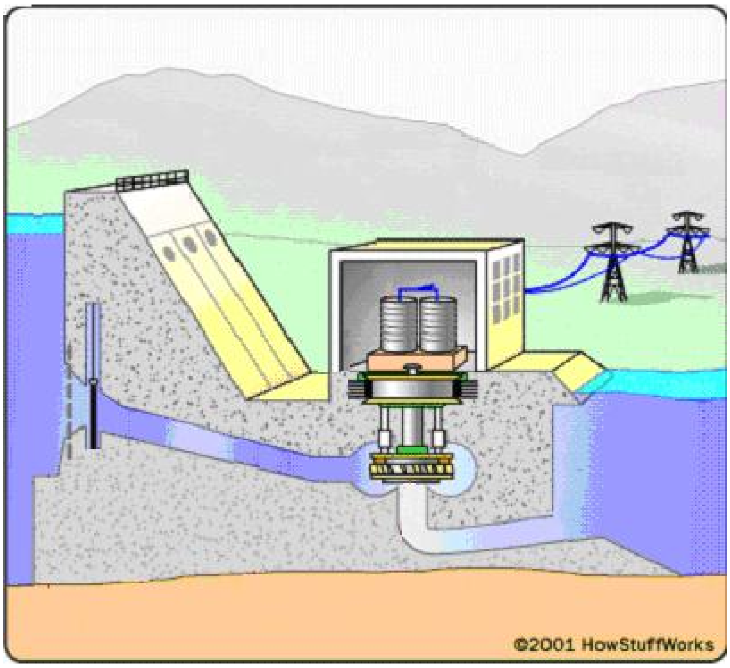
Small-scale hydropower:
A methodology to estimate
Europe's environmentally compatible potential



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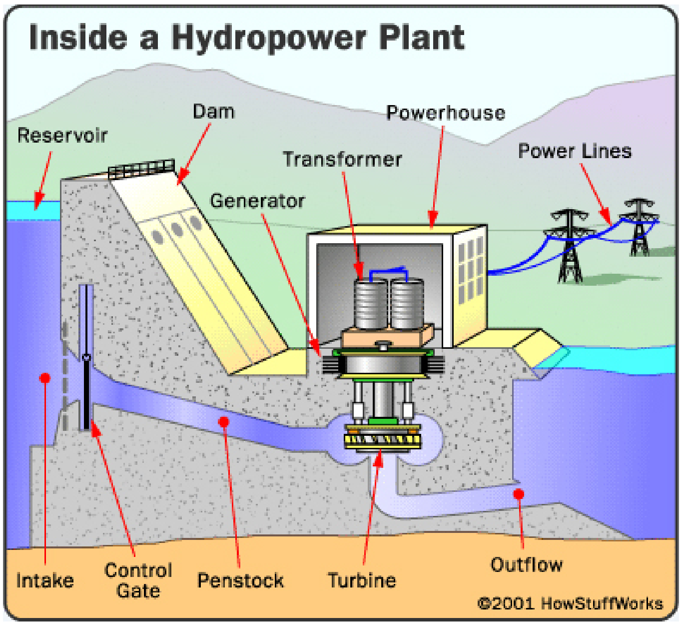
Front page picture: *Cross section of the inside of a hydropower plant*



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Executive summary

This final is submitted to the European Environment Agency in fulfilment of Task 2.8.2 – Renewable Energy of the EEA European Topic Centre on Air and Climate Change 2010 Work plan. The work is performed by AEA Technology with guidance from Paul Ruyssenaars and Hans Eerens of the Netherlands Environmental Assessment Agency (PBL), and David Owain Clubb and Philippe Crouzet of the European Environment Agency.

Study Objectives

The objective of this study is to outline a 'roadmap' for the development of a methodology for estimating the Small Scale Hydropower (SHP) technical and environmentally compatible potential SHP for the European Union plus the five other European countries which fall within the EEA's remit. The main data source for this development is the EEA's European Catchments and RIvers Network System (ECRINS) suite of Microsoft Access geo-databases. The methodology tested to investigate how this could be delivered had the following sequential stages:

A. Evaluate Theoretical Potential - Defined as the total energy production potential of the water that flows in rivers and streams over a given land mass as they make their way to the sea.

B. Evaluate Technical Potential – Accounting for the ability to capture energy in a discrete number of hydro schemes deployed so as to maximise the economic use of the potential. It implies a number of assumptions that were spelt out in a previous report.[1] In order to differentiate it from the next category, the Technical Potential assumes a low level of environmental constraint on the location and operation of SHP plant.

C. Evaluate Environmentally Compatible Potential - Is based on the Technical Potential but takes into account a range of environmental constraints on the location and operation of SHP plant. These factors could include fish migration, requirements for reserve flow and exclusion from geographically designated areas etc.

The earlier work also described a further level of assessment, Realisable Potential; this is the environmentally compatible potential, factored down to take into account the share that is considered socially acceptable. Inherent in this is a value judgement concerning the maximum deployment density that is likely to be acceptable at a given point in time. This last element has not been tested in this work due to the limitations in defining the earlier sequential stages.

ECRINS Data

ECRINS contains a range of data on river networks; such as elevation, dam/weir head, co-ordinates and monthly flow linked to main drain line segments.

Assessment of the initial data available identifies some initial limitations, these include:

- Main Drain flow data – Currently this covers less than 50% of the main drains across Europe.

[1] http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2008_16_pots_ren_energy_techn

- Tributary flow data - An important point is that no flow data is supplied directly on the flow for Tributaries. For this study an estimate will be calculated based on the length of tributaries and the increase in flow between given nodes
- Elevation data - Is only available at the nodes, in some cases there can be a significant distance between these, resulting in poor granular resolution.
- Dams data – The data available for dams is limited, only c.4,600 structures are contained in the database, however based on a recent UK study[2], this could be expected to represent in the region of c.3% of the total number of river barriers/structures.

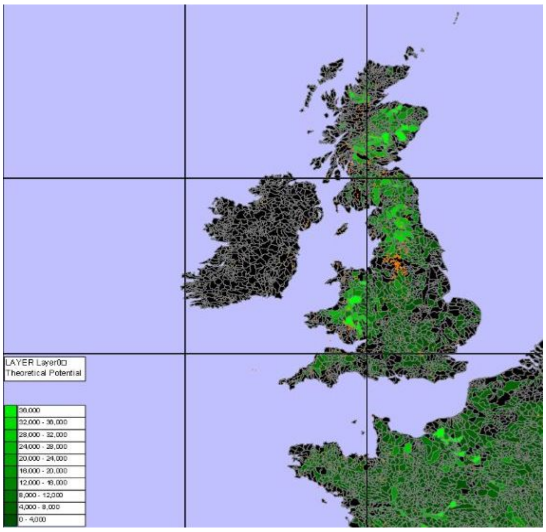
However, based on the data available this report still considers the proposed methodology to test if the data available in ECRINS can be used to deliver an assessment of Europe's environmentally compatible hydro-power potential.

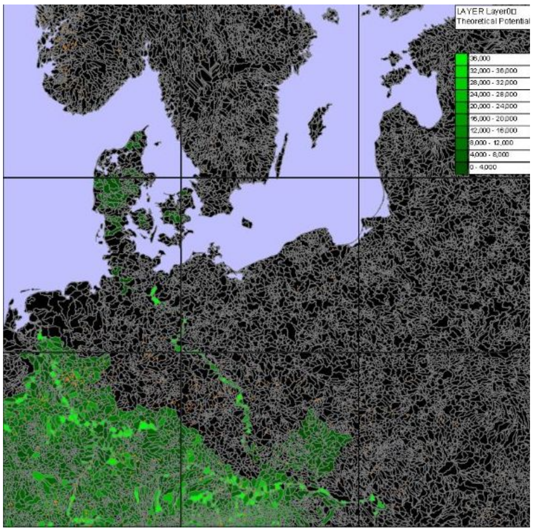
Theoretical Potential

The first stage of this assessment was to try and understand the theoretical potential using ECRINS. In terms of hydropower, the power represented by potential energy contained in the water flow in an ECRINS Main Drain or Tributary Line Segment (stretch of water course) is:

Average flow rate (Q_{mean}) at lowest point x Head x 9.8 (acceleration due to gravity)

Based on this analysis it was possible to plot maps showing the theoretical potential of different catchment areas, this is shown in Figure 1.





