

- **Run-of-River:** This kind of SHP is used when the flow rates in the dry season are equal or greater than the discharge required for the installed power meet the expected peak demand, eliminating studies for dams and regulations of flows and it is usually located in perennial rivers.

Meteorologia > Área Educativa > Clima em Portugal", available at <http://www.meteo.pt/pt/areaeducativa/otempo.eoclima/clima.pt/index.html>, accessed on 12 August.

- **Regulation of Flow:** This type of SHP is used when the river flow are lower than the necessary to provide power. In this case, a reservoir is installed to regularize the flow.

Water Supply

There are two types for water supply from the river to the powerhouse in SHP: a) water supply at low pressure by free flowing channel and high pressure by penstock; and b) water supply at low pressure through a pipe and high pressure by penstock.

Installed Power, Head Design and Flow

Hydraulic power potential can be captured wherever a flow of water falls from a high level to a lower level. This may occur where a stream runs down a hillside, passes over a waterfall or manufactured weir.

The vertical fall of the water, known as the “head”, is essential for hydropower generation; fast-flowing water on its own does not contain sufficient energy for useful power production except on a very large scale, such as offshore marine currents. Hence two quantities are required: a Flow Rate of water (Q), and a Head (H). It is generally better to have more head than more flow, since this keeps the equipment smaller.

The Gross Head (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head.

The Flow Rate (Q) in the river is the volume of water passing per second, measured in m³/s. For small schemes, the flow rate may also be expressed in l/sec where 1000 l/sec is equal to 1 m³/sec.

There is no clear consensus regarding the classification of scales of hydroelectric power varying from each country and can be up to 50 MW. In his thesis, however, we used the classification commonly adopted by the European Commission for power classification and the proposed by Souza *et al.* (1999) for the head classification (Tab. 3).

Table 3: Classification of small hydropower plants considering the Power (P) and Head (H).

| Classification | Power - P(MW) | Gross Head -H (m) | | |
|----------------|---------------|-------------------|--------------|---------|
| | | Low | Medium | High |
| Micro | < 0.5 | H < 15 | 15 < H < 50 | H > 50 |
| Mini | < 2 | H < 20 | 20 < H < 100 | H > 100 |
| Small | < 10 | H < 25 | 25 < H < 130 | H > 130 |

Hydro-turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator, or other machinery. The power available is proportional to the product of head, flow rate and turbine efficiency. The general formula for any hydro system's power output is:

Equation 1

$$P = g\mu QH$$

Where:

P – power produced (Watts);

g - gravity acceleration = 9.81 (m/s);

μ - efficiency of the turbine;

Q - volume flow rate passing through the turbine (m³/s);

H - effective head of water across the turbine (m).

The best turbines can have hydraulic efficiencies in the range 80 to over 90% although this will reduce with size. Micro-hydro systems (<100kW) tend to be 60 to 80% efficient. We assumed an efficiency of 85% for following calculation.

2.2.3. Components of Small Hydropower Plants

A general small hydropower scheme (Fig. 5) and the main components are illustrated and described below (BHA, 2005, Teixeira, 2009):

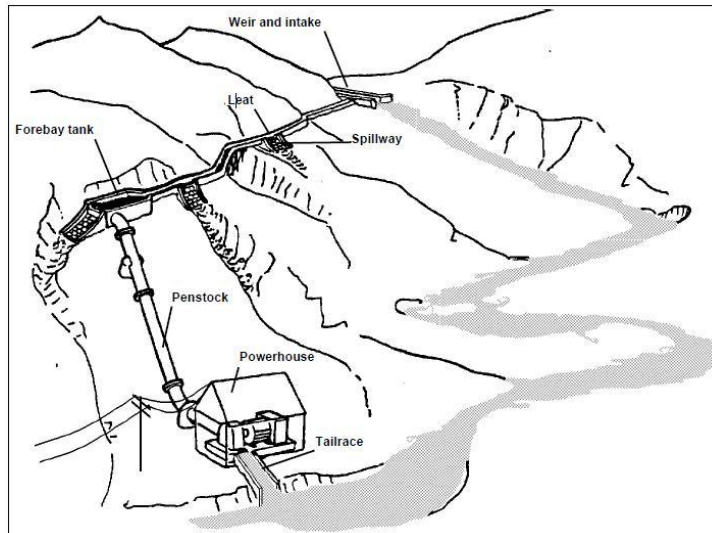


Figure 5: General small hydropower scheme and main components.

- **Intake**

Intake is the name given to the quantity of water formed by rivers or streams when there is a structure that prevents its natural passage. This structure is built by a small dimensions pond for run-of river systems and by a large pond for the hydroelectric exploitation through dam (Fig. 11).

- **Weir**

Is used essentially to control the extraction of water at the intake - the water flowing in the channel must be regulated during high river flow and low flow conditions. Using a weir we allow a constant supply from the intake protecting the system from damages caused by uncontrolled and different river flows. The weir type is related with the intake type and position. Using a well-dimensioned weir we can have a more water level's control and little maintenance needed on the system but oblige their construction, which makes the system more expensive.

- **Leat**

It is a canal responsible for carry the water horizontally from the intake to the forebay.

- **Forebay**

Is a reservoir or canal from which water is taken to the turbine. This element allows to promote the transition from a free flow existing in the intake to an outlet pressure of penstock and to reduce the hydraulic shock that happens when sudden closure of the control flow in the turbine is forced. The forebay provides water to the penstock when the flow control device is opened, until he settles back into the intake the steady flow. It is noted that the design of this element is dependent on the height of head, since the higher the altitude, the greater the amount of water needed to fill the penstock.

- **Penstock**

It is the element responsible to lead the water discharges of the forebay to the powerhouse where the turbines are. This element has a circular surface, usually constructed of steel and presents unearthed. However, in the impracticality of this fact, a burial is carried out.

- **Powerhouse**

This building is composed of mechanical and electrical equipment that will enable the production of electricity by converting gravitational potential energy into kinetic energy and rotation mechanical energy into electrical energy in that order. In terms of location, this building is situated at the end of the whole structure, i.e. only after the water is retained in the reservoir, carried by the leat, stored in the forebay and conducted by the penstock, that is forced to come in the powerhouse.

- **Tailrace**

After the water leave the turbine, is discharged back to the river by a canal called “tailrace”.

2.2.4. Electrical and Mechanical Equipment

The primary mechanical and electrical components of small hydro are turbines and generators.

Turbines

Turbines are the main part of a hydroelectric plant. It is fundamental to know the types of turbines to define which hydraulic machine best suits the characteristics of the plant.

The choice of a particular turbine depends on the available pressure head and the design flow. Depending on the availability of head, turbines are broadly classified into low, medium, and high head turbines. Based on the water flow, turbines are classified into two categories as impulse and reaction turbines.

- **Impulse turbines**

Convert the kinetic energy of a jet of water into mechanical energy. These turbines are driven by a high-speed jet of water and are generally used for high-head and low flow applications.

The most common are the Pelton turbines (Fig. 6). Bucket-like blades are attached to its runner, subdivided into two half-shells respectively by a sharp edge. The water flow may be influenced through one or several needle jets that may be controlled finely. The water leaves the nozzles, hitting the subdivided runner blades tangentially.

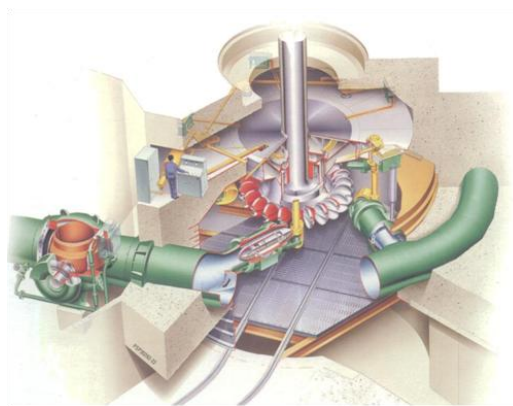


Figure 6: Pelton turbine.

- **Reaction turbines**

They are used for low and medium-head applications. The blades of a reaction turbine are completely immersed in water and the linear, angular momentum of water is converted into shaft power, and there are two that deserve more attention: Francis turbines and Kaplan turbines.

Francis Turbine: A radial turbine that contains a runner that has water passages through it formed by curved vanes or blades. The runner blades, typically 9 to 19 in number, cannot be adjusted. As the water passes through the runner and over the curved surfaces, it causes rotation of the runner. The rotational motion is transmitted by a shaft to a generator. The Francis turbine has a wide range of applications and can be used for head between 2 and 800 meters. The largest Francis turbines have an output of 750 MW (Fig. 7).

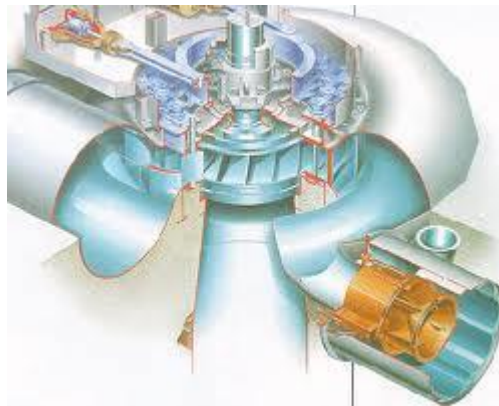


Figure 7: Francis turbine.

Kaplan Turbine (Fig. 8): An axial turbine that has two or more blades, the pitch of which is adjustable; it resembles a marine propeller. The turbine may have gates to control the angle of the fluid flow into the blades. They are well suited to situations in which there is a low head and a large amount of discharge. The adjustable runner blades enable high efficiency even in the range of partial load, and there is little drop in efficiency due to head variation or load. Because of recent developments, the range of Kaplan turbine applications has been greatly increased. They are being applied, for example, in exploiting many hydro sources previously discarded for economic or environmental reasons, and have also been used as wind turbines. The adjustable runner blades add to the complexity of construction of a Kaplan turbine. The runner blade

operating mechanism consists of a pressure oil head, a runner servomotor, and the blade-operating rod inside the shaft.

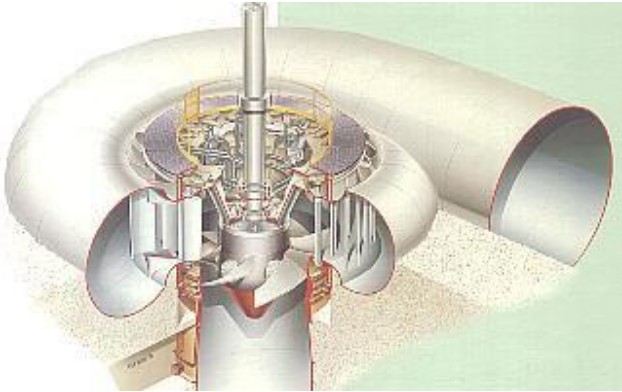


Figure 8: Kaplan turbine.

To show what was said earlier, Figure 9a presents a chart that shows the layout of the different turbines according to the head and flow and Figure 9b shows the efficiency in relation with flow characteristics for different turbine types.

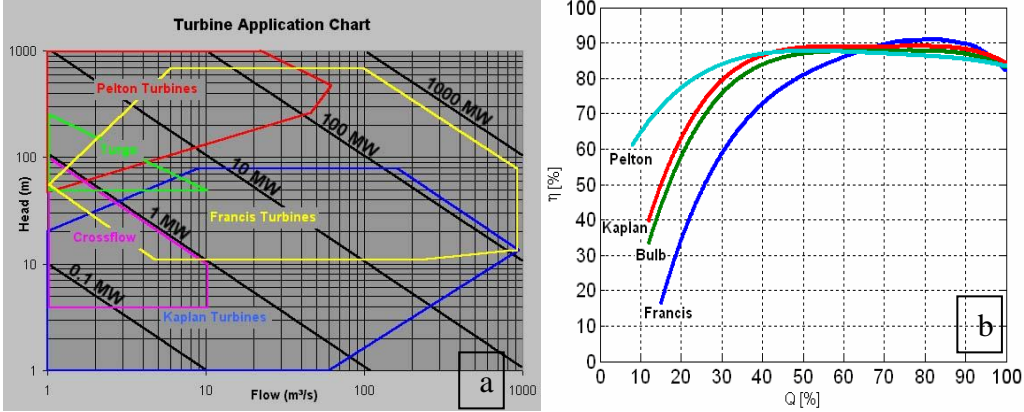


Figure 9: a) The recommended operating areas for different water turbines and b) Efficiency/flow characteristics for different turbine types (Magureanu *et al.*, 2008).

Generator

In small hydropower plant, the generator is connected to the turbine so that the mechanical output from the turbine is fed into the generator to produce electrical energy. Both the synchronous and induction type generators are used by small hydro developers.

- Synchronous generator can be operated autonomously and is therefore used for off-grid applications.
- Induction generators (less costly than synchronous) are best suited for on-grid applications.

Electrical switchgear, electrical protection and control system, backup power supply (batteries), fire and security alarm systems, water shut-off valves for the turbine, hydraulic control system, transformers for power transmission, cooling and lubrication, ventilation, etc. form the remainder of the electrical and mechanical equipment of small hydropower plant.

2.2.5. Configuration of a Small Hydro Plants

According to the characteristics, different configurations are possible for SHP (Camus and Eusébio, 2006). In practice, sites that are suitable for small-scale hydro schemes vary greatly. They include mountainous locations where there are fast-flowing mountain streams and lowland areas with wide rivers. In some cases development would involve the refurbishment of a historic waterpower site. In others it would require an entirely new construction. This section illustrates the four most common layouts for a small hydro scheme (BHA, 2005).

A variation on the canal-and-penstock layout for medium and high-head schemes (Fig. 10a) is to use only a penstock (Fig. 10b), and omit the use of a canal. This would be applicable where the canal construction is difficult due terrain characteristics, or in an environmentally sensitive location where the scheme needs to be hidden and a buried penstock is the only acceptable solution.

For low head schemes, there are two typical layouts. Where the project is a redevelopment of an old scheme, there will often be a canal still in existence drawing water to an old powerhouse or watermill (Fig. 10c). It may make sense to re-use this canal, although in some cases this may have been sized for a lower flow than would be cost-effective for a new scheme. In this case, a barrage development may be possible on the same site. With a barrage development, the turbine(s) are constructed as part of the weir or immediately adjacent to it, so that almost no approach canal or pipe-work is required (Fig. 10d).