[2] "Mapping hydropower opportunities and sensitivities in England and Wales (technical report)" (Environment Agency, February 2010), http://www.environment-agency.gov.uk/shell/hydropowerswf.html.

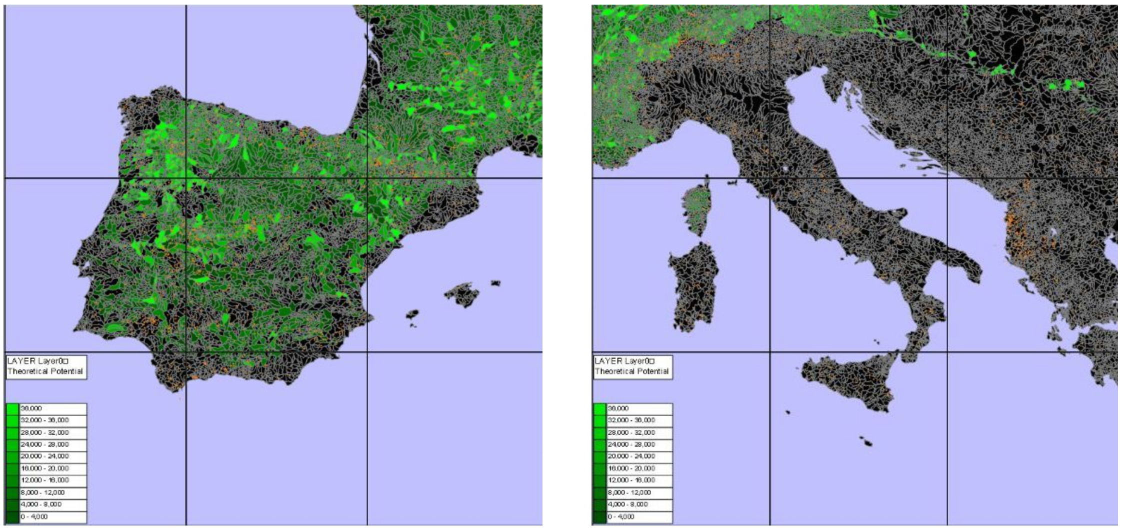


Figure 1: the theoretical hydro potential across Europe calculated from the data contained in ECRINS

This Theoretical Potential calculated from ECRINS has been compared to a similar potential value calculated for 8 Scottish catchments as part of the Scottish Hydropower Resource Study[3]. The average variation between the potential calculated in this report and the Scottish calculation methodology was 10%, which indicates overall the different methods broadly agree for the catchments evaluated, although the methodology used in this report tended to somewhat lower potential estimates.

Technical Potential

The aim of trying to understand the Technical Potential is to understand the locations where hydropower could reasonably and practically be deployed.

A review of 5 different methodologies was carried out and reported in ETC/ACC Technical Paper 2009/13 December 2009. These methodologies work on the basis of analysis of specific sites or tend to rely on costly propriety software such as HydroBot[4] (for a description of HydroBot see the paper produced for Hidroenergia 2010[5]). This approach would be the ideal method for evaluating Technical Potential. It would require detailed topographical and flow information (ideally elevation data is provided on a resolution of 10m), data on infrastructure and environmental constraints on a far finer geographical grid than is contained in ECRINS.

On balance using software such as HydroBot on a Europe wide basis is likely to be an expensive process when considering the man-hours and amount commercial data that could be required. Therefore a method that could produce these results in a more cost effective and holistic would be of significant value.

Using ECRINS to Evaluate Technical Potential

Based on the data available it was decided to trial the methodology on an area in the Pyrenees. A methodology to estimate the SHP on this scale needs to be based on a series of assumptions which can provide a reasonable approximation at each

[3] 'Scottish Hydropower Resource Study' August 2008, Nick Forrest Associates, SISTech and Black & Veatch, http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf
[4] 'Scottish Hydropower Resource Study' August 2008 – Nick Forrest Associates - http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf
[5] "HydroBot: remote surveys of national hydro resources"; Nick Forrest, Conference Paper, Hidroenergia 2010, July 2010

site/node. These parameters may need to be modified as the methodology is developed. The following assumptions have been applied in the example tested:

- Each catchment node has been selected as the hypothetical location for a SHP scheme;
- The energy output assumes that each of the sites selected (in this example) is a high head run-of-river scheme;
- The abstraction point for each SHP site is the node immediately upstream of it. Consequently the difference in elevation can be used to provide the head (H). This means that no water entering the watercourse between the two nodes is considered in the calculation;
- The rated power and annual energy output for each SHP, are calculated from the mean flow at the abstraction point and the head from the abstraction point to the hydro installation;
- The capital cost (CAPEX) and operating cost (OPEX) are based on a range of values provided by ESHA for SHP development in different EU countries. The size of the plant (based on its rated power) has also been used to define the cost estimate.

Using standard hydro power calculations, estimates on design flow rates, and plant utilisation rates the unit costs (€cent/kWh) of hydro plants a cost of energy was estimated. This then allowed the estimation of a resource cost curve to be developed for the catchment, and allow comparison of the cost and quantity of generation once environmental constraints are applied.

For chosen example catchment in the Pyrenees, the Theoretical Potential identified is 5,361MWe of SHP hydro capacity. This methodology described can only approximate the gross SHP Technical Potential, as it suffers from two main uncertainties. One component of the methodology overestimates the realistic potential of the main drains as it assumes that a plant would be built at every node and make full use of the available head from the previous node. It also does not consider the distances between the nodes and how this might affect the capital cost of the scheme. It is difficult to quantify how much the methodology over estimates capacity and this will be specific to the catchment and terrain.

Another component underestimates the potential as there is no flow information in ECRINS for the tributaries (which could provide a significant share of the total potential). From analysis of 8 catchments in Scotland, of total the identified catchment capacity using ECRINS data the contribution from tributaries represents around 35% of the overall capacity; this capacity is not accounted for the above methodology.

It should be noted that there could be options for refining the methodology – this may include seeking higher resolution data on the topography to help identify likely locations for siting SHP plant and the hydraulic heads that they would use. A full evaluation of Technical Potential also requires information on the proximity of the electricity grid and access for construction, a better appreciation of low head and high head costs could also be used to provide more robust unit cost of energy.

Whilst it can be seen that there is scope for the methodology for evaluation of the Technical Potential to be refined. It was felt worthwhile to consider an environmental proxy in parallel to demonstrate how the methodology would work in full and the potential impact of environmental constraints on the cost of energy from hydro installations.

As an initial assessment of the effect of environmental constraints, two elements have been considered to demonstrate the potential impact of an environmental constraint (as from the stakeholder workshop held on 27th November 2009 these elements are most affected by environmental constraints):

1. Reduced design flow – resulting in a smaller installed capacity and energy generation.
2. Increases capital costs - the CAPEX has also been increased by a third to simulate the added cost of environmental mitigation measures.

Due to the reduced design flow rate, both the installed capacity the annual energy generation is reduced. In the example catchment the Technical Potential is reduced by 44% to an Environmentally Compatible Potential of 2,359kWe. The is reduction in without considering which SHP sites might not be economically attractive any longer and therefore unattractive to develop, hence further reducing the Environmentally Compatible Potential to a Realisable Potential when considered with deployment rates.

Using this it was also then possible to demonstrate the hypothetical increase in cost of generation and also the reduced potential generation capacity as a resource cost curve, the results of this for the example evaluated are shown in Figure 2. From this it can be seen that the resource cost curve shifts to the right and down, representing that both the generation potential is lower, and the cost of energy generated is more expensive. The reduction in the amount of energy generated is simply created by the limit on the water than can be abstracted from the watercourse and passed through the SHP system and the reduced capacity of the hydro plant. The increase in the cost of energy generated is however caused by the increase cost of the plants capital cost an also as hydro plant is more expensive at smaller scales.

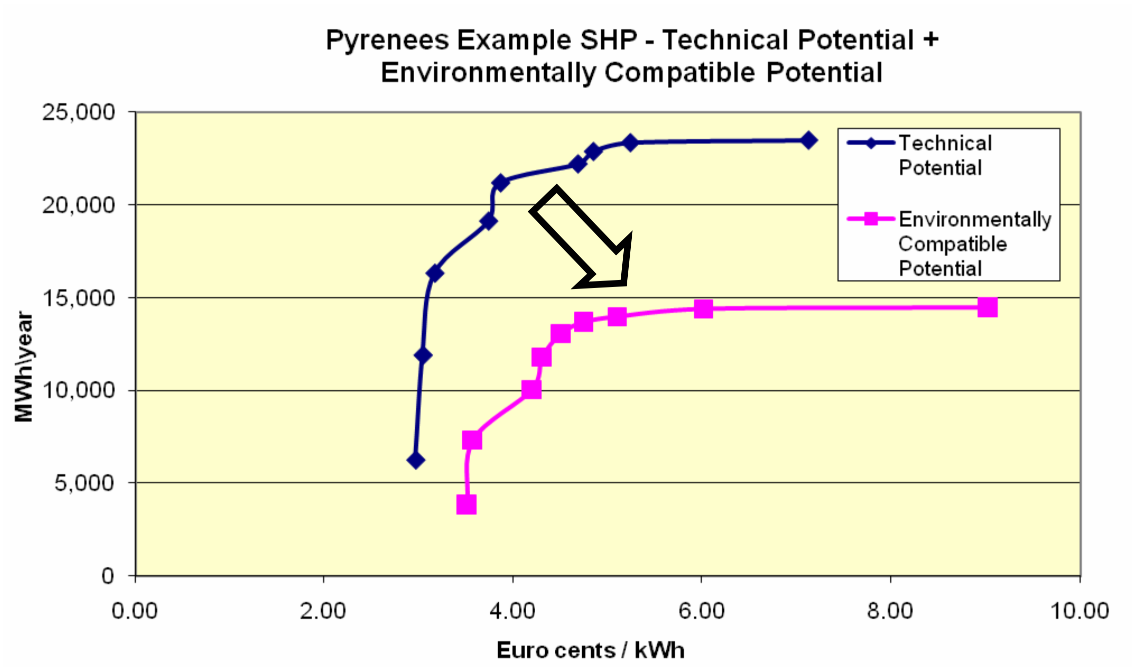


Figure 2: **Comparative resource cost curves for technical and environmentally compatible potential for the Pyrenees example catchment area**

From evaluation of the results, it can be seen that costs estimates are quite low when compared to current and foreseen electricity wholesale prices. So even with the limitations (mentioned before with respect to Technical Potential), which would bring down the costs even more, there seems to be a financially attractive Technical Potential which can be exploited. In case of a European wide assessment the costs could be grouped in Attractive Potential (30% or more below the whole sale prices), Plausible Potential (-30% up to + 30% of the foreseen whole sale prices) and Limited Technical Potential (up to electricity prices paid by consumers including tax, i.e. 20 Eurocent/kWh). It should also be considered that even if the capital cost were under estimated by a factor of 3, there is still likely to be significant SHP that is economically viable and contribute in delivering the EU renewable energy targets.

Identifying Areas of Environmental Importance

The report has reviewed the use of the Natura 2000 network. This is one of the key instruments for promoting biodiversity and conservation. It is thus an important resource for evaluating the environmentally compatible potential.

It was possible to map this data across the catchments identified, thus identifying areas which could be more sensitive to hydro power developments. This demonstrates that environmental designations can be applied to catchments, and where data allows more specific areas within catchments. As part of the process of exploring environmental constraints on SHP a workshop was held with hydro practitioners in 27th November 2009 and reported in the previous report[6]. The next stage of the methodology if developed further would be to match the designations with the potential impact on hydro plants. These could include key factors such as:

[6] "Small-scale hydropower: how to reconcile electricity generation and environmental protection goals?", ETC/ACC Technical Paper 2009/13, December 2009

- Abstraction rate restrictions to maintain residual flow under specific scenarios and designations.
- Fish deterrence / passage and associated capital costs.
- The allowable deployment density of SHP developments in a catchment or group of catchments.
- Exclusion from certain designated areas. There are many different types of designated areas and restrictions could vary considerably from one type to another.

This would then allow the environmentally compatible potential to be defined and the cost of this SHP potential to be demonstrated. In particular to build on the previous work, quantification of the cost of different environmental constraints would allow a more accurate picture of the cost of environmentally compatible potential. It was identified in the stakeholder workshop that there are varying standards across Europe, this makes refining a single set of parameters across Europe assessment more complex.

As concluded by the workshop, at this early stage of assessment it is important not to exclude new SHP potential that fall under areas that are designated, such as Natura 2000 and only those sites where a vulnerable aquatic habitat has been identified need to be considered. It could be that development could proceed in these areas if it was Water Framework Directive (WFD) compliant.

Rather than assuming complete exclusion from designated areas, the SHP potential in these areas should be estimated. Then the environmentally compatible potential could be estimated with and without SHP potential in such designated areas.

Summary and Further Development

It can be seen that whilst the overall methodology would seem to allow the end goal of defining Europe's environmentally compatible SHP potential to be identified, there are some significant challenges in actually technically delivering this using the ECRIN database alone; these challenges are mainly are based on the granular resolution of the data available in ECRINS.

It was found that the Theoretical Potential can be defined using the methodology described in this work, and yields comparative results when tested against similar studies in limited catchments (such as HydroBot). However, evaluating Technical Potential is much more complex requiring both a higher resolution of data and also a wider range of data than contained in ECRINS.

The identification of the Environmentally Compatible Potential seems like could be achievable, if the challenges presented in identifying the Technical Potential can be overcome. Although to define the impact of different environmental designations / constraints would require consultation and consensus with the hydro and environmental community to establish both the impact on development of SHP in these areas, and also the impact on the capital cost.

If the evaluation of Europe's environmentally compatible SHP potential is to be pursued using the ECRINS data, a more robust estimate of Technical Potential would need to be defined. This would need to be done though identifying additional data sources, refining the methodology and then testing the results (possibly against another method such as HydroBot) across a limited area. If this could be demonstrated to be successful and replicable across Europe then it would be worth further developing the final step of the methodology to define the Environmentally Compatible Potential.

Table of contents

1 Introduction and background 1

1.1 Context 1

1.2 Objective 1

1.3 Background 1

2 Data available from ECRINS 2

2.1 Objects within ECRINS 2

2.2 Key Data Issues in ECRINS 4

3 Methodology to quantify the small-scale hydropower potential 6

3.1 Background to the development of the methodology 6

3.2 Estimating SHP Resource from ECRINS for a selected catchment 15

3.3 Factoring in the Environmentally Compatible Potential 20

4 Further Development of the Methodology 23

4.1 Refinement of the SHP Technical Potential 23

5 Conclusions 33

7 Literature 35

8 Appendix 1: Technical Potential – a suggested individual site approach 36

1 Introduction and background

1.1 Context

The European Environment Agency (EEA) has been asked by the European Commission to help define the “environmentally compatible potential” for renewable energy in the period to 2030. This must be seen in the context of the recently agreed Renewable Energy Directive 2009/28/EC requiring the European Union to obtain 20% of its final energy demand from renewable energy sources by 2020[7] from a starting position of 8.5% in 2008. This is a very challenging mandatory target and all actors at European, national and local level will need to work together to secure its achievement. Each Member State has been assigned its own binding target based on its current level of deployment and its capacity to bring forward new projects. Member States were required to submit national action plans for submission to the Commission by the end of June 2010[8], although by the beginning of December there were still four missing. These National Renewable Energy Action Plans (NREAPs) set out detailed estimates of deployment and energy generation for each renewable energy technology on a yearly basis from 2010 to 2020.

1.2 Objective

The objective of this study is to outline a ‘roadmap’ for the development of a methodology for estimating the Small Scale Hydropower (SHP) technical and environmentally compatible potential SHP for the European Union plus the five other European countries (Norway, Switserland, Iceland, Liechtenstein and Turkey) which fall within the EEA’s remit. The main data source for this study is the EEA’s ECRINS suite of Microsoft Access geo-databases which has been developed by Philippe Crouzet at EEA.