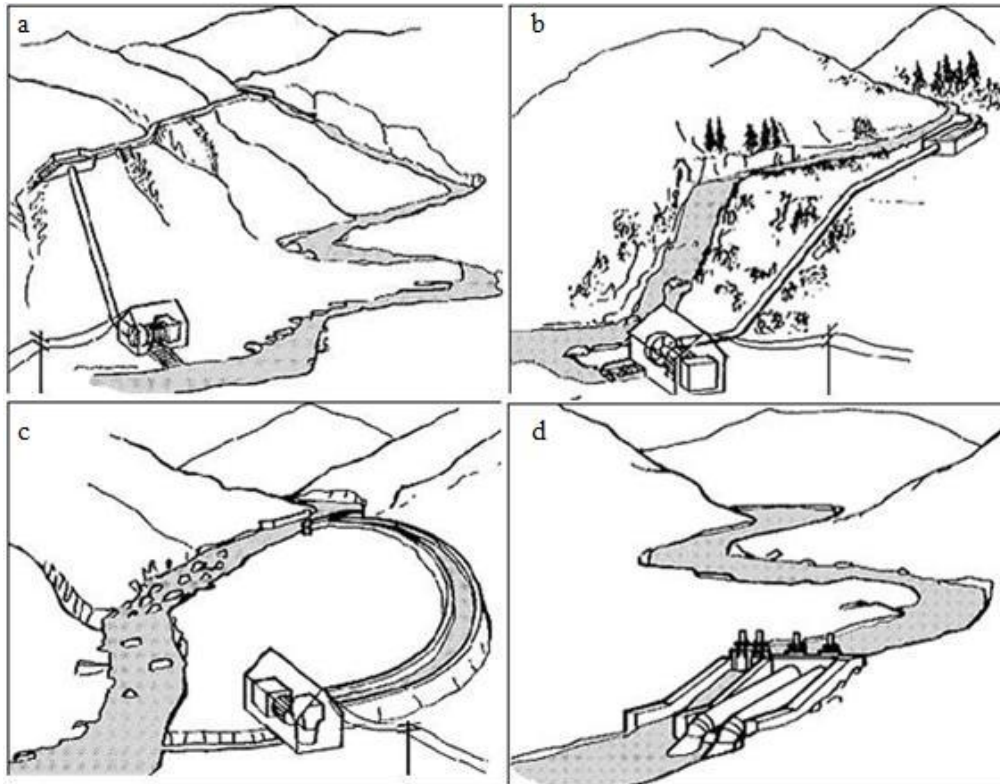


Figure 10: Different configuration for small hydropower plants, where, a) central with intake and penstock with high drop away from the dam; b) central only with penstock and high drop near the dam; c) central only with intake and forebay, with low drop, located away from the central dam; d) central in the dam with low drop. (BHA, 2005)

However, it is striking to note that these elements are a general scheme for run-of-river power plants. Nevertheless, in Portugal, there are some SHP schemes holding a reservoir, which is characterized by having only the dam, which is incorporated into the plant as we can see below (Fig. 11).

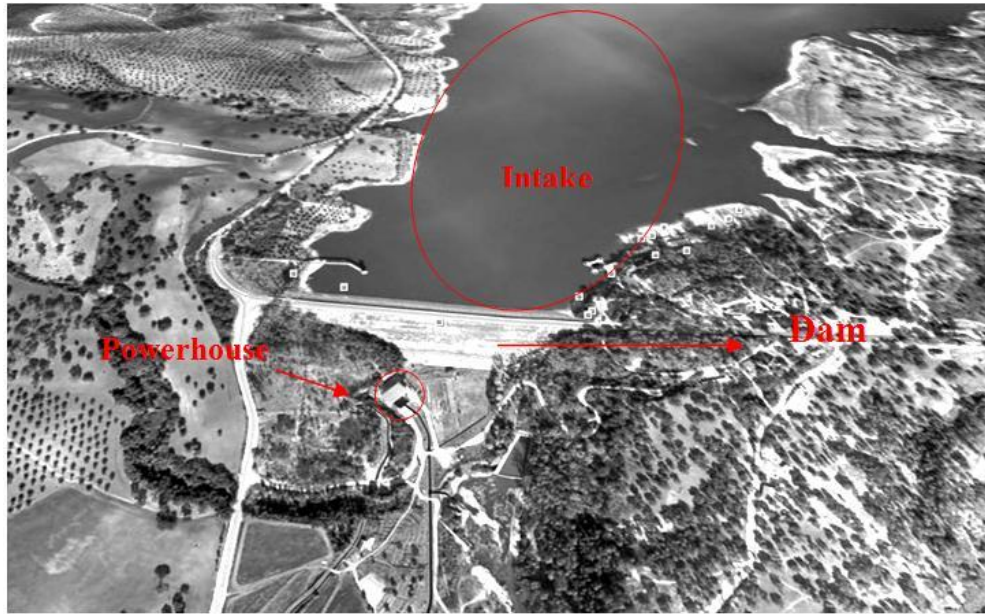


Figure 11: Small Hydropower scheme showing the reservoir and their component. Source: Teixeira, 2009.

3. Geographical Information Systems

After the characterization of SHP and its elements, we will explain the tool used to develop the methodology center of this study. While the Geographic Information System was designed to work in computer mapping, there is a clear notion that the field is broader in scope today than simply automated map production. The advances in Geographical Information Systems (GIS) have increased rapidly since the subject first appeared in the 1960 and has now been developed into a geographical information science (Goodchild *et al.*, 1999).

The term Geographic Information Systems (GIS) is applied to systems that perform computational treatment of spatial data and retrieve information not only from their alphanumeric characteristics, but also through their spatial location, providing to the user a fascinating insight into his working environment, where all available information about a particular subject are at your fingertips, interrelated based on a common characteristic – the geographic location (Câmara *et al.*, 2001). With a quick literature review, it is possible to find many definitions for GIS (Calkins and Tomlinson, 1977, Clarke, 1986, Goodchild, 1985, Tomlinson, 1972). However, the Cowen's (1988) definition seems to encompass all of those: “(...) *a decision support system involving the integration of spatially referenced data in a problem solving environment*”.

A main characteristic of GIS is the ability to handle information of very diverse origins and formats. Data can be in the form of maps, photographs, satellite images, tables, records, historical time series, etc., and can be related to different fields like as in territorial arrangements, infrastructures, energy systems, environmental conservation, and others applications.

GIS can manipulate data in 3 basics digital support models: the raster (divides the studied area into a regular grid of cells where each cell contains a value and a geographical position), the vector (used to store and manipulate well defined graphical elements), and the surface data models (represents surfaces as a series of linked irregular triangles) (Ramirez-Rosado *et al.*, 2005).

3.1. Geographical Information Systems and Energy

The processing capability of GIS make them suitable for planning and optimal location of distributed generation and have been used for a number of renewable

energy projects. (Ramirez-Rosado et al., 2005). These projects have usually been developed in order to evaluate resources and to solve localization problems (Dominguez and Amador, 2007) and also, the users can obtain useful information on the economic or technical viability.

During the energy planning, several variables are analyzed as: potential expansion of demand, distance from the network and appropriate technology. Specific tests are done for each of these parameters, and require manipulation of databases and projections that may not restrict them to a purely economic sphere. Moreover, the introduction of new variables often complex to measure, such as environmental and natural resources, makes the task more difficult and prone to failures (Carvalho *et al.*, 2007). Geographic information systems (GIS) are suitable tools for solving these problems and they allow the simultaneous evaluation of key technical, economic, and environmental factors.

Governments, environmental agencies, utilities, private investors, financial corporations, and local authorities can become users of these tools and active players in the field of distributed power generation planning. Furthermore, GIS can be used in DG planning to study negotiation processes among those different energy actors (with planning interests in conflict initially) to help them understand the point of view of the others and look for satisfactory geographical planning solutions for most of them.

The applications of GIS can be used to a whole region in regarding to energy planning for an integrated strategy by analyzing all the technical and economic variables of interest for that region. Multiple scenarios with different economic or technical parameters can be simulated, which helps find the optimal planning solution. Graphical and/or statistical results from the calculation process are immediate, allowing strategic planning conclusions in an agile, visual, and global way with an analysis effort much lower than that required from other planning tools (Ramirez-Rosado et al., 2005).

With this variety of data support and applications, it is possible to say, generically, "*If where is important for your business, then GIS is your tool*". Given the importance which geography and location has on renewable energies – with respect to the large difference in the availability of renewable resources across the globe - the geographic dimension will play a key role in determining the optimal solution of the future energy system (Biberacher, 2008) and for this reason, the GIS can be a recommended tool.

3.2. Methodologies for Small Hydropower Potential Assessment

3.2.1. Classical Approach

Before the emergence of GIS, the classical form used in the exploration of potential hydropower is the study of topographical maps associated with field campaigns which verifies the information gathered in the office studies.

Despite the simplicity of the methodology, its use requires availability and time for fieldwork for the surveys. Nevertheless, the main disadvantage of using this methodology is related to the costs of the long field campaigns, as it is necessary to check whether the information collected on topographical maps are real. Another difficulty in applying this methodology is the scale of existing topographic maps, where, depending on the region of the country, the distance between the contour lines, can hide the real head information.

Regarding the assessment of potential power there are several software developed to help these evaluation. Wilson (2000) conducted a review of all software. However, most of these software have been developed to assess individual sites and are not helpful to the attainment of national and regional assessments. Beyond that, many programs are developed specifically for the country requesting the study. Table 4 presents a list of those software used in the past two decades to carry out the assessment of sites with favorable conditions for the installation of SHP.

Table 4: Software and methodologies used to evaluate available power for installation of SHP.

| Assessment Tool | | Features | | | | |
|------------------------------------|----------------------|-----------|----------------|---------|---------------------|--------------------|
| Product | Applicable Countries | Hydrology | Power & Energy | Costing | Economic Evaluation | Preliminary Design |
| ASCE Small Hydro | USA | ✓ | | | | |
| HES | USA | ✓ | | | | |
| Hydra | Europe | ✓ | ✓ | | | |
| IMP | International | ✓ | ✓ | | | |
| PEACH | France | ✓ | | ✓ | | ✓ |
| PROPHETE | France | ✓ | ✓ | | ✓ | |
| Remote Small Hydro | Canada | ✓ | ✓ | | ✓ | |
| RETScreen® | International | ✓ | ✓ | ✓ | ✓ | |

3.2.2. Regional Approach

However, a need for broader assessment of the available hydropower potential for regions or even entire countries arose. Having this in mind and the technical capabilities of GIS some studies have been developed and are summarized below.

The study done by Das and Paul (2006) aimed to select the most technically suitable site for small hydropower plants in one watershed. The basic methodology identifies manually the sites having suitable elevation (using Digital Elevation Model) and the flow was only calculated for these points by linear regression from base flow measured at the 5 nearest hydrometric stations. The total flow was then calculated (the sum of base flow and runoff – by CN^n method) as well as the generating capacity^o. With these information, the authors determined the position of intake, reservoir, and generator location.

The principal weakness of this paper is the subjective factor on evaluating the head and for hydropower components localization. In addition, this methodology can only be used for small watersheds, once the site must be assign manually.

In a technical article (Ávila *et al.*, 1995) they aimed to develop a methodology in GIS to determine the most favorable areas for installation of SHP in the west end of Bahia, Brazil. The flow was estimated by a linear regression considering the contribution area for each pixel^p at DEM from knew hydrometric stations. The topographical difference was calculated considering two different situations (exploitation of natural river slope and by a diversion of water flow) both utilizing the *Focalmin* tool in *ArcInfo* and identifying slopes higher than 3% or 10 – 15 meters^q. The best locations were chosen using a dispersion graphic between the two variables with the *ENVI*^r program.

This methodology can be used for a large area than the methodology described before, however, only analyzes the potential for some slopes. Nevertheless, a tool to

ⁿ Explained on section 4.1.2.

^o $P = 9.81 * Q * H * E$, Where P = Power in kW; Q = Discharge available in m³/sec; H = Net head in m; E = Overall unit efficiency (85% to 90%).

^p Specific Flow for the know station: $Q_e = Q/A$, Where: Q_e : Specific flow; Q: Flow; and A: Contribution area; and for the flow in each point : $Q_{eP} = Q_e \cdot A_p$; where: Q_{eP} : specific pixel flow; Q_e : specific flow; and A_p : contribution pixel area.

^q Moreira, M. G., R. Z. Pinaud, A. C. Barreto and M. V. Freitas, "Pequenas Centrais Hidrelétricas - Alguns Tipos de Instalações, Sistemas e Componentes", available at http://www.portalpch.com.br/index.php?option=com_content&view=article&id=216:pequenas-centrais-hidrelicas-alguns-tipos-de-instalas-sistemas-e-componentes&catid=13:artigos&Itemid=134.

^r RSI (1997), "Envi 3.0User's Guide ", Colorado, USA, Colorado, USA.

eliminate the existing plants should be incorporate in the process to allocate only available sites. Another weak point is related to the use of DEM generated using digital topographical maps. When the basis of studies of potential is based on this type of material, we can face certain limitations and difficulties, such as:

- Delay in obtaining results, especially when dealing with large drainage areas;
- Potential not identified according to the scale of topographic maps.

In the studied realized by Kusre *et al.* (2010) to identify the potential hydropower sites they considered only fifth and higher order streams to ensure sufficient amount of water flow and the average gradient along the stream should be 1:50 (i.e. 2%) or more to ensure sufficient potential head. They also considered that the distances between two consecutive hydropower sites should not be less than 500 m. Only naturally available sites where power can be generated without construction reservoir were identified.

The application of this methodology in Portugal can be difficult. The model purposed (SWAT2000) requires a huge amount of data to calculate the flow rate (flow rate data for calibration and validation of the model, DEM, stream network data, land use map, soil map - texture, hydraulic conductivity, porosity fraction, moist bulk density, water capacity -, climatic data - and precipitation, daily maximum and minimum temperature) that is not always available and the analysis can be very time consuming. Nevertheless, the principal weakness is the disregards of layouts with stream diversion to possible SHP sites.

Another approach was made by Tanutpongpalin and Chaisomphob (2004), using GIS program to define sites for SHP based on environmental criteria in Nan province in the northern region of Thailand. The proposed methodology utilized environmental constraints (watershed class, wildlife sanctuary and heritage), that were set up according to the regulation of Thailand government and physical characteristics, and parameters (land use type, mean annual suspend sediment and population density) that indicate the degree of suitability based on literature review. They created layers for each criteria and made an overlay to exclude unwanted areas based on the weigh determined. A previously study had been made (as describe below), in which engineering and economic criteria were considered, and 50 feasible projects were selected. Overlaying this result with the environmental criteria, only 16 point could be developed.

This study showed the importance of the analysis of environmental factors in conjunction with economic and engineering. This kind of analysis should be made in preliminary project phases to avoid extra costs or non-suitable site selection despite some subjective decision on weight layer.

Rojanamon *et al.* (2009) proposed a new method to select feasible sites of small run-of-river hydropower projects by using Geographic Information System technology for the upper part of the Nan river basin in Thailand. A combination of engineering, economic, and environmental criteria, as well as social impact is employed in this study (Fig. 12).

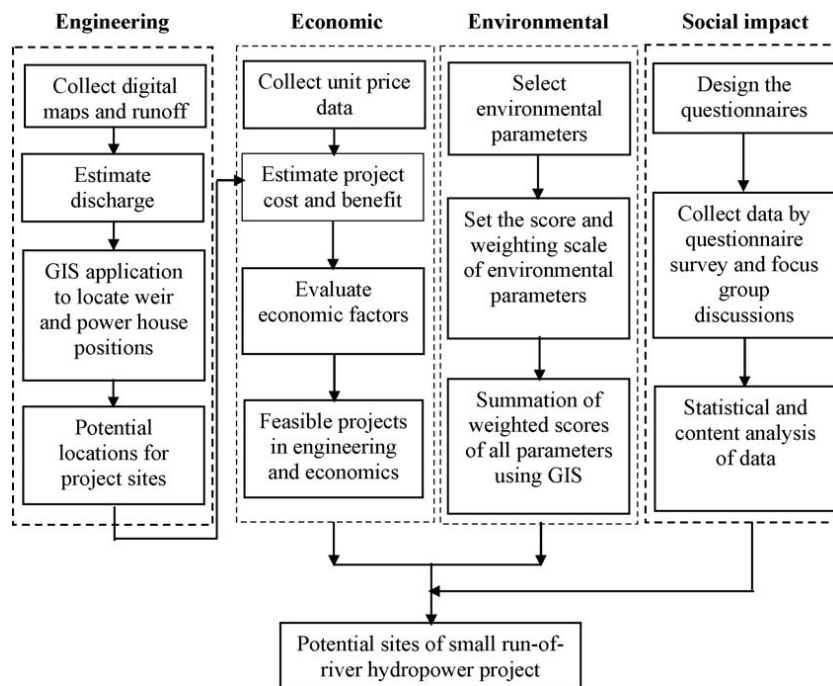


Figure 12: Analytical framework of the study.

This methodology seems to be very complete but only a small part of it is done using GIS tools and also requires field work development.

4. Developed Methodology

In this section we present the methodology developed for each step in the site selection for SHP process preceded by the description of the common approach utilized. This methodology uses some information that is crucial for many steps.

This information is acquired by terrain pre-processing in ArcGis 9.3 of the DEM (Digital Elevation Model^s – Fig. 13a). As example, we used the northern region of Portugal, encompassing the Ave, Cávado, Douro, Lima, and Minho basins (Fig. 13b).

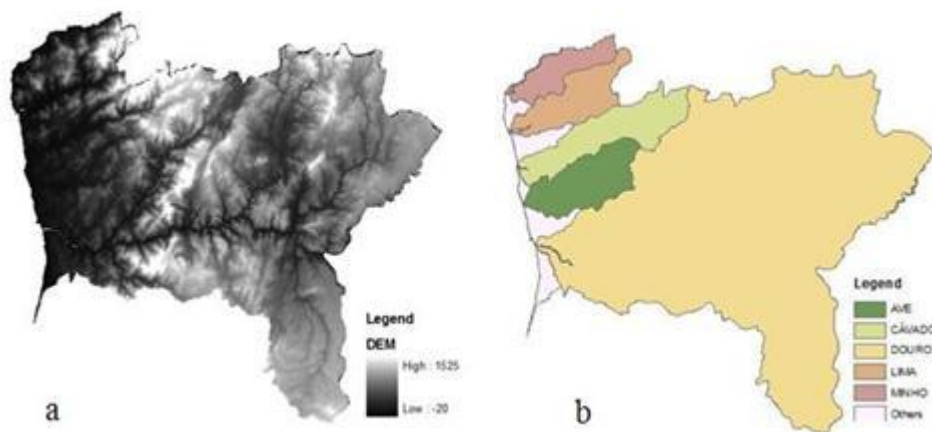


Figure 13: a) Digital elevation model of northern region of Portugal and b) basins of northern region of Portugal, including Ave, Cávado, Douro, Lima, and Minho.

4.1. Hydrologic Evaluation

The Geographic Information System (GIS) allows the integration of data that characterize the spatial watershed variability in a single system so, in conceptual terms, it can be stated that the GIS is able to support hydrological modeling (Santos *et al.*, 2006).

The basic elements for a hydrological analysis are the drainage line, watersheds, and sub-watersheds. Therefore, its characterization becomes indispensable to any study with this scope and can be done using the DEM, since it contains information to identifying the drainage network. To access this information, a set of operations should be performed. This includes:

^s Digital Elevation Model with resolution of 25m x 25m.

- Flow Direction: this is performed to all cells in the DEM raster. This is based on the basic and obvious principle that water in its path move to the least possible potential, i.e., the nearest neighbor cell is identified for which the slope is maximum.

The algorithm which describes the flow directions was developed by O’Callaghan and Mark (1984) and is known as D8 algorithm. This methodology is based on fact that water can move in 8 possible directions (Fig. 14).

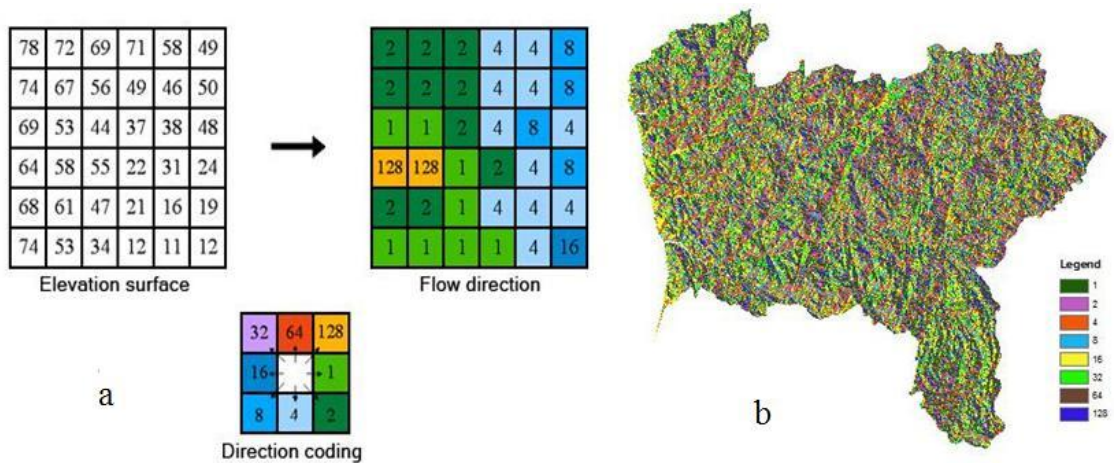


Figure 14: a) Eight direction (D8) flow model scheme (ESRI, 2009) and b) flow direction map for northern region of Portugal.

- Flow Accumulation (Fac): this function calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. If no weight raster is provided, a weight of one is applied to each cell, and the value of cells in the output raster will be the number of cells that flow into each cell (ESRI, 2009).

In the graphic below, the top left image shows the direction of travel from each cell and the top right the number of cells that flow into each cell. (Fig. 15).

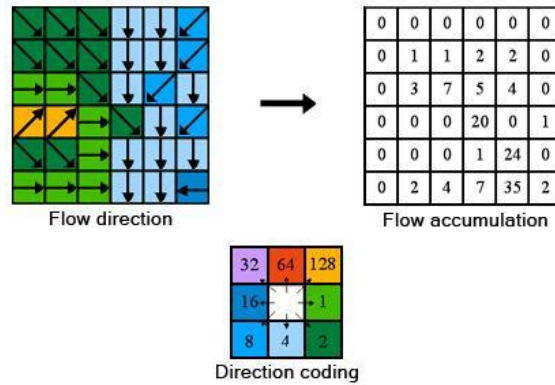


Figure 15: Flow accumulation scheme (ESRI, 2009).

In this process we used the Mean Annual Rainfall (MAR) (Fig. 16a) as weight raster (provided by APA (1989)), and the Flow Accumulation were calculated resulting in the image below (Fig. 16b):

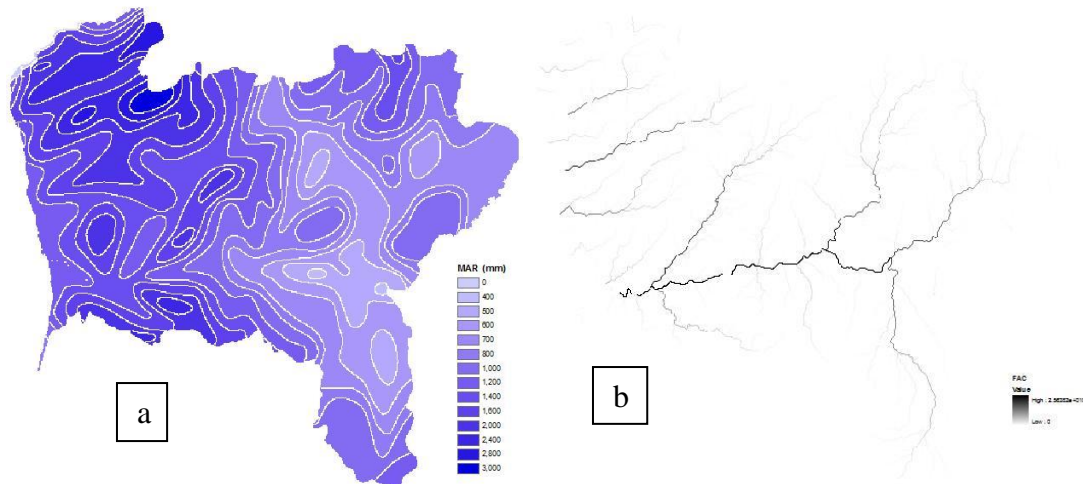


Figure 16: a) Mean annual rainfall and b) flow accumulation for the northern region of Portugal.

With this data, we can delineate the drainage network (synthetic rivers) for the northern region of Portugal. This is generally extracted from the above analysis. Theoretically, this process is based on the presence of drainage lines that are defined as concrete structures depend on the action of the flow and the degree of importance of their disposal. Then, cells with a high flow accumulation are areas of flow concentration and were used to identify stream channels (Fig. 17).

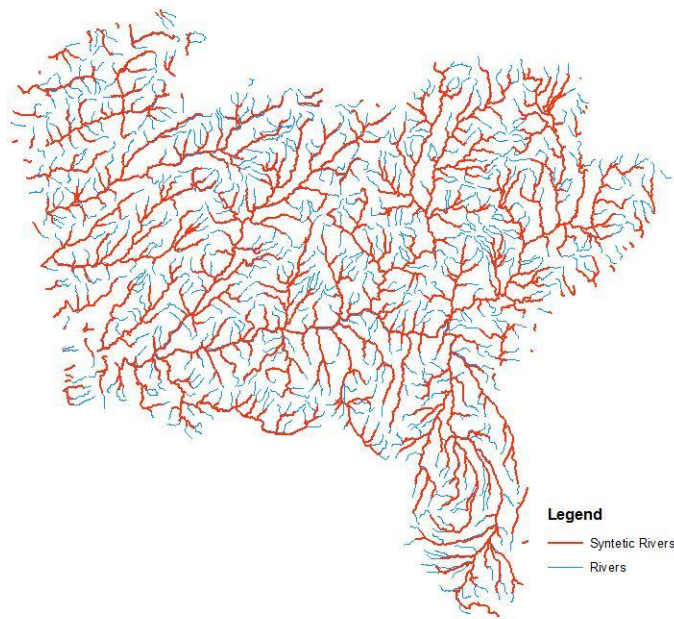


Figure 17: Synthetic rivers generated from digital elevation model in ArcGis 9.3 and rivers (APA, 1989) from northern region of Portugal.

With this information, it is possible to obtain the sub-watersheds using GIS tools (Fig. 18).

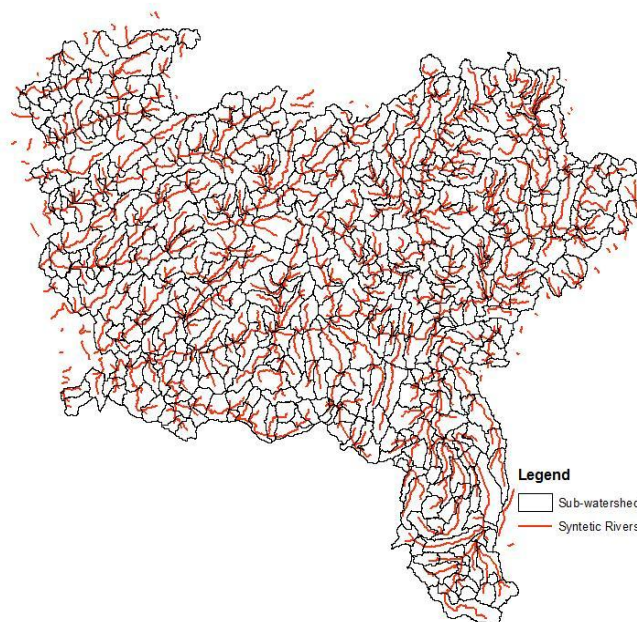


Figure 18: Synthetic rivers and correspondent sub-watersheds for northern region of Portugal generated in ArcGis 9.3.

These produced maps are used to flow, head and potential assessment as well as to localization of the best sites for SHP.

4.1.1. Flow Assessment with GIS

The flow rate is a key feature for sizing SHP, since that is the determining factor and constraint for the production of electricity. Without water, flow does not exist and thus there is no electricity.

The flow rate passing through a section of a river is a random variable with non-uniform distribution throughout the year. This can be measured directly, based on surface velocity V (m/s), cross-section S (m²) and a coefficient representing the shape of the riverbed, by the equation below:

$$\text{Equation 2}$$
$$Q = \frac{8}{10} \times V \times S$$

Where:

Q = Flow rate (m³/s);

V = Velocity (m/s);

S = Cross-section in the river (m²).

It is important to notice that there are different types of flow that can be calculated. Those are (Fig. 31):

- Modular flow (Q_{mod}): is the annual mean flow measured from many years;
- Ecological flow (Q_e): flow that cannot be turbinable for ecological and environmental reasons;
- Installed Flow (Q_i): also known as maximum turbinable flow; is the flow guaranteed for 20% (Q_{20}) to 30% (Q_{30}) of the year. It is usual higher than modular flow (which will be between the Q_{15} and Q_{20}). It is the flow used to dimension the equipment.

When is not possible, or inconvenient, to measure the rate flow directly, there is two basic ways to assess the flow rate using GIS tools at ungauged or poorly gauged basins that are usually used in the literature. The first and most accurate is using the hydrometric data and the second is the calculation with the pluviometric data measured

in pluviometric gauge station. These models are described below and following then, we present our methodology based on pluviometric forecasting.

- Hydrometric model:

The hydrologic regionalization is a hydrological statistic method that aims to assess the flow rate in the drainage network of a basin, in places with poor or inadequate data. It is obtained from the frequency analysis of historical series of flow at gauging stations in a basin and, with regression function, is possible to establish the relationship between the flow rate and one or more independent variables, such as the area of contribution, soil type, precipitation and others (Zeinhofer and Lima, 2006).

From the hydrometric stations located in the study area (Fig. 19), much information can be extracted like the monthly mean flow. The flow accumulation (Fac) raster provides the contributing area to each point of the river by multiplying Fac values by the cell area (in this case 625m^2). The others variables are available in many formats for ArcGis calculations, as the precipitation map shown before.