1.3 Background

The development of this methodology was discussed in the two earlier technical papers[9,10] and also discussed at a meeting with the EEA in Copenhagen on 14th April 2010. Following that meeting it was agreed that a methodology would be developed to estimate the SHP technical and environmentally compatible potential. This would have two main strands:

- Europe-wide – based on the available data from ECRINS, develop and validate automated calculation algorithms that could be applied to all catchments across Europe. The approach we have adopted for this strand is to create ‘Stages’ with defined outputs, starting from high level ‘Theoretical’ potential and progressing to increasingly realistic ‘Technical’ and then ‘Environmentally Compatible’ potentials. Each stage is expected to require progressively more ancillary data and increasingly complex calculations, and to have greater uncertainties in the quantification of the resource available.

[7] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF
[8] The template for the national RE action plans can be found at http://ec.europa.eu/energy/renewables/transparency_platform_en.htm
[9] “A methodology to quantify the environmentally compatible potentials of selected renewable energy technologies”, ETC/ACC Technical Paper 2008/16, December 2008
[10] “Small-scale hydropower: how to reconcile electricity generation and environmental protection goals?”, ETC/ACC Technical Paper 2009/13, December 2009

The validation of each Stage will require comparison of outputs with those from similar independent studies, for example the 2008 HydroBot evaluation of catchments in Scotland[11].

- Catchment-scale – select two individual ECRINS catchments and manually develop formulae and calculations to estimate the Technical Potential and economic factors. This would be a pilot exercise to develop the modelling approach to evaluate turbine type, capacity and economic performance. This was expected to involve additional data sources, estimates of values, and general judgement calls based on experience that could not be immediately easily transferred to an automated calculation algorithm that could be applied to all catchments across Europe.

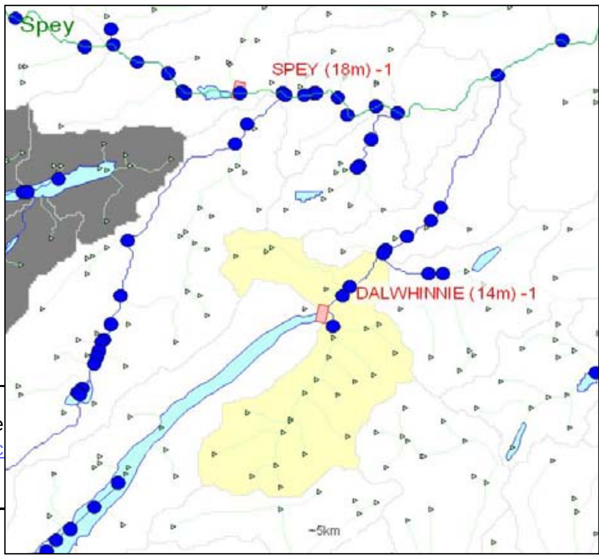
This report summarises the basis of the methodology and presents the results from one of the catchment areas. It also explains the next stages in the development of the methodology. Chapter 2 provides a description of the information relevant to the assessment of hydro potential in the ECRINS database. Chapter 3 then shows how this information can be used to estimate the theoretical, technical and environmentally compatible potentials.

2 Data available from ECRINS

'ECRINS' is a suite of Microsoft Access databases prepared and managed by the European Environment Agency (EEA). ECRINS stands for 'European Catchments and RIvers Network System. ECRINS contains connected, geographically (GIS) shape file' outlines for watersheds, rivers, lakes, monitoring stations, and dams. Some ancillary linked data on flow is also available. ECRINS contains 138,000 elementary catchments with an average area of 92km^2.

2.1 Objects within ECRINS

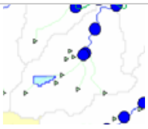
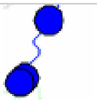
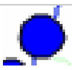
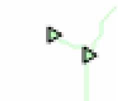
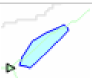
Figure 3 shows a graphic plot from ECRINS of a 25 km square. Table 1 contains the legend to the image. The key point to consider for ECRINS is that it has been compiled as a hydrogeological data source, and the key 'nodes' are defined as points at which there are major confluences/sources of watercourses. This is not necessarily ideal for the more complex stages in evaluating realistic hydro power potential as there is no information on elevation changes within each segment between the defined nodes.



11 'Scottish Hydropower Resource ... tch,
http://www.scotland.gov.uk/Resourc

Figure 3: visualisation of objects in ECRINS

Table 1: Key to Figure 1 - objects within ECRINS

Icon	Object	Description
	Catchment	Grey bordered polygon defining boundary of area where the rainfall runoff gravitates to common watercourse. In ECRINS these have been created on a average scale of 100 km^2. White areas have flow data; grey areas have no flow data. The yellow area depicts the GIS output currently selected by the spreadsheet utility tool that has been developed.
	Main Drain	Main Drain – blue line segment (polyline with vertices) between two blue circles (nodes) – this is a discrete part of a Main Drain and therefore major watercourse that is the ultimate destination of rainfall runoff from the catchment.
	Main Drain Node	Blue circles defining ends of a Main Drain line segment. At a Main Drain Node there will usually be one or more Tributary flows joining.
	Tributary	Tributary – the green line segment between two green triangles (nodes) – this is a discrete part of a minor watercourse that feeds into the Main Drain
	Tributary Node	Green triangles define the ends of a Tributary line segment. At a Tributary Node there will either be a source of a watercourse or a confluence of two or more tributaries.
	Dam	Red inclined rectangle showing the site of existing a dam or weir structure.
	Lake	Cyan polygon bordered in dark blue showing a lake or reservoir.
	Named River	Green Track joining blue Main Drain Nodes with a river name attached. Named Rivers are geometrical polyline objects that span multiple catchments.

2.2 Key Data Issues in ECRINS

For this study, the key data contained in ECRINS that have been used in this assessment are:

- Elevation – the height at each Main Drain Node and Tributary Node is recorded in the database. These Nodes are defined as hydrogeological confluences and therefore can be relatively sparse; this therefore means that resolution in elevation data along the watercourses can be quite granular.
- Head - the altitude difference between nodes at each dam or weir. At the moment ECRINS contains about c.4,600 dams.
- XY Coordinate (shape) – the geographical locations of key objects are contained within binary ‘Shape’ fields in relevant tables. XY Coordinates can be extracted from the Shape fields for Main Drain and Tributary Nodes, and for each of the vertices along a Line Segment for a MainDrain or Tributary.
- XY Coordinate (Lat-Long) – these are Latitude and Longitude coordinates that are contained in the database and identify specific dam locations.
- Flow (Main Drain) – the EEA has supplied an ‘ancillary’ database that is not part of the publically available ECRINS suite. This contains monthly flow data linked to selected ECRINS Main Drain line segments by the ‘TR’ Field code. At the moment this covers less than 50% of the main drains across Europe. The ancillary database contains up to 40 monthly flow readings that can be used to evaluate average, maximum and minimum flow and variability.
- Flow (Tributary) – no data is supplied directly on the flow for Tributaries. For this study an estimate will be made by calculating the sum total length of the line segments in a Tributary network connected to a Main Drain node (e.g. the larger network in the yellow shaded area of Figure 1), and the fraction of this total length upstream of each Tributary Node. The estimated flow at each tributary Node is then this fraction multiplied by the increase in flow across the Main Drain node.