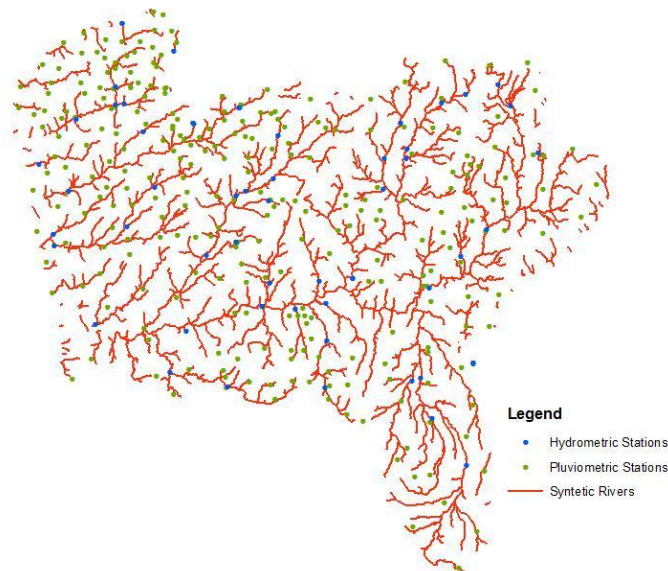


Figure 19: Hydrometric and pluviometric gauge stations for the northern region of Portugal.

An easier way is only a proportion relationship between the flow and the contribution area, as in the equation below. The relation of the measured flow at the closest hydrometric stations is directly proportional to the contribution area upstream

the hydrometric station. To determine the flow in some point of the river, as first step, the area of contribution (S_a) in each point of the river could be directly computed, by the hydrologic functions of the GIS, in all possible locations along the river. In a second step, for each location, a GIS function selects the closer downstream hydrometric stations and the area of contribution for this point is calculated (S_b). In a third step, the flow at the unknown point (Q_a) is estimated based on the measured values (Q_b) in the closer downstream hydrometric station.

Equation 3

$$Q_a = \frac{S_a}{S_b} \times Q_b$$

Where,

Q_b = Flow at gauged site a;

S_a = Contribution area from the site a;

S_b = Contribution area from the site b;

Q_b = Flow at ungauged site b.

- Pluviometric model registered in meteorological station:

The use of pluviometric data, registered in meteorological station (Fig. 19), to assign the flow rate implies the determination of the average rainfall (MAR) over an area. For this, three methods are frequently used: Arithmetic model, Thiessen Polygons, or Isohyteal maps.

The basic way is the *Arithmetic model*. In this model, the average rainfall in some basin is taken as the arithmetic mean of the readings of all gauges stations within this basin. The advantage of this method is that it is simple and fast, but averages are not representative if the gauges stations are not uniformly distributed.

Usually, the gauge stations are not uniformly distributed, so *Thiessen polygons* method is used. The Thiessen polygons are “domain” areas of a rainfall station and are depicted in the figure below (Fig. 20).

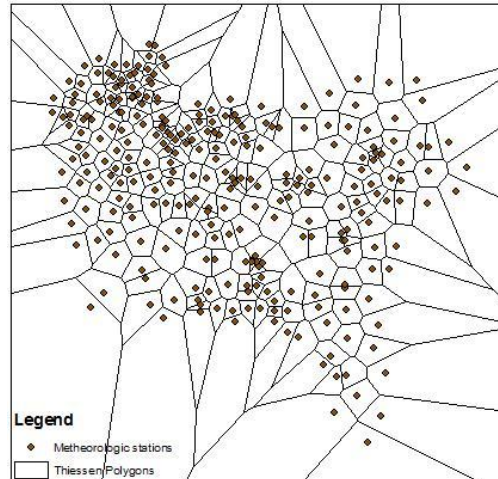


Figure 20: Thiessen polygons calculated for meteorological station located in northern region of Portugal.

It is considered that within the polygons area the rainfall has the same height of the gauge stations and is calculated using the following equation:

Equation 4

$$\bar{P} = \frac{\sum_{i=1}^n A_i \bar{P}_i}{A}$$

Where,

P = mean rainfall in the basin;

P_i = rainfall at gauge station;

A_i = polygon area inside the basin;

A = total area.

A failure of the method is that it does not directly consider the orthographic influences on rainfall or variations of spatial distribution of intensity of a storm.

The *Isohyetal method* can fix some of these problems. The isohyetal are lines that represent the rainfall distribution of a region, through curves of equal precipitation. The isohyetal map is constructed by plotting the station and their appropriated precipitation values on a topographic base map. In ArcGis, the isohyetal map is automatically produced by a geostatistical method, kriging. Kriging is a interpolation technique based on the estimated spatial covariance structure of the observed data (Coskun et al., 2010).

For determination of rainfall, the average values of two consecutive lines is calculated and multiplied by the referent area. This method, however, needs a great amount of gauge stations with good quality measures to produce a reliable map.

All of these methodologies can be used, and should be chosen accordingly to the available data for the region.

After the calculation of the mean precipitation, the flow rate must be calculated. To do this, the soil characterization is also important since they affect the runoff distribution over the time. These characteristics exert a modifier action in translation and storage of useful rainfall in the basin. The type and land cover conditions the water infiltration potential. Regarding the soil type (Fig. 21), its textural composition influences the flow, inasmuch as, for example, the higher the percentage of sand, the greater the amount of water infiltrated. On the land cover (Fig. 22), an obvious example of how it can influence the water infiltration is the increase in urban areas. The fact that these areas are quite impervious causes a decrease in water infiltration into the soil (Santos *et al.*, 2006).

The methodology that is generally used was developed by the Soil Conservation Service (SCS)[†] to determine the flow, based primarily on the Curve Number (CN) (Fig. 23). This variable is estimated taking into account the combination of hydrologic soil type, its utilization, and conditions of the surface, with respect to the potential to cause runoff. The CN is between 0 and 100, corresponding zero to a basin infinite hydraulic conductivity and hundred to a totally waterproof basin. The parameter CN is incorporated into the calculation of time of concentration and loss of precipitation, as follow:

Equation 5

$$Q = \frac{(P - 0.2 S)^2}{P + 0.8 S}$$

Equation 6

$$S = \frac{1000}{CN} - 10$$

[†] Soil Conservation Service. National Engineering Handbook. Washington: USDA, 1972.

Where,

Q = the flow rate;

P = precipitation dept;

S = the maximum storage depth;

CN = runoff curve number.

The land cover map (Fig. 22) presented below is a modification by reclassify function^u of the CORINE Land Cover 2006 map of Continental Portugal, provided by European Environmental Agency (EEA, 2006) to make the analysis easier. The soil type (Fig. 21) map is a edition of the soil type map provide by Portuguese Environment Agency (APA, 1989).

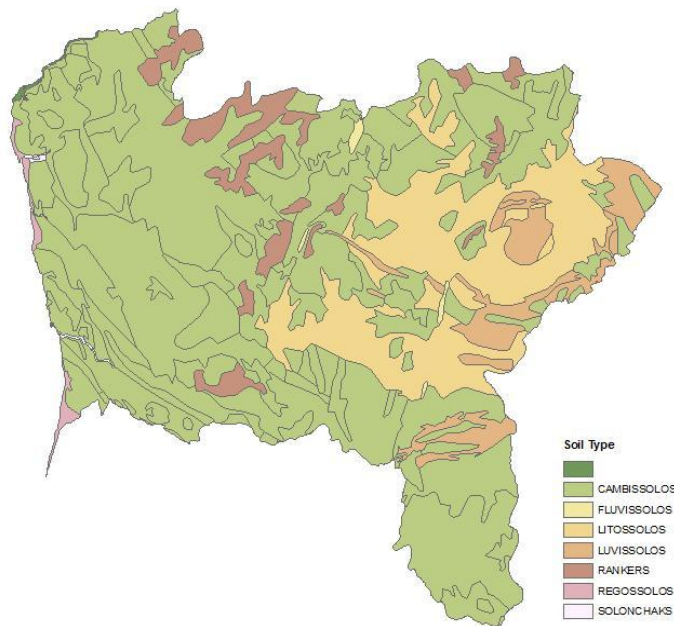


Figure 21: Soil type map for the northern region of Portugal.

^u The table with the original and the reclassified values for land cover is on the Annex I.

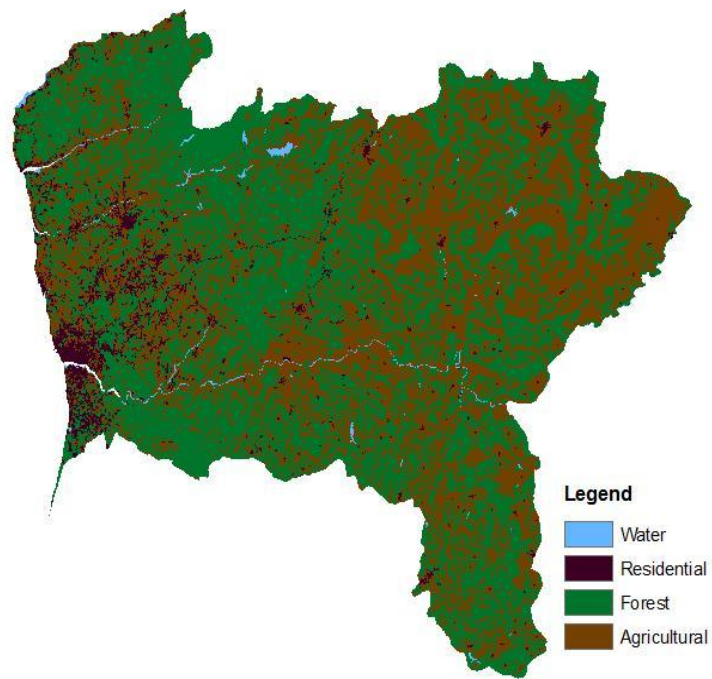


Figure 22: Land cover map type for the northern region of Portugal.

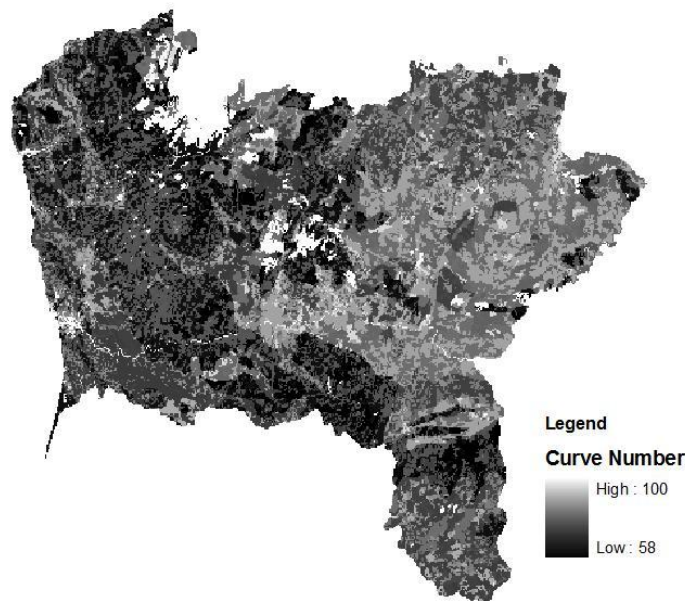


Figure 23: Curve number for the northern region of Portugal.

However, it is important to note that the value of CN (Curve Number) does not express the percentage of impermeable area of the basin and so this method is generally used only for small catchments.

For the both analysis to estimate the flow rate, a set of real data from hydrologic and pluviometric stations is needed to calibration and validation of the model. For Portugal, these data is provided by INAG^v. Model calibration is the adjustment of model parameters, within recommended ranges, to optimize the agreement between observed and simulated results. Validation of the calibrated model is essential to test the performance of the method; this is usually done with standard statistical methods available in ArcGis statistical tools.

- Pluviometric model based on HNWF grids:

The methodology proposed in this dissertation to access the flow rate is also based on pluviometric data, however, does not involves meteorological gauge station as primary data provider. This methodology is based on Hourly Numerical Weather Forecasting^w. For Portugal, this data is available for general public at CLIMAUA website (CLIMAUA, 2010). With these premise, it can be applied to a larger area and is possible to provide detailed information about the hydrologic behavior at any point in any river as explained below.

The HNWF provides the pluviometric forecasting maps (in terms of total rainfall - mm) for determined area hour by hour. As example, we show below 4 hours forecasting for Portugal (Fig. 24).

^v INAG - Instituto da Água (2010), "Sistemas de Informação de Recursos Hídricos", available at <http://www.inag.pt/>, accessed on 17/03/2010.

^w This forecast methodology is a computer system designed to make projections of atmospheric conditions, calculated from data collected in a given area as relative humidity, wind and temperature of the air. This is a complex methodology and wont be described in detail in this thesis. For a completed description, see the CLIMAUA website. CLIMAUA - Grupo de Meteorologia e Climatologia da Universidade de Aveiro (2010), "O tempo - Precipitação total", available at <http://climetua.fis.ua.pt/fields/atlantic/precip>, accessed on 08/10/2010.

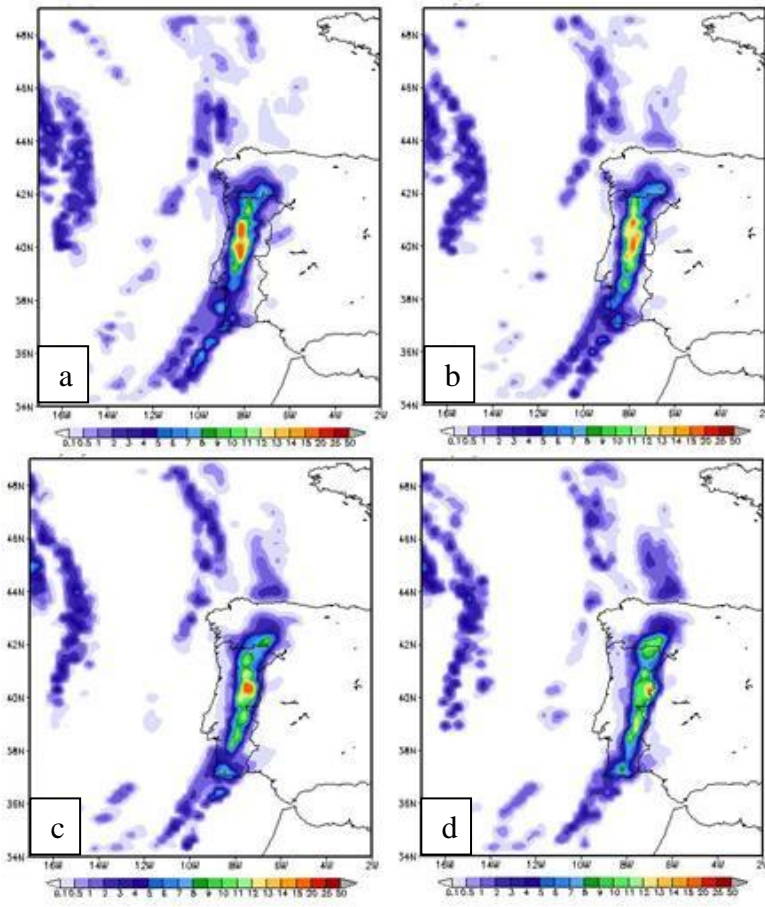


Figure 24: Total rainfall-forecasting (mm) on the day 08/10/2010 in the following hours: a) 19hs; b) 20hs; c) 21hs and d) 22hs for Portugal. Source: CLIMAUA (2010).

The first step is transported those images to ArcGis to create rasters for each hour representing the pluviometric data provided covering all the study terrain. Here, the resolution of the DEM and of the forecasting maps provided has a great influence on the results, and the best quality option available should be chosen. On these rasters, each cell will contain a precipitation value. This process should be done for every hour during a year, so, as result, we will have 8760 rasters and for each cell 8760 values of forecasting precipitation.