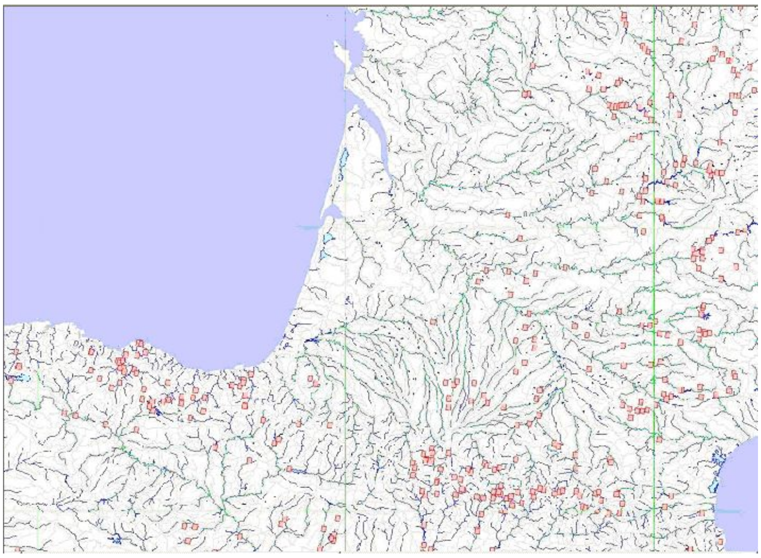


Figure 4: Image generated from the ECRINS database showing the position of main rivers, lakes and dams around the Pyrenees region

ECRINS provides a useful basis for encapsulating the key information for estimating the SHP theoretical potential. Within each catchment the main rivers (referred to as the main drains) and their tributaries can be identified. The locations of c. 4,600 dams and weirs are also included within the database. The EEA reports that there are c.7,000 major dams in Europe[12] with thousands of smaller dams. There are however likely to be other river structures (barriers) such as weirs where there are up-steam and down-steam head differentials that could be used for deployment of SHP.

This is demonstrated by the recent Entec UK report for the Environment Agency[13]. Table 2 shows totals of river barriers that were identified, it can be seen that in the England and Wales dams only represent c.3% of the overall number of river barriers. Assuming a simple correlation and extrapolating across Europe there could be in the region of c.150,000 structures, indicating a significant lack of barrier data in the model.

The study also reports that natural features (i.e. waterfalls) represent c. 53% of the estimated hydro resource and weirs represent 32% of the resource potential. This demonstrates that if considering SHP potential at existing barriers, that both natural features and weirs can have a significant impact and contribution towards the MWe resource available, and additional river barrier data (to just dams) is required.

Table 2 Summary of river barrier feature types present in the UK (Entec)

Feature Type	Count
Barrage	6
Dam	564
Lock	1,730

[12] http://www.eea.europa.eu/themes/water/european-waters/reservoirs-and-dams
[13] "Mapping hydropower opportunities and sensitivities in England and Wales (technical report)" (Environment Agency, February 2010), http://www.environment-agency.gov.uk/shell/hydropowerswf.html.

Mill	274
Unknown	538
Waterfall	6,098
Weir	16,725
Total	**25,935**

Along the main rivers there are a series of data points or nodes which represent locations where flow measurements have been recorded. There is a record of the elevation for each node. This information can potentially be used to estimate the overall SHP Theoretical Potential without recourse to expensive propriety software which would rely on greater resolution data (some of these methods are discussed) where it could be argued this is not required for establishing theoretical potential. Whilst calculating the top level Theoretical Potential provides an indication of the maximum available energy, it is only when the specific locations can be identified at which one would build real hydro projects that an estimate of Technical Potential can be calculated.

In ECRINS, most catchments have several nodes along the course of main rivers. These nodes are a logical starting point for evaluating as locations for hypothetical SHP sites because the vertical distance between them can be easily determined (although as discussed previously, there is no elevation information between nodes), and when combined with flow rate, the annual energy output calculated.

3 Methodology to quantify the small-scale hydropower potential

3.1 Background to the development of the methodology

The upper limit of generation capacity for SHP needs to be selected to ensure uniform consistency across all countries. SHP is generally defined as single generation plant of up to 10 MWe[14]. In reality this definition may vary across Europe depending on the average size of individual scheme within different countries.

We should recognise that the design of SHP schemes vary depending on the vertical head and flow. Since different designs have implications for the methodology and environmental impacts, we refine the definition of SHP into different categories. This analysis encompasses a range of different types of hydro schemes, which could include:

- **High head schemes** - have extraction points some distance from the SHP generation plant. A leat or pipe transfers the water to the power plant depleting the stretch of river between the abstraction point and the SHP generation plant. The greater the vertical height between the abstraction point and the SHP generation plant the greater the power output. This distance between the abstraction point and the SHP generation plant might be several

[14] Oliver Paish, Small hydro power: technology and current status, Renewable and Sustainable Energy Reviews, 6 (2002) 537–556

kilometres. Some high head hydro plants rely on continuous abstraction which is dependent on the natural flow in the river (run-of-river). Typically the design of these schemes needs to consider the potential for seasonal and yearly variability depending on rainfall and, in some areas, snow melt.

- **Low head schemes** - Generally low head SHP is built either adjacent to or even on top of existing structures (dams or weirs) previously constructed across rivers or canals to control flow. In these cases SHP exploits an artificial head created by the weir. The scheme design may require varying degrees of civil structures to divert water into an adjacent SHP generation plant. They can also vary in scale from ~5 kWe to 10 MWe, with larger plants having significant civil structures to enable large volumes of water to be diverted.
- **Schemes installed at dams** - SHP can also be directly linked to water storage which provides the operator with some degree of flexibility to circumvent the restrictions imposed by direct abstraction. In these cases water is abstracted either from an artificial reservoir created by a dam or a natural lake. In the latter case additional storage capacity can be achieved by raising the lake's water level with embankment.
- **Existing schemes** – The analysis does not distinguish between existing systems that have been installed and potential schemes.

It is important to be clear about the definitions that are used in describing SHP potentials. In this report we use three distinct resource definitions:

- ***Theoretical potential*** is defined as the total energy production potential of the water that flows in rivers and streams over a given land mass as they make their way to the sea. A 'water to wire' generation efficiency of 70% is often quoted to translate the mechanical power into electrical power. This study considers the gross available potential and the 'water-to wire' efficiency is not considered at this stage of the analysis.
- ***Technical Potential*** takes into account the ability to capture energy in a discrete number of hydro schemes deployed so as to maximise the economic use of the potential. It implies a number of assumptions that were spelt out in a previous report[15]. In order to differentiate it from the next category the Technical Potential assumes a low level of environmental constraint on the location and operation of SHP plant.
- The ***Environmentally Compatible Potential*** is based on the Technical Potential but takes into account a range of environmental constraints on the location and operation of SHP plant. These factors could include fish migration, requirements for reserve flow and exclusion from geographically designated areas etc. These issues were covered in a preliminary report which included the outcome of a stakeholder workshop held in November 2009[16].

We propose to demonstrate the impact of environmental constraints through the use of resource cost curves, as introduced in the previous reports referenced below.

[15] http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2008_16_pots_ren_energy_techn
[16] http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2009_13_smallscale_hydropower

3.1.1 Estimation of Theoretical Potential from ECRINS

In terms of hydropower, the power represented by potential energy contained in the water flow in an ECRINS Main Drain or Tributary Line Segment is:

Average flow rate (Q_{mean}) at lowest point x Head x 9.8 (acceleration due to gravity)

The theoretical hydropower potential in an ECRINS catchment is the sum of this figure over all main drain and tributary line segments contained within the catchment. This analysis provides the total potential before consideration of efficiency losses of the hydro power plant. It is thus:

- easy to calculate
- does not need additional data sources

However, it is not a realistic estimate of the actual hydropower energy that could be extracted from each catchment. The main practical use of the Theoretical Potential is to identify catchments that are most appropriate for more detailed investigation. It can also be used to compare the results obtained by this methodology with those produced by other studies.

The main issue with estimating the Theoretical Potential is the lack of measured flow data for tributaries. This is important (and demonstrated later in the report) because the contribution from tributaries is typically at least equivalent to the contribution from main drains (each tributary may have less flow but is likely to have much higher head values. The flow at each tributary node has to be estimated from the flow information at the relevant main drain nodes:

- The total flow contribution from the tributary 'network' connecting to a selected main drain node (QTributaryTotal) is taken to be the increase in flow between the 'previous' main drain node immediately upstream, and the flow at the selected mode.
- The 'tributary' flow at a tributary node connected to the selected main drain node is taken to be QTributaryTotal * FTributaryFraction, where FTributaryFraction is the cumulative length of all tributary segments 'upstream' of the tributary node divided by the total length of all tributary networks connected to that main drain node.

Figure 5 shows a series of 4 'tiles' with the results of the calculation of Theoretical potential across Western Europe (and includes an estimate of Theoretical Potential of tributaries). The maximum value for the catchment plots has been set to Theoretical Potential of 40 MWe, showing the catchments of very high potential. The black areas are those for which no flow data was available.

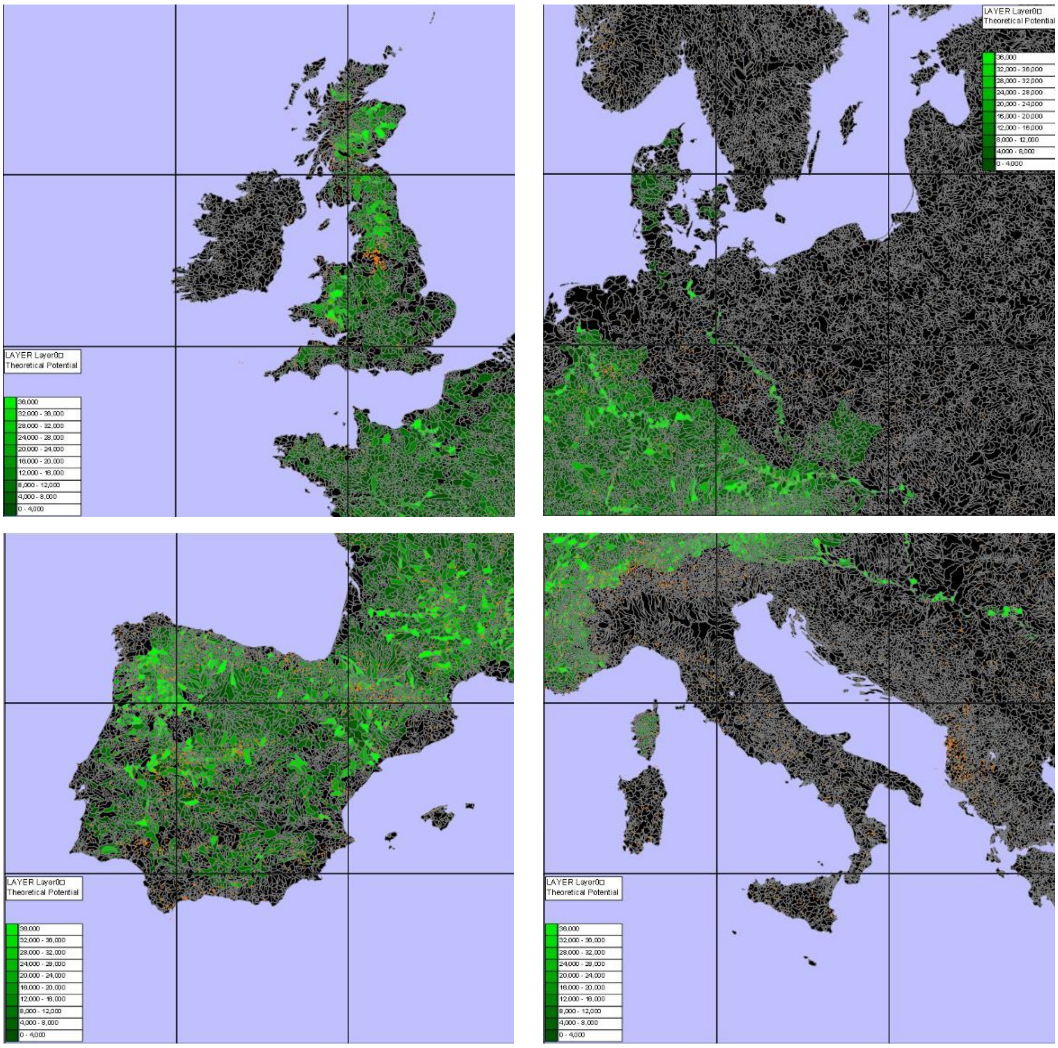


Figure 5: the theoretical hydro potential across Europe calculated from the data contained in ECRINS

Detailed inspection of Figure 5 reveals a pattern of localised regions of high potential comprising many interconnected catchments within the same river valley. In particular, North Western Spain, Southern France, Central Wales, Scotland, Belgium, and Central Germany. These should be the first choice for detailed assessment of the Technical Potential. It also reveals that large areas have no flow data (shown in black), and so cannot be assessed. One of the key future actions must be to increase the coverage of flow data, particularly in Italy, Greece, Scandinavia, and Eastern Europe.

This Theoretical Potential calculated from ECRINS has been compared to a similar potential value calculated as part of the Scottish Hydropower Resource Study (Final Report), August 26th 2008 produced by Nick Forrest Associates Ltd, The Scottish Institute of Sustainable Technology (SISTech), and Black & Veatch Ltd[17]. This 2008 Study (referred to hereafter as HydroBot2008) produced a detailed evaluation of Hydropower resource for Scotland, going from a 'top-level' estimate of 'Theoretical Maximum Potential for Hydropower' for each defined catchment, to a full evaluation of individual potential sites using the HydroBot model (equivalent to the Technical Potential covered below). The catchments used in HydroBot2008 are far larger than

[17] 'Scottish Hydropower Resource Study' August 2008, Nick Forrest Associates, SISTech and Black & Veatch, http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf

those defined in ECRINS, but fortunately each HydroBot2008 catchment usually exactly matches the sum of several ECRINS catchments.

ECRINS currently only has flow data for about 50% of the catchments, and so it was necessary to find matching HydroBot2008 and ECRINS catchments with flow data.

Figure 6 shows an overlay of the ECRINS catchments (boundaries in orange) over those used in HydroBot2008. ECRINS catchments with no flow data are shaded in pink.

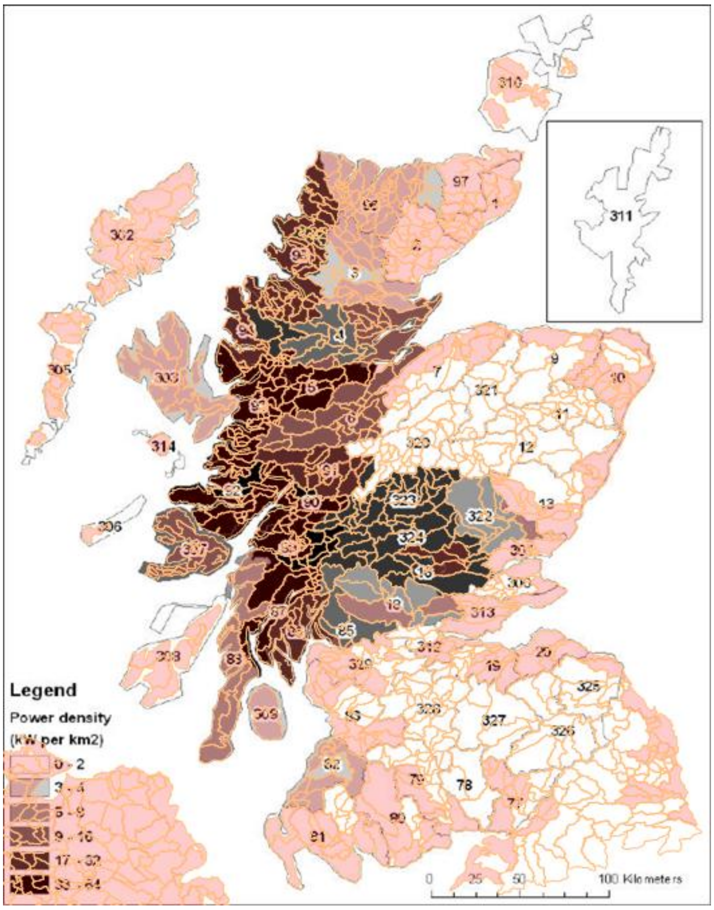


Figure 6: HydroBot catchments with ECRINS catchments overlaid, shaded pinks areas depict where there is no flow ECRINS data, white and other colours show where there is flow data available.

From this overlay it is possible to identify eight HydroBot2008 catchments that are completely matched by 129 ECRINS catchments with flow data. The method described by HydroBot is as follows[18]:

"HydroBot was devised in 2006 and applied to the catchment of the North and South Esk near Edinburgh, as part of an award-winning MSc dissertation for the University of Edinburgh. HydroBot remotely identifies likely reaches of river in the area of interest and identifies the closest grid connections to suit a range of generation levels. It then models a range of positions for the turbine, the water intake and the grid/load connection. Energy prices, typical equipment costs and discounting are used to determine the financial viability of each potential solution."