The second step is the calculation of the flow-weighted accumulation as the process described on the section 4.1 but using HNWF rasters despite MAR. In addition, we can use the CN grid as weight raster. With this calculation, we will have the stream

network cells assign with the flow accumulated for each hour. However, precipitation unit is millimeters and we should transform to m^3/s to obtain the flow rate in each cell^x.

It is known that there is a delay between the time the rain falls to the ground until it is accumulated into the rivers. However, this type of analysis is not considered in this thesis, since the goal is merely to characterize the frequencies of occurrence of the flow and not exactly the precise time they occur.

The third step should be a scale adjustment among the calculated and the measured flow rate at hydrometric gauge stations to all cells within the stream network to calibrate the model. This can be done by the kriging method described above in this section.

Therefore, every cell within a river has the 8760 foreseen flow rate values and the fourth step can be performed. This step is related to the probability of flow in determined river point. The flow rate varies during the year and their probabilities tend to be approximated to a normal distribution (normally a *Wiebull* distribution). These probabilities are calculated for each cell, and the accumulation values graph is derived from that. Multiplying these values for (-1) we will have the flow duration curve (FDC) for every point in the river. This FDC will be describe in more details in the next topic.

This model is based on weather forecasts and as we might expect there is some error between the predicted and the real values, between 20 to 30%. However, during the year these errors occur to more or less of the real values. It is important to analyze if they occur in a equally proportion, so the error will be uniformly distributed in the year.

4.1.2. Flow Duration Curves Characterization

The hydrological studies provide the probability of flow throughout the year. It required an analysis of records over several years in order to calculate the water resource over the lifetime of the SHP. This distribution function can be obtained by the pluviometric or hydrometric methods described previously.

The FDC (Fig. 25) is a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest. For example, it can be used

$$^x Q = \frac{\frac{Fac}{1000} \times Cell\ area}{3600}$$

to show the percentage of time river flow can be expected to exceed a design flow of some specified value or to show a discharge of the stream that occurs or is exceeded some percent of the time (or days).

The information provided from these data can be:

- Daily average flows and monthly average flow, to calculate the average energy produced;
- Flow in dry years, wet and normal, to consider scenarios;
- Flood flows, for the design of retaining structures and water dischargers;
- Ecological flows, to calculate the turbinable flow.

The basic unit used in preparing a flow-duration curve will greatly affect its appearance. For most studies, mean daily flows are used. These will give a steep curve. When the mean flow over a long period is used (such as mean monthly flow), the resulting curve will be flatter due to averaging of short-term peaks with intervening smaller flows during a month. Extreme values are averaged out more and more, as the time period gets larger (e.g., for flow duration curve based on annual flows at a long-record station). With the HNWF the results will be more accurate.

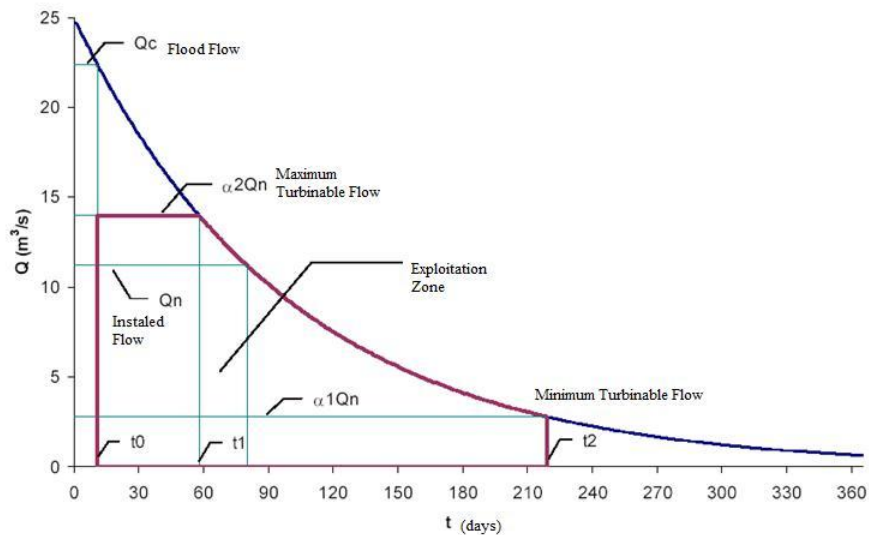


Figure 25: Schematic flow duration curve.

Therefore, the characterization of the flow duration curve for is essential also to characterize the catchment, validate the outputs of hydrologic models, and compare

observed and modeled hydrologic response. Then, the construction of FDC is a prerequisite of hydropower planning. From this graph, the information about the minimum turbinable flow is extracted and subtracted from the total flow available to preserve the ecological flow. The result of this subtraction is the flow assign to each cell in the rivers streams.

4.2. Head Assessment

In addition to the flow rate, determination of existing head along a river is fundamental to assess the potential power. As we said before, this can occur in a natural way, when the head is concentrated in a waterfall, by human work through a dam when small heads are concentrated, or through river diversion of its natural bed, concentrating all the small heads and conducting to the penstock (see fig. 10).

In order to calculate gross hydraulic head (the elevation change that occurs in traversing a stream), the elevation values at the upstream and downstream ends of the stream reach are needed. Since no existing hydrographic data has an elevation attribute, the synthetic rivers (Fig. 17) from digital elevation models (DEMs) can be used, and with intrinsic tools in GIS the elevation is assign (Lee *et al.*, 2008).

The common way to access the head is by reach slope calculation, once GIS can inform the stream length.

Equation 7

$$Slope = \frac{Eu - Ed}{Rl}$$

Where,

Eu = Elevation at upstream point (m);

Ed = Elevation at downstream point (m);

Rl = River length (m).

This value can be assign for each cell in the raster and is the generally applied method for head determination.

4.2.1. Head Scenarios Assessment with GIS

In order to improve the method presented before, we suggest a new approach to assess the head measurement, as follow.

Despite the slope approach we suggest different head scenarios estimation. For each cell in a river we admit a certain length (L) of influence (100m, 1km, 2km, 5km, and 10km) meaning the distance between the powerhouse and the intake point measured horizontally, so the head is the difference between upstream and downstream elevations. With a fixed length, the analysis starts at the downstream point, going up until the rivers ends, to analyze the head differences along the river. Moreover, the distance scenario analyzed will be taken in consideration for calculate the penstock length.

The figure below depicts an example of Poio river located at the northern region of Portugal, showing the 1km scenario and the difference in head that can be achieved within the same distance (Figure 26).

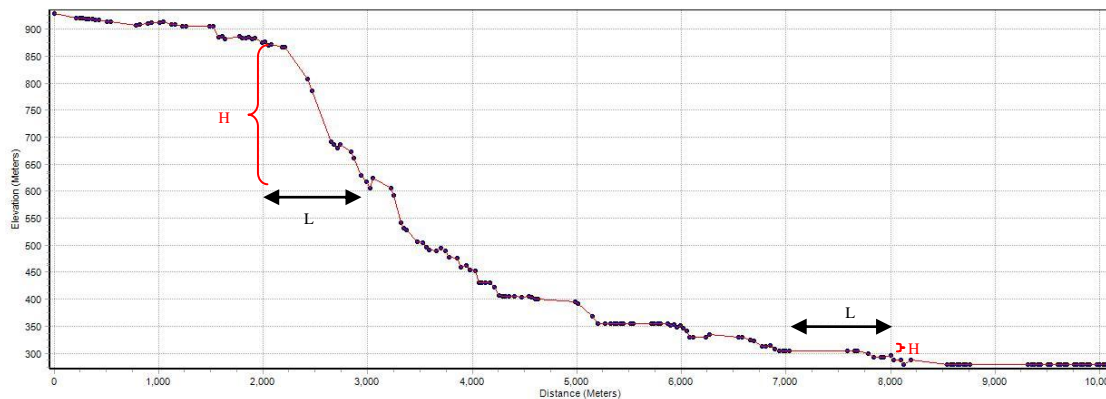


Figure 26: Schematic representation of 1km scenario to determine head for Poio river northern region of Portugal.

Therefore, for every point in the river, each cell will contain 5 values of head and related flow that can be utilized for small hydropower generation referent to the 5 scenarios proposed.

4.3. Power Assessment for Each Scenario

As we said before, the head and flow determines the potential power. To determine this power along the river, this methodology proposes an analysis in stages. For each head scenario (100m, 1km, 2km, 5km, 10km) an assessment is made across

the entire length of the river from downstream to upstream and using equation 1, the potential is calculated for each river cell.

When a diversion in the river is made, the flow to consider is the measured at intake spot, and this is the flow to be use in the equation 1. The scenario of 100m, by their short length, represents the SHP that does not use diversion of river to produce electricity. As result of this process, all river cells will contain a potential power for every distance scenario considered.

The figure below (Fig. 27) shows a schematic representation of Poio river (the same as before) with a transversal black line representing the flow. These is not real values but a representation that the more downstream, the greater the available flow. The colored lines below the figure, represents the process that should be carried out for each analyzed scenario.

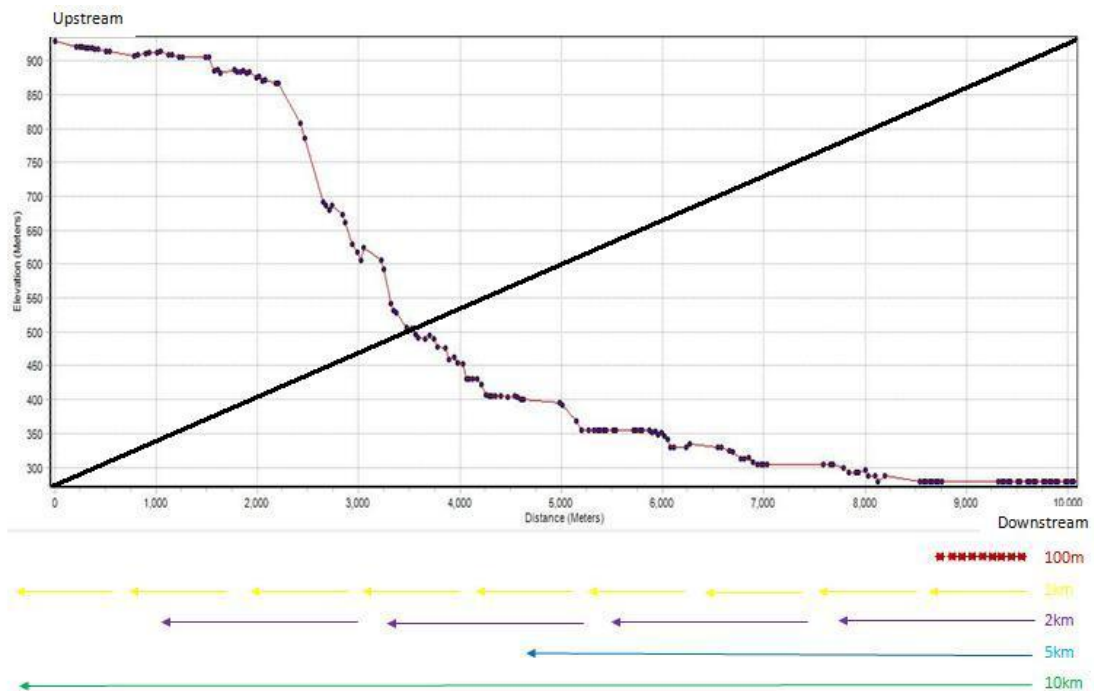


Figure 27: Representation of Poio river slope and schematic flow as well as the process for access the potential power available.

However, to choose the best option to construct a SHP, the cost of build a plant must be take in consideration, once sometimes, apart of the highest potential, the costs can derail the project. In our example, in the 10km scenario, if we are evaluating a scheme with river diversion, we will have the smallest flow but the biggest head. This is

the best choice for small hydropower plants. However, the costs of penstock and leat can spoil the project.

The cost calculation for every component is described in the following section.

4.4. Assessment of Plant Costs

Naturally, the estimation of costs associated with installation of SHP is a complex task, depending, among other things, the installed power (related to head and flow), the network connection, cost with diversion stream by leat and the penstock construction.

4.4.1. Variable costs

Leat Cost (Lc)

The leat cost is related to its length and to the volume of water that have to transport. The leat length is set as the scenario length plus 20%. This is due irregularities on the ground and deviations that should be made in order to carry the river horizontally until the penstock localization. The volume of water (the flow referent to the scenario analyzed) determines the diameter of the leat, and also influences the cost. The usual acceptable cost of leat is €200 per meter. Consequently, the total leat cost for the SHP in question, will be calculated for the following equation:

Equation 8

$$Lc = Lsc \times 1.2 \times Q \times 100$$

Where,

Lc = Leat cost (€);

Lsc = Length of the analyzed scenario;

Q = Flow at upstream point for the analyzed scenario.

For the 100m scenario, this cost should be considered zero, once no diversion in the river is made.

Penstock Cost (Pnc)

The penstock cost is related to the head and flow rate. In order to calculate its costs, the net head should be considered (10% shorter than the gross head). The cost per meter is also considered as €200 and the follow equation represents the total penstock cost:

Equation 9

$$Pnc = H \times 0.9 \times Q \times 100$$

Where:

Pnc = Penstock cost (€);

H = Head for the analyzed scenario;

Q = Flow at upstream point for the analyzed scenario;

Grid Connection Cost (Gc)

Specifications for connection to the grid can also be a deterrent to the development of SHPs and/or affect the viability of a scheme. Utilities that require unreasonable specifications or conditions (locating the connection point far away from the plant) strongly affect the feasibility of a scheme. In connection with the liberalization of the electricity sector, access to the grid is the first and most important step which allows independent producers to operate in the market and use the grid under fair conditions. When the costs to connect are unequivocally high, even attractive prices per kWh are an ineffective measure.

The connection point will be chosen by agreement between the producer and EDP. The line between the powerhouse and the grid has to be built at the expenses of the producer but then becomes part of the grid. Consequently, the closer the connection point, better for the developer.

In addition, with the maps presented previously (Land Cover – Fig. 22 - and DEM – Fig. 13a) we can see the areas where the lines will pass. With ArcGis is possible to visualize the vegetation that should be removed and the slope that will go through, making possible an estimate of the cost to construct a line crossing these areas.

With the exception of isolated schemes, the plant cannot be operated without connection to the grid. The figure below (Fig. 28), shows a scheme of the 60kV and

132kV lines and the substation points for the northeast part of Portugal that can be used to calculate the distance, and the relative cost, to connect the generation to the grid done with intrinsic functions in ArcGis.