[18] 'Scottish Hydropower Resource Study' August 2008 – Nick Forrest Associates - http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf

A more complete description is available in a paper produced for Hidroenergia 2010[19].

The comparison of the catchment totals (Table 3 below) shows reasonable correlation. To account for the variation in method, *'HydroBot Gross'* figures are presented. These correct for the 70% 'water to wire' efficiency that has been applied by HydroBot. Comparing the figures with the ECRINS calculated catchment potential; there are some differences (as would be expected). The average difference between the predicted Theoretical Potential is 10%, with the ECRINS based data tending to provide a lower estimate of the potential compared with HydroBot.

It is not possible to make any clear conclusions from this as the calculations are based on different sets of data and also slightly different methods to establish flow rates in the catchment water courses. However, the average variation of 10% indicates the different methods broadly agree the overall potential for the catchments evaluated.

Table 3: Comparison of ECRINS catchment potential versus HydroBot catchment analysis for selected catchments in Scotland

HydroBot Catchment #	*ECRINS*			*HydroBot (MW)*	*HydroBot Gross (MW)*	*Ratio ECRINS/HydroBot (MW)*
	Tributary (MW)	*Main Drain (MW)*	*Total (MW)*			
78	34.51	21.45	55.96	53.40	76.3	0.73
327	32.39	39.47	71.85	116.50	166.4	0.43
326	29.05	58.29	87.34	72.70	103.9	0.84
328	23.48	89.75	113.22	86.80	124.0	0.91
12	78.87	131.04	209.92	182.30	260.4	0.81
11	13.60	47.45	61.05	53.30	76.1	0.80
321	38.00	171.37	209.37	82.00	117.1	1.79
320	88.02	88.61	176.63	150.50	215.0	0.82

A study was also carried out by Entec for the Environment Agency (EA) in England and Wales (found at http://www.environment-agency.gov.uk/shell/hydropowerswf.html).This analysis did not evaluate catchment potential and therefore cannot be compared to the ECRINS analysis.

[19] "HydroBot: remote surveys of national hydro resources"; Nick Forrest, Conference Paper, Hidroenergia 2010, July 2010

3.1.2 Proposed methodology to estimate Technical Potential

The SHP Technical Potential is an estimate of the actual power that could be extracted from a catchment. This will always be less than (in many cases a small fraction of) the theoretical hydropower potential for the catchment because:

- Power is lost converting the mechanical energy of the water into electricity
- Turbine installations will usually be sized to use a fraction of the available flow based on variability of flow, and environmental and economic factors.
- Turbine installations do not always map directly onto line segments. An individual line segment may have several individual turbines each sized and sited to use the local head on a particular 'stretch' (sub-segment) of an ECRINS line segment. There may be stretches of a line segment that have no turbines, and so not all of the head for the line segment will always be exploited. In the real world the river stretches selected and the head available will be determined by the economics of engineering the installation, engineering practicalities (which may well be manifested in capital cost) and environmental sensitivities for fish migration, etc.

Because of these local factors, a rigorous evaluation of Technical Potential would have to predict the location, turbine type, turbine capacity, head exploited, flow fraction exploited, for individual turbine installations. In order to get an accurate result the exercise would start to become an 'individual site' approach rather than 'catchment-wide' and thus much more complex and costly.

During 2009 a review was conducted of five methodologies that have been used to estimate SHP resource, these included:

- Salford study (UK);
- US Hydroelectric Power Resources Assessment;
- HydroBot (Scotland);
- HydrA, and;
- SHERPA.

These are discussed in more detail in the previous ETC/ACC Technical Paper 2009/13 December 2009. Most of these rely on costly proprietary software, e.g. HydroBot. Other methodologies, for example the one developed by Salford University, evaluates selected sites by simple physical inspection of topographic and resource maps. Some of the principles from these methodologies could be applied to resource estimation on a European scale, but at the moment none of these could be easily applied as they stand.

The ideal approach

The ideal approach to evaluating the realistic Technical Potential would be to follow the methodology used in the HydroBot2008 Report for Scotland, using a model such as HydroBot. This would evaluate potential SHP sites along the rivers and tributaries in a catchment, and produce the required design flow, head, capacity, turbine type, and economic performance data for sites deemed suitable.

HydroBot is also able to assess hydro potential at existing structures as well as assessing potential changes in head in the natural environment. This is not a small undertaking. It would require detailed topographical and flow information (ideally elevation data is provided on a resolution of 10m), data on infrastructure and environmental constraints on a far finer geographical grid than is contained in ECRINS. This analysis is also similar to the Entec study for the EA[20], although this analysis considered river structures only and did not assess hydro power potential due to natural changes of head (other than waterfalls).

It is worth noting that the individual site approach is very different from the catchment-wide calculation basis for the Theoretical Potential (which is more broad-brush), making it difficult to simply derive Technical Potential from the Theoretical Potential without a significant amount of data, the data requirements could include:

- Flow data (i.e. EEA's and commercial data)
- Some elevation data (i.e. EEA's and commercial data)
- Detailed mapping for locating features
- European river catchments
- Higher voltage distribution network
- Existing hydro schemes
- Other existing abstractions
- Location of dams and some large weirs
- Lower voltage distribution network; towns and buildings
- Detailed roads, railways, lakes

It would not be easy to sensibly derive 'top-down' catchment-specific factors to apply to the theoretical potential to calculate the Technical Potential for that catchment. On a Europe wide basis this is likely to be an expensive process when considering man-hours and amount commercial data that could be required.

Using ECRINS

On initial inspection, ECRINS would not appear to be a good starting point for such a rigorous evaluation of Technical Potential. In ECRINS, Main Drain and Tributary nodes are defined purely by looking at merging of flows, and may be separated by tens of kilometres. The information at any ECRINS node is very local and may not be representative of the surrounding topography – detailed information that is needed for any realistic evaluation of a possible SHP site. ECRINS nodes also may not be located close to key locations, in particular existing dams and weirs.

However, ECRINS does have the advantage that it contains data covering most of Europe. For this reason it was decided it would be useful to try the simplistic approach of applying catchment-specific factors to ECRINS data. The outcome of this approach could then be compared to data from existing installations and studies to evaluate how well it correlated, if at all.

The ECRINS catchment approximation for evaluating Technical Potential requires some common-sense assumptions to be made concerning the maximum deployment density likely to be acceptable, and the need to leave a residual flow within depleted

[20] "Mapping hydropower opportunities and sensitivities in England and Wales (technical report)" (Environment Agency, February 2010), http://www.environment-agency.gov.uk/shell/hydropowerswf.html.

sections of rivers. For the purposes of this study the maximum rate of extraction will be capped at Q_{95} (i.e. the flow exceeded for 95% of the time, and used as a marker of low flow)[21]. This is a value (typically used by the EA in England and Wales) which must always remain in the water course, this is of most importance at times when there is limited water in a water course and water extraction must be curtailed (to maintain appropriate wetted area).

In reality the extraction rate may vary according to the necessity to meet environmental criteria. The impact of this variation needs to be applied to provide an estimate of the Environmentally Compatible Resource and is discussed later in the report.

For the purposes of this exercise:

- A flow rate equivalent to $0.75Q_{mean}$ has been applied to estimate the Technical Potential[22];
- The potential hydropower capacity is calculated at each Main Drain and Tributary node, i.e. at this stage no environmental or conservation restrictions are applied.

NB: in a full, formal appraisal, these assumptions could not be used appropriately. As a starting point a sensible constraint to apply to the Technical Potential is to assume that new SHP schemes will only be built at nodes with an existing dam or weir. This reflects the fact that the cost of new large-scale civil structures would be prohibitive for SHP. However, this cannot be applied at the moment because of the sparse data on Dams and Weirs (only 4,600 sites which represents a small percentage of the estimated hundreds of thousands across Europe).

Another aspect that could be visited if the concept was further developed would be to evaluate algorithms that can be used to look at difference in head/distance between nodes. Based on a certain gradient it would then be possible to evaluate specific locations in the natural environment where hydro plant could be located.