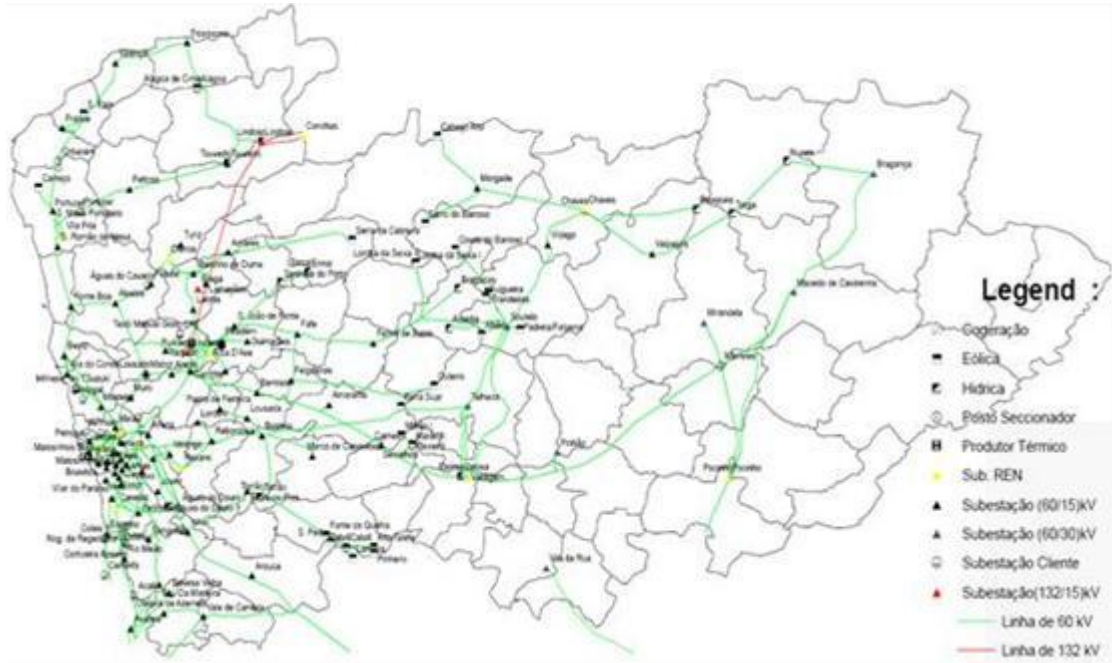


Figure 28: Low power lines and substations for the northern region of Portugal.

The subsequent table (Tab. 5) depict the number of substations and their installed and available connection power.

Table 5: Substation characterization for the northern region of Portugal.

| Subregion | Substation Number | Installed Power (MVA) | Connection Power Available (MW) |
|--|-------------------|-----------------------|---------------------------------|
| Alto Trás os Montes; Douro | 13 | 416 | 75 |
| Grande Porto | 28 | 1745 | 371 |
| Minho-Lima | 8 | 264 | 68 |
| Cávado; Ave; Tâmega; Entre Douro e Vouga | 41 | 1940 | 274 |
| Total | 90 | 4365 | 788.3 |

This information is important when many generation plants are near and want to connect to the grid.

Providing the costs of building a line (in this case set as €60000/km) the ArcGis calculate the total cost for every available option considering the grid layout.

Installed Power Cost (Ipc)

In addition, the power installed in the SHP has its influences in the costs in build a plant. When we want to install higher potential it implies in more powerful turbines, and consequently more generators, what increase the costs. The turbine represents a very significant portion of the SHP costs (can reach 50%) (Castro, 2002), so their careful selection is covered of particular interest. With the graphs on figure 9 we can chose the best option for the SHP project. Teixeira (2009) identified the turbine type for every SHP in Portugal and plotted in the graph below (Fig. 29).

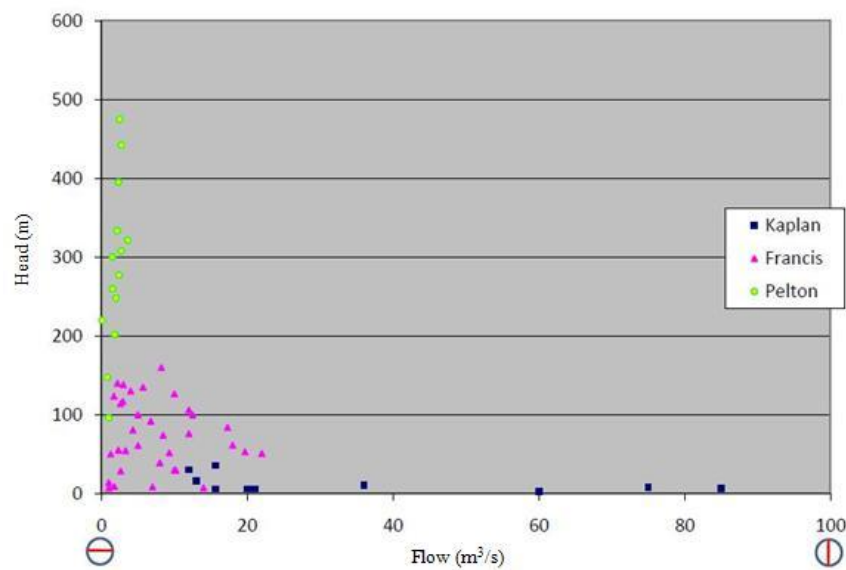


Figure 29: Identification of turbine type in Portugal by the relation of head and flow.

Then, to consider these cost we set a variable cost in €800 per kW installed referent to those elements.

4.4.2. Fixed Costs (Fc)

Moreover, some fixed cost exists in building a plant, and we set as €200000. This value is referent to the minimal cost of the civil structure needed for SHP.

4.4.3. Total Cost per kW

In order to compare all the options in some point in the river, only the total cost is not a good unit. So the relative cost (Rc) per kW produced should be calculated, as the equation below:

Equation 10

$$Rc = \frac{Lc + Pnc + Gc + Ipc + Fc}{P}$$

Where,

Rc = Total cost per kW (€/kW);

Lc = Leat cost;

Pnc = Penstock Cost;

Gc = Grid connection cost;

Ipc = Installed power cost;

Fc = Fixed cost;

P = Potential Installed

This value is calculated for the 5 scenarios in each cell. The known data permit us to place the total investment in a range of variation between 1000 €/kW to 3000 €/kW, so the spots with higher cost than that is automatically excluded from analysis.

4.5. Site Selection for Small Hydropower Plants

After all these calculations, is possible to select the best places for small hydropower plants, with the highest potential and the lowest cost. The process to select the SHP locations starts with the localization of the first best option in the river.

The process continues and the second best site is chosen. Here, some special considerations should be made.

The first special case that can occur is the location of the second site between the powerhouse and intake of the first option selected. The figure below (Fig. 30) exemplifies this case, being the red point the first spot selected with its related river segment and the yellow point the second site. Once no add SHP can be installed in this segment, this river section should be extract from the subsequent analysis. This can be performed with basic function in ArcGis.

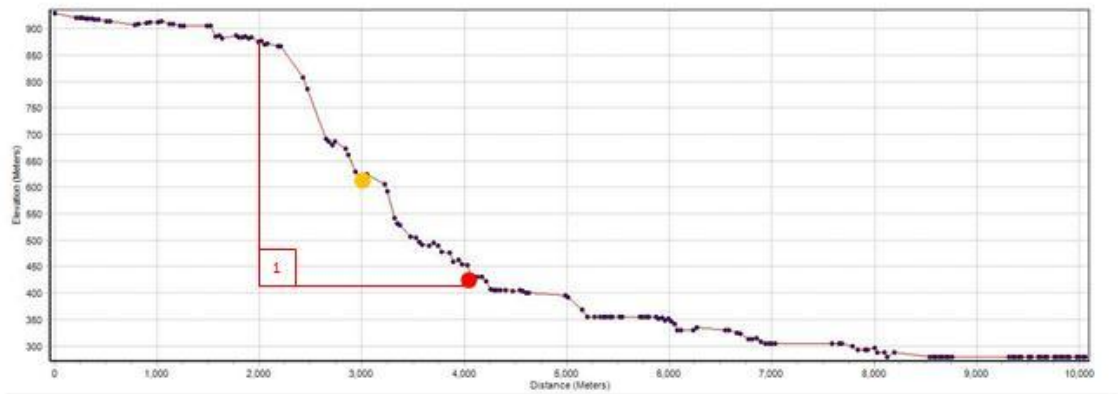


Figure 30: First selected point for SHP, in red, and the second, in yellow, between the intake and powerhouse of the first.

In addition, this also should be done for the already existing small and large hydropower plants. The next figure shows those places for the northern region of Portugal (Fig. 31). With an overlay tool in ArcGis, these sections can be easily removed in previous stages of the site selection process.

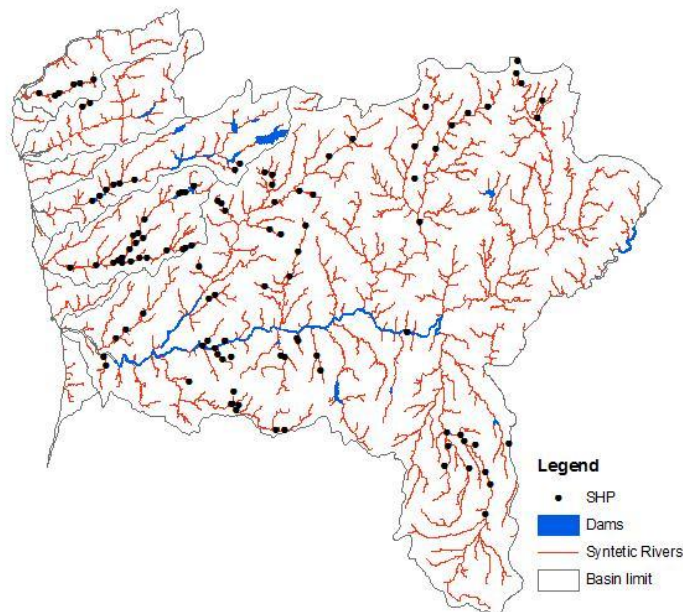


Figure 31: Existing hydropower plants for northern region of Portugal.

The second case is similar to the first, but here, we must be concerned to avoid the overlapping of the subsequent SHP scheme with the previous installation even if it is not located between the intake and powerhouse of the first. The next graph depicts this case (Fig. 32).

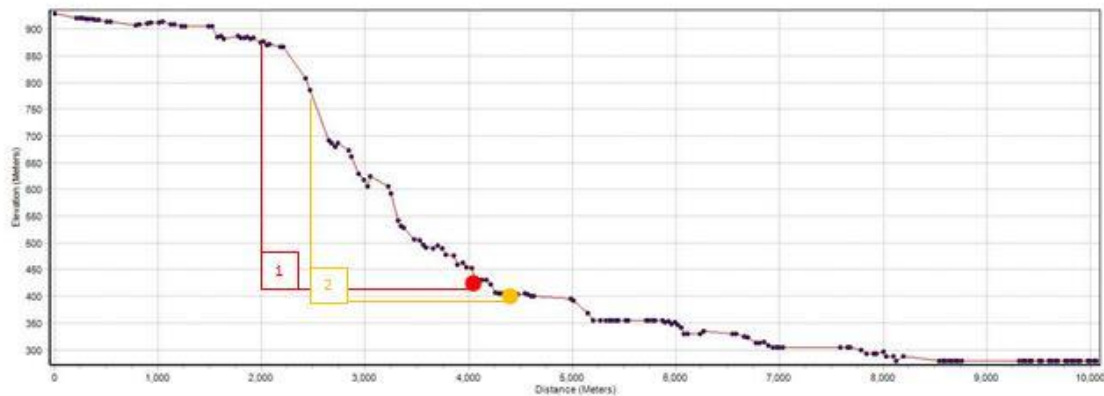


Figure 32: First selected point for SHP, in red, and the second, in yellow, overlapping the first.

Just as in the previous case, with intrinsic functions of ArcGis we can program to do not select hydropower schemes with the water collection point within a pre-selected site. A variation of this case is when the second best place encompasses the first. But, as in our first case, when removing the selected segment, the ArcGis will be unable to make any calculations with this segment, so the second option won't be selected.

Yet, another situation must be analyzed. This is not directly related to the deterrent of location due to the existence of other SHP, but with consideration of options. The next graph shows an example of this, our third case (Fig. 33).

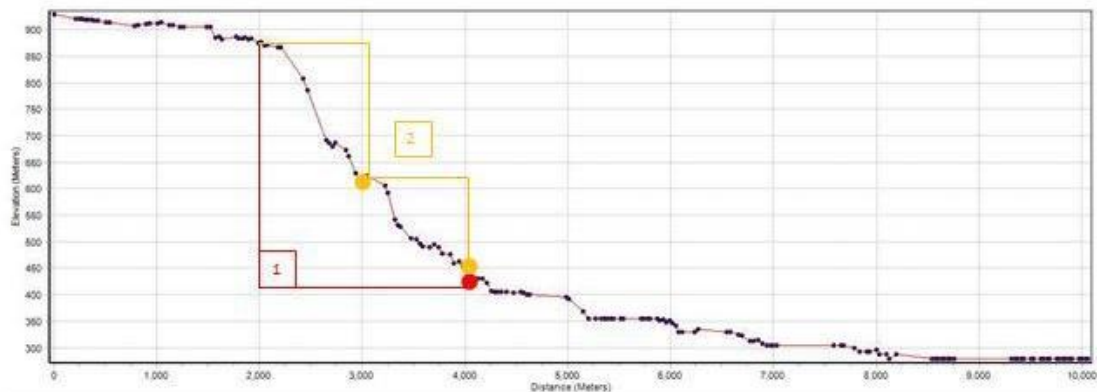


Figure 33: Two possible scenarios: 1) one SHP with 2 km distance between the intake and powerhouse, and 2) two SHP both with 1km between the intake and powerhouse.

The figure above shows two possible situations. The first, in red, shows the construction of a single plant considering the 2 km scenario. The second, in yellow, shows, for the same river segment, the ability to install two power plants with 1 km. What is the best option?

Generally, the best option, comparing the cost, will be the first since the fixed costs is reduced favoring a benefit of scale. On the other hand, we are dealing with small hydropower plants. Hence, with this methodology, it is possible that ArcGis identify areas with higher power potential than 10 MW, as would be the first cases, if we consider a flow of 3 m³/s and head of 425m. In this case, this plant should be overlooked, since it exceeds the maximum value of power established for SHP. Thus, we automatically select the second option.

The fourth and last case identified in this thesis is described below. To demonstrate what may happen we used hypothetical flow data for the intake points of the SHP schemes illustrated. Here, we want to compare if the biggest SHP is really the best option for a segment, and for that, we use the same river as example. The particularity in this case is the presence of a tributary that joins our river (represented by the blue line in the figure 34 and 35).

In this figure, we present four different possibilities. The option A refers to a single installation presenting the highest head. The cases B, C and D represent smaller plants with lower head, but with greater flow, as the water intake is located further downstream. It should be noted especially for the case D, where the water intake occurs just downstream of the confluence of the two rivers, and therefore, present an increased flow rate in relation to other situations.

By the equations and values proposed in topic 4.4, we calculated the costs and potential power for each case and the results are demonstrated in Table 6^y. We want to punctuate that, as stated earlier, the preference is for a single core despite several small hydropower plants. The “A” case has the greater power at a cost of €1138 per kWt. If the other three were installed, we would have an average cost of €1591 (represented by X line) even with higher potential power.

As we can see from the table 6, this increase in cost is mainly due to case B, where a longest deviation should be made to take advantage of a low head. Thus, the installed capacity is too low when compared to the costs it presents. Withal, this

^y The acronyms in the table 6 and 7 are:

H: head; F:flow; Ipc: installed power cost; L: leat; Pn: penstock; Gc: Grid Conection; Fc: fixed cost; Lc:leat cost; Pnc: penstock cost; Gcc:grid conection cost and Rc: relative cost.

hydropower plant does not exceed the upper limit of €3000/kW and can be installed if desire.

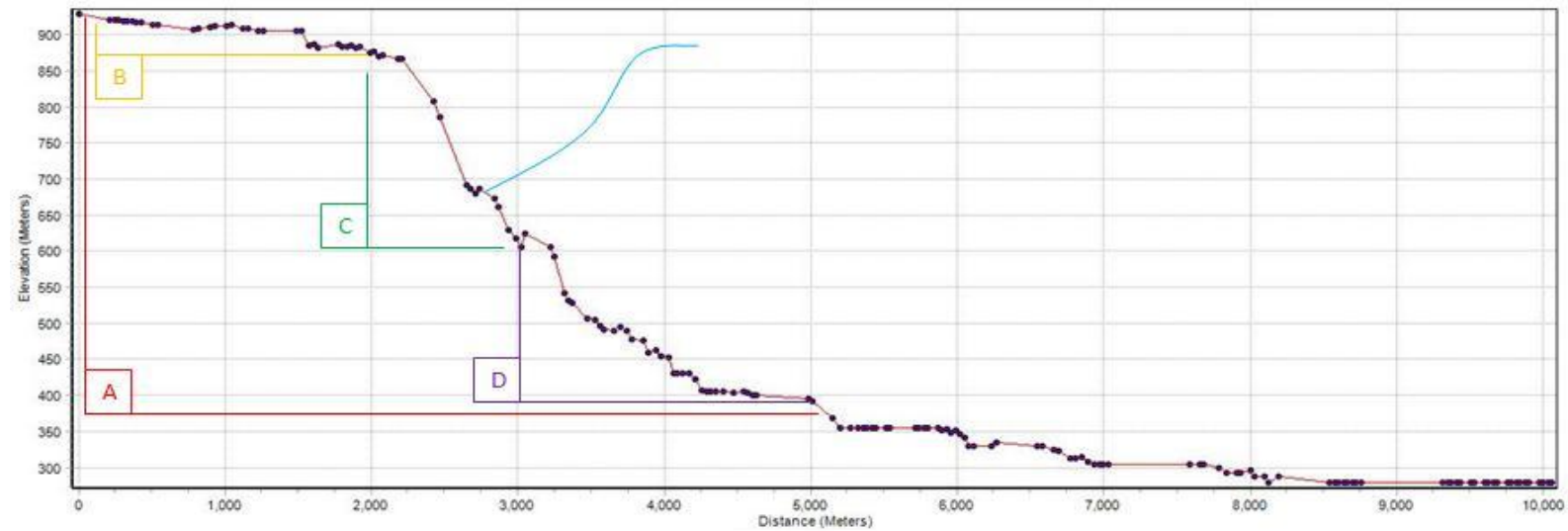


Figure 34: Four SHP options among 5km distance and a tributary river represented by the blue line.

Table 6: Calculations of the cost per kW for the 4 SHP options and the average of the last 3.

| | Scenario (m) | Unit | | | | | | Cost (€/kW) | | | | | €/kW |
|----------|--------------|-------|-----------------------|----------------------|-------|--------------------|---------------------|-------------------|--------------------|-------------------|--------------------|-------------------|----------------|
| | | H (m) | F (m ³ /s) | I _{pc} (kW) | L (m) | P _n (m) | G _c (km) | F _c /P | I _{pc} /P | L _c /P | P _{nc} /P | G _c /P | R _c |
| A | 5000 | 550 | 1.5 | 6879 | 6000 | 495 | 3 | 29 | 800 | 262 | 22 | 26 | 1138 |
| B | 2000 | 50 | 1.6 | 667 | 2400 | 45 | 3 | 300 | 800 | 1151 | 22 | 270 | 2543 |
| C | 1000 | 250 | 1.7 | 3544 | 1200 | 225 | 3 | 56 | 800 | 115 | 22 | 51 | 1044 |
| D | 2000 | 200 | 3 | 5003 | 2400 | 180 | 3 | 40 | 800 | 288 | 22 | 36 | 1185 |
| X | 5000 | | | 9214 | 6000 | 450 | 9 | | | | | | 1591 |

However, if we take the case B from the study, we have the situation depicted in next figure (Fig. 35), and their calculation in the following table (Tab. 7). What can be observed is that only with the cases C and D we can install greater power than the case A and also with lowest cost per kW (represented by Y in the table).

It is important to note that the case C shows the lowest cost per kW, and would be the first selected as the best place for a SHP. With the methodology proposed in these thesis, the case A would be ignored, even with lower potential power than 10MW and this supports the process proposed.

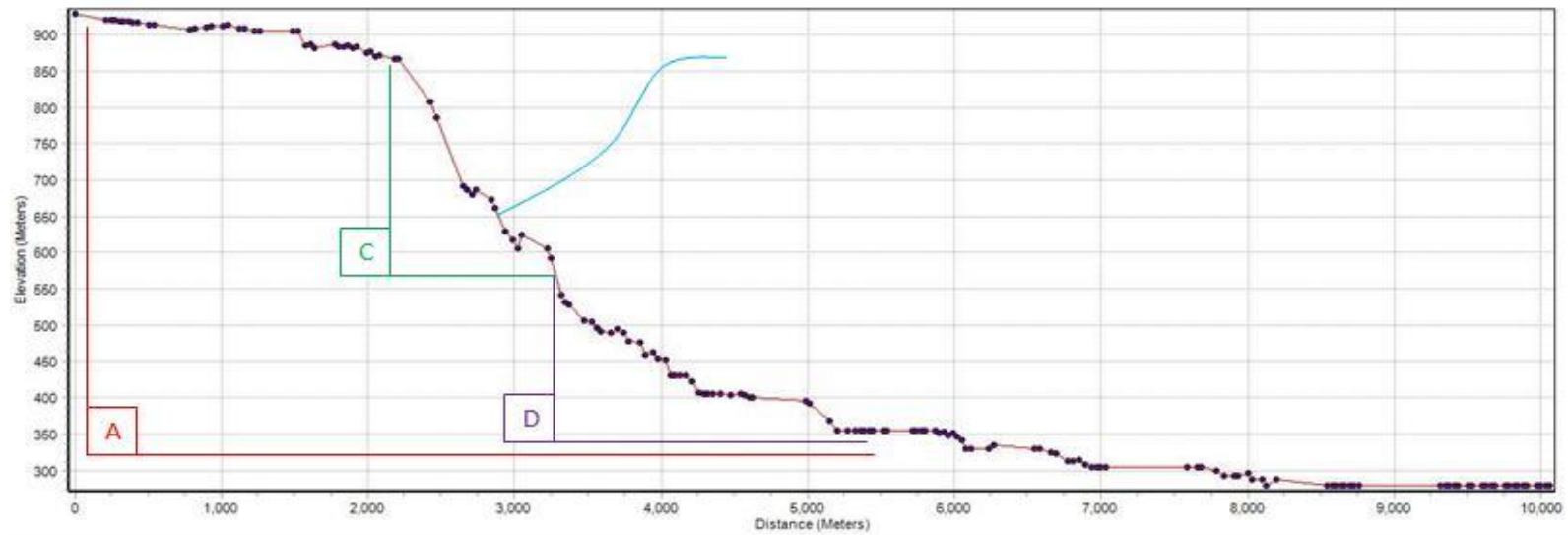


Figure 35: Three SHP options among 5km distance and a tributary river represented by the blue line

Table 7: Calculations of the cost per kW for the 3 SHP options and the average BCD (X) and only CD (Y).

| | Scenario (m) | Unit | | | | | | Cost per kW | | | | | €/kW |
|----------|--------------|-------|-----------------------|--------|-------|--------|---------|-------------|-----|------|-------|------|------|
| | | H (m) | F (m ³ /s) | P (kW) | L (m) | Pn (m) | Gc (km) | Fc/P | Ipc | Lc/P | Pnc/P | Gc/P | Rc |
| A | 5000 | 550 | 1.5 | 6879 | 6000 | 495 | 3 | 29 | 800 | 262 | 22 | 26 | 1138 |
| B | 2000 | 50 | 1.6 | 667 | 2400 | 45 | 3 | 300 | 800 | 1151 | 22 | 270 | 2543 |
| C | 1000 | 250 | 1.7 | 3544 | 1200 | 225 | 3 | 56 | 800 | 115 | 22 | 51 | 1044 |
| D | 2000 | 200 | 3 | 5003 | 2400 | 180 | 3 | 40 | 800 | 288 | 22 | 36 | 1185 |
| X | | | | 9214 | 6000 | 450 | 9 | | | | | | 1591 |
| Y | | | | 8547 | 3600 | 405 | 6 | | | | | | 1115 |

4.6. Environment Constraints

In order to ensure that the environmental impacts of small hydropower schemes are kept to a minimum, SHP operators are required to conduct environmental impact assessments for any small hydropower project. These assessments allow hydro-biological analysis to measure the impacts to the fauna and flora in order to avoid irreversible damage and to define environmental impact mitigation measures. It is also required to establish a minimum reserved flow to maintain the quality of the river ecosystem with any significant alteration due to the small hydropower plant (ESHA, 2008). Among these measures, the installation of fish by pass systems, fish friendly turbines, noise and visual impact should be considered.

This is an essential process made in field for each small hydropower project to respect their particularities. Nevertheless, using the GIS is possible to access previously information about environment sensitivity on determined areas in early stages of the project to evaluate possible constraints. With this analysis, forbidden areas or areas under environmental restriction can be easily identified, and, if needed, the GIS facilitate the consideration to allocate the plant in another site.

As we can see on the maps below^z (Fig. 36), those areas are easily visualized with GIS, and if perchance our project locates in one of these areas, we can analyze alternative spots with lower constraints.

^z Those maps are modifications from the data available at INAG website. They were produced to depict the European Directive 2000/60/CE and Decree law n° 58/2005 orientations for water and environment protection.

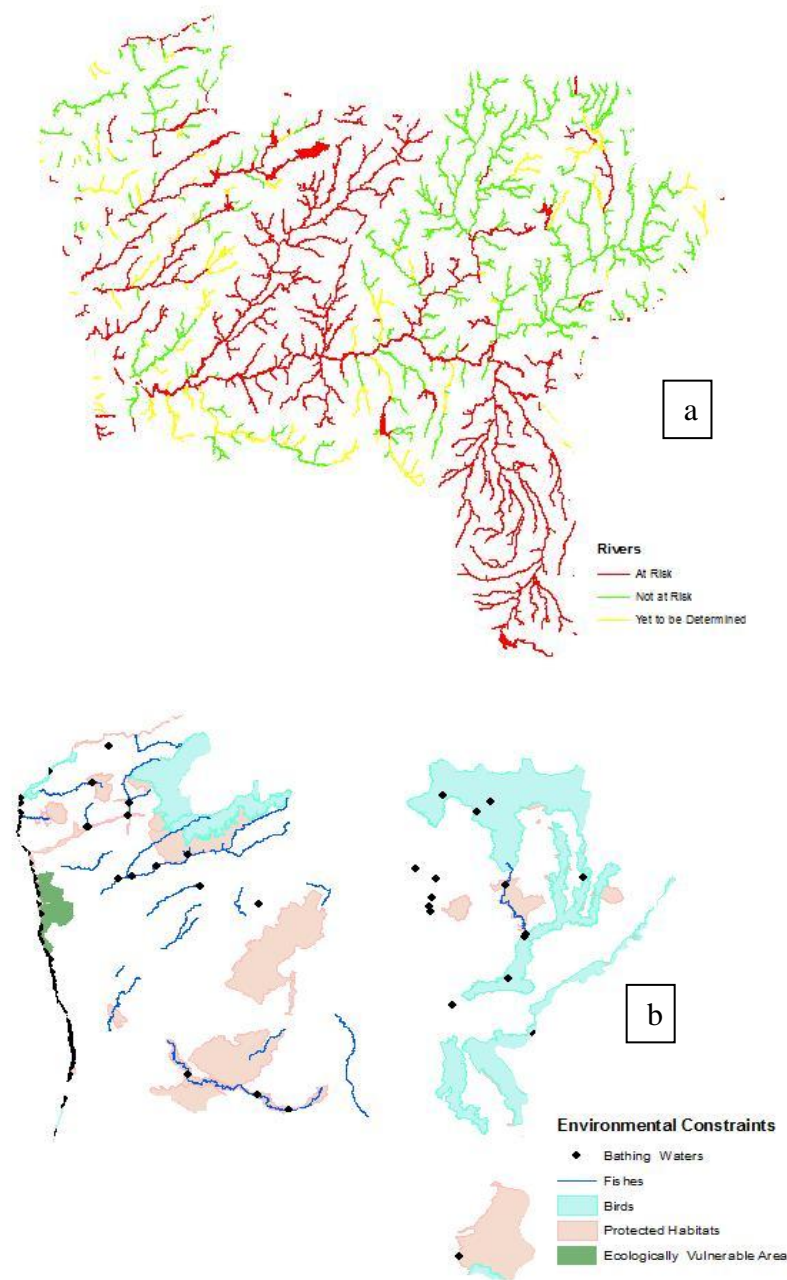


Figure 36: a) River risk classification and b) environmental constraints for the northern region of Portugal.

The first map (Fig. 36a) shows the rivers risk regarding ecological or chemistry factors. If the small hydropower is located in a river with “at risk” classification, we have the beforehand information that additional conditions to implementation may be imposed. The same can be visualized on the second map (Fig. 36b) in regarding to environmental constraints areas. In this map, besides the environmental protected areas, we can analyze some economical and social factors as the “Fishes” line that refers to

rivers with economical fishes species and “Bathing Water” assigning beach spots. In the same way, this informs us regions where conflict of interest may reside. This analysis make the decision making process much easier and faster, once the stakeholders can visualize their location options and restriction sites.

5. Conclusions

Considering that hydropower is one of the priorities covered by the National Energy Policies, is important to evaluate the sites with available potential for further development. This dissertation focused on the development of a methodology for resource assessment of small hydropower.

The general objective of this dissertation was to construct a methodology to select the best options, considering energy, economic and environmental factors, and this was performed aggregating all the information available in databases capable to execute an aggregated analysis. The ArcGis program shows to be a good tool for this process.

Referring to the specific objectives, the head assessment methodology developed permits the identification of different possibilities and scenarios for each point in the rivers streams and so is possible to choose the best economic option regarding potential and costs associated. Using Hourly Numerical Weather Forecasting we do not depend on the availability of pluviometric gauge stations to estimate the flow in the segment under analysis and we can directly assess the flow duration curve for the totality of plants we want to develop, fundamental information to best dimension our project.

In relation to the others methodologies exposed with the similar intention, the methodology proposed here presents some advantages. Using data as the Digital Elevation Model for head assessment and the Hourly Numerical Weather Forecasting to flow computation, we excluded the necessity of fieldwork, and all the study can be executed from digital information saving resources in previously stages and thus reducing the overall project costs. In addition, considering the availability of these data, it is possible to apply to a large area encompassing many basins, to an entire region or even for the all country. This methodology also permits selection of the best design for the SHP considering the potential and the referent costs. Likewise, this methodology is not restrict to a specific country and can be applied in any region around the globe.

The examples presented depict that this methodology is efficient in select the best location for SHP, also considering the best option between all the proposed. This is useful to an integrate basin management promoting a holist view under the region, instead of analyzing each case separately.

This methodology is based on digital elevation models and weather forecasting, which gives the model its peculiar characteristics with possible application to large areas. However, this can have its influence on the results and we have to beware to choose the best resolution maps and consider the possible errors in the forecasts to do not compromise our analysis.

As a proposed methodology, this method should be applied to support the model. For this purpose, we suggest for future work the compilation of rainfall data and the calculations related to determining the flow rate and potential remaining on the rivers of Portugal. So, this information may be used for energy policies in order to determine priority areas for construction of small hydropower plants and a resource to be used to achieve the goals of the country.

6. Bibliographical References

- ADENE & INETI (2001), "Relatório Síntese", Lisbon: Agência de Energia & Instituto Nacional de Engenharia e Tecnologia Industrial, Lisbon.
- APA - Agência Portuguesa do Ambiente (1989), "Atlas do Ambiente", available at <http://www.iambiente.pt/atlas/est/index.jsp>, accessed on 28/03/2010.
- Araújo, J. L., L. P. Rosa and N. F. da Silva (2010), "Hydroelectricity: Future Potential and Barriers" *Generating Electricity in a Carbon-Constrained World*, pp.323-344, Boston: Academic Press, available at: <http://www.sciencedirect.com/science/article/B8N7K-4X55N8F-C/2/c25d264490b33b8aaf4aa78e35bce192>.
- Ávila, C. P., O. C. Júnior, R. F. Guimarães and J. V. Bentancurt (1995), "Uso de Ferramentas de sig para Inventário Preliminar de Potenciais Remanescentes", Brasília: Departamento de Geografia - Universidade de Brasília, Brasília.
- Ballance, A., D. Stephenson, R. A. Chapman and J. Muller (2000), "A geographic information systems analysis of hydro power potential in South Africa", *Journal of Hydroinformatics*, Vol. 02, N. 4, pp. 247-254.
- BHA - British Hydropower Association (2005), "A Guide to UK Mini-Hydro Developments".
- Biberacher, M. (2008), "GIS-based modeling approach for energy systems", *International Journal of Energy Sector Management*, Vol. 2, N. 3, pp. 368-384.
- Calkins, H. W. and R. F. Tomlinson (1977), "Geographic Information Systems: Methods and Equipment for Land Use Planning.", Ottawa, Ottawa.
- Câmara, G., C. Davis and A. M. V. Monteiro (2001), *Introdução à ciência da Geoinformação*, São José dos Campos.
- Camus, C. and E. Eusébio (2006), "Gestão da Energia - Energia Mini-hídrica", Lisbon: Instituto Superior de Engenharia de Lisboa.
- Carvalho, P. M., J. A. Júnior, S. S. Jucá, M. B. Neto and M. A. Santos (2007), "Sistemas de Informação Geográfica (SIG) para Energias Renováveis", Fortaleza.
- Castro, R. G. (2002), "Energias Renováveis e Produção Descentralizada - Introdução à Energia Mini-Hídrica", Lisbon.
- Clarke, K. C. (1986), "Advances in Geographic Information Systems", *Computers, Environment and Urban Systems*, Vol. 10, N. 3-4, pp. 175-184.
- CLIMAUUA - Grupo de Meteorologia e Climatologia da Universidade de Aveiro (2010), "O tempo - Precipitação total", available at <http://climetua.fis.ua.pt/fields/atlantic/precip>, accessed on 08/10/2010.
- Coskun, H. G., U. Alganci, E. Eris, N. Agralioglu, H. K. Cigizoglu, L. Yilmaz and Z. F. Toprak (2010), "Remote Sensing and GIS Innovation with Hydrologic Modelling for Hydroelectric Power Plant (HPP) in Poorly Gauged Basins", *Water Resources Management*.
- Cowen, D. J. (1988), "GIS versus CAD versus DBMS: what are the differences", *Photogrammetric Engineering and Remote Sensing*, Vol. 54, N. 4.
- Das, S. and P. K. Paul (2006), "Selection of Site for Small Hydrel Using GIS in the Himalayan Region of India", *Journal of Spatial Hydrology*, Vol. 6, N. 1.

- DGEG - Direcção Geral de Energia e Geologia (2010), "Renováveis - Estatísticas Rápidas", available at <http://www.dgge.pt/>, accessed on Access 28 de Agosto de 2010.
- Dominguez, J. and J. Amador (2007), "Geographical information systems applied in the field of renewable energy sources", *Computers & Industrial Engineering*, Vol. 52, N. 3, pp. 322-326.
- Dragu, C., T. Sels and R. Belmans (2005), "Small Hydro Power State of The Art and Applications".
- EEA - European Environmental Agency (2006), "CORINE Land Cover", available at <http://www.eea.europa.eu/publications/COR0-landcover>.
- EIA - Energy Information Administration (2010), "International Energy Outlook", available at <http://www.eia.doe.gov/>, accessed on 27/08/2010.
- ESHA - European Small Hydropower Association (2004), "State of the Art of Small Hydropower in EU-25".
- ESHA - European Smallhydropower Association (2008), "Hydropower Respects the environment - A clean and indigenous Renewable Energy", available at http://www.esha.be/fileadmin/esha_files/documents/SHERPA/SHERPA_fiche_Environment.pdf.
- ESRI (2009), "ArcGis Desktop Help 9.3 - Hydrological Analisis", available at http://webhelp.esri.com/arcgisdesktop/9.3/printBooks_topics.cfm?pid=6050.
- EU - European Union "Directiva 2001/77/CE do Parlamento Europeu e do Conselho". Published on 27/09/2001.
- EU - European Union (2006), "Metas de Quioto na UE (a alcançar ate 2012)", available at <http://ec.europa.eu/>, accessed on 30/08/2010.
- EU - European Union "Communication from the Commission to the European Council and the European Parliament - An Energy Policy for Europe", Brussels.
- Gomes, J. F. P. (2008), "Reflections on the use of renewable power sources and nuclear energy in Portugal", *International Journal of Environmental Studies*, Vol. 65, N. 6, pp. 755 - 767.
- Goodchild, M. F. (1985), "Geographic Information Systems in Undergraduate Geography: A Contemporary Dilemma", *The Operational Geographer*, Vol. 8, pp. 34-38.
- Goodchild, M. F., C. Kottman and M. J. Egenhofer (1999), *Interoperating Geographic Information Systems* Kluwer Academic Publishers.
- Gorenstin, B. G., N. M. Campodonico, J. P. Costa and V. F. Pereira (1993), "Power system expansion planning under uncertainty", *Power Systems, IEEE Transactions on*, Vol. 8, N. 1, pp. 129-136.
- Governo de Portugal "Resolução de Conselho de Ministros n.º 1/2008 - Novas Metas 2007", 1.ª série - N.º 3.
- Governo de Portugal "National Energy Strategy - ENE 2020", Cabinet Resolution nº 29/2010.
- INAG - Instituto da Água (2010), "Sistemas de Informação de Recursos Hídricos", available at <http://www.inag.pt/>, accessed on 17/03/2010.
- Kubečka, J., J. Matěna and P. Hartvich (1997), "Adverse ecological effects of small hydropower stations in the Czech Republic: 1. Bypass plants", *Regulated Rivers: Research & Management*, Vol. 13, N. 2, pp. 101-113.

- Kusre, B. C., D. C. Baruah, P. K. Bordoloi and S. C. Patra (2010), "Assessment of hydropower potential using GIS and hydrological modeling technique in Kopili River basin in Assam (India)", *Applied Energy*, Vol. 87, N. 1, pp. 298-309.
- Lee, R., J. Brizzee, S. Cherry and D. G. Hall (2008), "Virtual Hydropower Prospecting: A Foundation for Water Energy Resource Planning and Development", *Journal of Map & Geography Libraries*, Vol. 4, N. 2, pp. 336-347.
- Magureanu, R., M. Albu, V. Bostan, A. M. Dumitrescu, M. Pelizza, F. Andreea, G. Dimu, F. Popa and M. Rotaru (2008), "Optimal operation of Francis Small Hydro turbines with variable flow", proceedings of Industrial Electronics, available at 10.1109/ISIE.2008.4677281.
- Meteorologia, I. d. (1960-1990), "Clima de Portugal Continental - Instituto de Meteorologia > Área Educativa > Clima em Portugal", available at <http://www.meteo.pt/pt/areaeducativa/otempo.eoclima/clima.pt/index.html>, accessed on 12 August.
- Moreira, M. G., R. Z. Pinaud, A. C. Barreto and M. V. Freitas, "Pequenas Centrais Hidrelétricas - Alguns Tipos de Instalações, Sistemas e Componentes", available at http://www.portalpch.com.br/index.php?option=com_content&view=article&id=216:pequenas-centrais-hidrelicas-alguns-tipos-de-instalas-sistemas-e-componentes&catid=13:artigos&Itemid=134.
- O'Callaghan, J. F. and D. M. Mark (1984), "The extraction of drainage networks from digital elevation data. ", *Computer Vision, Graphics and Image Processing*, Vol. 28, pp. 323-344.
- PER - Portal das Energias Renováveis "Hídricas - Estado em Portugal", available at <http://www.energiasrenovaveis.com/>, accessed on 30/10/2010.
- Ramirez-Rosado, I. J., L. A. Fernandez-Jimenez, C. Monteiro, V. Miranda, E. Garcia-Garrido and P. J. Zorzano-Santamaria (2005), "Powerful planning tools", *Power and Energy Magazine, IEEE*, Vol. 3, N. 2, pp. 56-63.
- REN - Rede Eléctrica Nacional S.A. (2006), "Potencial Hidroeléctrico Nacional - Importância Sócio Económica e ambiental do seu desenvolvimento".
- Rojanamon, P., T. Chaisomphob and T. Bureekul (2009), "Application of geographical information system to site selection of small run-of-river hydropower project by considering engineering/economic/environmental criteria and social impact", *Renewable and Sustainable Energy Reviews*, Vol. 13, N. 9, pp. 2336-2348.
- RSI (1997), "Envi 3.0 User's Guide ", Colorado, USA, Colorado, USA.
- Santos, S., A. Monteiro, S. Mourato and P. Fernandez (2006), "Os Sistemas de Informação Geográfica na Modelação Hidrológica", proceedings of Congresso Nacional de Tecnologías de la Información Geográfica, Location: Granada, available at http://age.ieg.csic.es/metodos/docs/XII_1/033%20-%20Santos%20et%20al.pdf.
- Schwartz, F. H. and M. Shahidehpour (2006), "Small Hydro As Green Power", proceedings of EIC Climate Change Technology 10-12 may, available at <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4057327&isnumber=4057291&tag=1>.
- Souza, Z., H. M. Santos and E. C. Bortoni (1999), "Centrais Hidrelétricas: Estudos para Implantação": Eletrobrás,.
- Tanutpongpalin, N. and T. Chaisomphob (2004), "Proposed Methodology for Site Selection of Run-of-river Type Small Hydropower Project Based on

- Environmental Criteria", proceedings of Sustainable Energy and Environment (SEE), Location: Hua Hin, Thailand.
- Teixeira, H. S. (2009), "Caracterização da Produção de Centrais Mini - Hídricas", Porto: Universidade do Porto, accessed on Access Junho de 2009.
- Thilak, B. G. (2009), "Global Small Hydro Power Market Analysis to 2020 - Installed Capacity, Generation, Investment Trends", available at: http://www.altenergymag.com/emagazine.php?art_id=1532.
- Tomlinson, R. F. (1972), "Geographical data handling", proceedings of Symposium on Geographical Information Systems, Location: Ottawa, 1-9/08/1972, available at <http://nla.gov.au/nla.cat-vn2123573>.
- UN - United Nations (1998), "Kyoto Protocol to the United Nations Framework Convention on Climate Change".
- Wilson, E. M. (2000), "Assessment Methods for Small-Hydro Projects": International Energy Agency - EIA, available at <http://www.small-hydro.com/index.cfm?Fuseaction=planning.tools>.
- Zeihofer, P. and R. N. Lima (2006), "Regio: Uma Aplicação SIG para Subsidiar a Regionalização de Vazões", *Caminhos da Geografia*, Vol. 6, N. 17, pp. 54-61.

7. Annex I: The original and the reclassified values for land cover.

| Original Code | Original Class | Reclassified Code | Reclassified Class |
|---------------|---|-------------------|--------------------|
| 335 | Eternal snow and glaciers | 1 | Water |
| 411 | Pauls | 1 | Water |
| 412 | Mires | 1 | Water |
| 421 | Marshes | 1 | Water |
| 422 | Salinas | 1 | Water |
| 423 | Intertidal | 1 | Water |
| 511 | Water Lines | 1 | Water |
| 512 | Plans for water | 1 | Water |
| 521 | Coastal lagoons | 1 | Water |
| 522 | Estuaries | 1 | Water |
| 523 | Sea and ocean | 1 | Water |
| 112 | Discontinuous urban fabric | 2 | Residential |
| 121 | Industry, commerce and general equipment | 2 | Residential |
| 122 | Road and rail networks and associated spaces | 2 | Residential |
| 123 | Port areas | 2 | Residential |
| 124 | Airports | 2 | Residential |
| 131 | Areas of mining | 2 | Residential |
| 132 | Areas of waste disposal | 2 | Residential |
| 133 | Areas under construction | 2 | Residential |
| 141 | Urban green spaces | 2 | Residential |
| 142 | Sports and leisure | 2 | Residential |
| 311 | Hardwood forests | 3 | Forest |
| 312 | Coniferous forests | 3 | Forest |
| 313 | Mixed forests | 3 | Forest |
| 321 | Rangelands | 3 | Forest |
| 322 | Matos | 3 | Forest |
| 323 | Vegetation esclerofitica | 3 | Forest |
| 324 | Degraded forest areas, cuts and new plantaces | 3 | Forest |
| 331 | Beaches, sand dunes | 3 | Forest |
| 332 | Bare rock | 3 | Forest |
| 333 | Sparse vegetation | 3 | Forest |
| 334 | Areas burnt | 3 | Forest |
| 211 | Annual crops in rainfed | 4 | Agricultural |
| 212 | Annual crops irrigated | 4 | Agricultural |
| 213 | Rice | 4 | Agricultural |
| 221 | Vineyards | 4 | Agricultural |
| 222 | Orchards | 4 | Agricultural |
| 223 | Groves | 4 | Agricultural |
| 231 | Pastures | 4 | Agricultural |
| 241 | Annual crops associated with permanent crops | 4 | Agricultural |
| 242 | Cultural systems and complex partial | 4 | Agricultural |
| 243 | Agriculture spaces with natural | 4 | Agricultural |
| 244 | Agroforestry systems | 4 | Agricultural |