Because of the limited coverage of ECRINS data on flow, dam and elevation data, it does not make sense to complete the full exercise and generate incomplete and misleading maps of pure Technical Potential at this point. Once data is available to do this, the next steps would be to apply other geographical constraints such as proximity to infrastructure, and then apply environmental and conservation constraints to produce an environmentally compatible potential. However, it does make sense to undertake a few example calculations to demonstrate the possible further analysis after this point.

Example Catchment: Cost Resource Curves

One of the ultimate outputs from a complete evaluation of Environmentally Compatible SHP Potential across Europe would be a consolidated Cost Resource Curve showing the SHP Potential power output versus cost per kilowatt hour (kWh) of energy. This would be created by aggregating up the calculated SHP Potential

[21] http://publications.environment-agency.gov.uk/pdf/GEHO0310BSCT-E-E.pdf

[22] Q is a standard designation for the flow in a river or water course. By convention it is measured in m^3/sec. Flow measurements can be instantaneous or a mean taken from a series of measurements each month. Initial SHP resource estimates need to be based on the annual mean Q_{mean} flow because this takes account of the seasonal variability within a river. In reality the amount of flow that can be used for SHP will be restricted to ensure that there is sufficient residual flow in the river. $0.75Q_{mean}$ implies that only the 75% of the annual mean flow would be available for SHP generation. The practical impact of sizing on a smaller flow is that the utilisation or capacity factor of the plant will be higher this will result in higher electricity generation per £ of CAPEX spent providing a more economic project.

and cost for each node and plotting them on the x and y scales appropriately. As a pilot exercise, this has been done for a single selected catchment in the Pyrenees to illustrate the principle and explore some of the issues.

Ideally, the selection of turbine type, design flow, and capacity would be undertaken by inspecting a full Flow Duration Curve (FDC) at each node/potential site. The ancillary ECRINS database contains flow information for about 50% of the catchments in Western Europe, comprising a set of up to 36 monthly mean flow data per node, depending on node. This data covers the years 2000, 2001 and 2005. For the purposes of this methodology the mean flow is calculated and used in subsequent calculations.

The mean flow and head values are used to estimate the design and costs of SHP plant at each node, which is then aggregated to generate a composite Cost Resource curve for the catchment.

3.2 Estimating SHP Resource from ECRINS for a selected catchment

Figure 7 shows a detailed plot of a series of catchment areas in the Pyrenees. The catchment selected for this example exercise is coloured light yellow.

Main Drains are shown as blue lines joining blue circles (Main Drain Nodes). In some cases these are overplotted with a dark green line where they form part of one of the larger, named rivers included in ECRINS, whose name is shown in dark green.

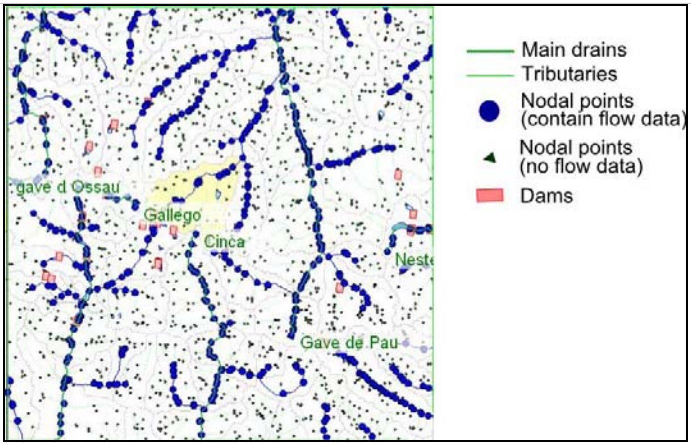


Figure 7: Catchment area, of approximately 40km square, in the Pyrenees (yellow area used in subsequent examples)

Figure 8: Location of the selected catchment area

The data from the catchment highlighted in yellow in Figure 7 have been selected as a basis for demonstrating the methodology for SHP Technical Potential in the next section.

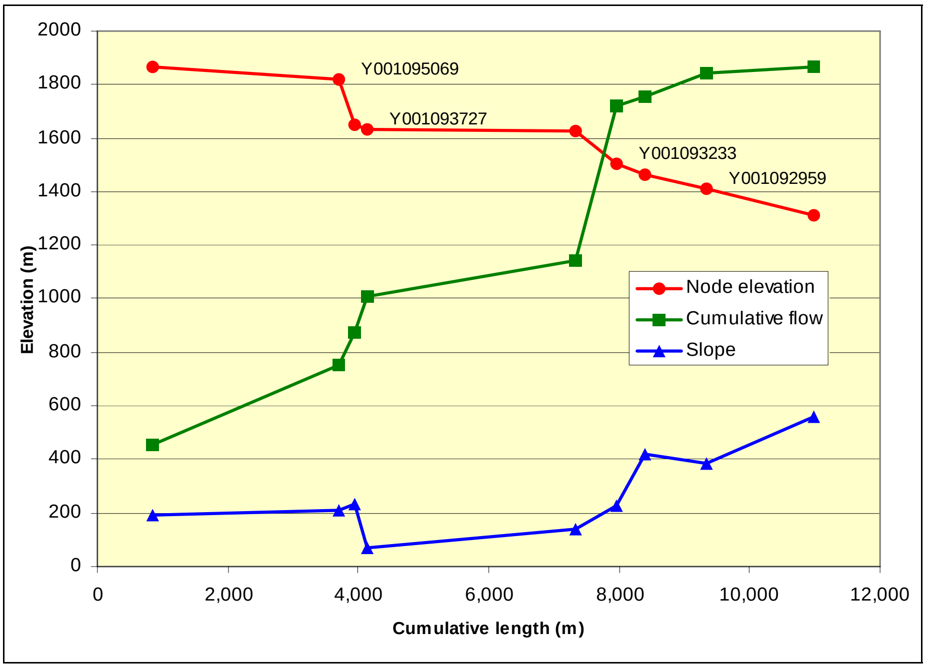


Figure 9: Summary of key nodal data from the catchment highlighted in yellow in Figure 7. Flow, Q (m^3/s), is cumulative. Slope is the average between nodal points

Figure 9 shows a plot of the flow and elevation data against the cumulative length along the key Main Drain for the catchment. Each node on the graph matches a Main Drain node. For this initial exercise the Tributaries have not been considered as they often have highly branched networks and are not easy to visualise in a simple plot.

A methodology to estimate the SHP on this scale needs to be based on a series of assumptions which can provide a reasonable approximation at each site/node. These parameters may need to be modified as the methodology is developed. The following assumptions have been applied:

- Each catchment node has been selected as the hypothetical location for a SHP scheme;
- The energy output assumes that each of the sites selected (in this example) is a high head run-of-river scheme;
- The abstraction point for each SHP site is the node immediately upstream of it. Consequently the difference in elevation can be used to provide the head (H). This means that no water entering the watercourse between the two nodes is considered in the calculation;
- The rated power and annual energy output for each SHP, are calculated from the mean flow at the abstraction point and the head from the abstraction point to the hydro installation;
- The capital cost (CAPEX) and operating cost (OPEX) are based on a range of values provided by ESHA for SHP development in different EU countries. The size of the plant (based on its rated power) has also been used to define the cost estimate (see Table 5).

The amount of energy, *E*, released when an object of mass *m* drops a height *h* in a gravitational field of strength *g* is given by

$$E = mgh$$

The energy available to hydropower installations is the energy that can be liberated by lowering water in a controlled way. The power output is proportional to the mass flow.

$$\frac{E}{t} = \frac{m}{t} gh$$

Substituting *P* for $^{E}/_{t}$ and expressing $^{m}/_{t}$ in terms of the volume of liquid moved per unit time (the rate of fluid flow, Q) and the density of water, we arrive at the usual form of this expression

$$P(Watts) = \rho Qgh$$

Where:

P is the mechanical power produced at the turbine shaft (Watts),
ρ is the density of water (1000 kg/m^3),
g is the acceleration due to gravity (9.81 m/s^2),
Q is the volume flow rate passing through the turbine (m^3/s),
h is the effective pressure head of water across the turbine (m)

The best turbines can have hydraulic efficiencies in the range 80-90% although efficiency declines with size (i.e. its installed capacity)[23]. Micro-hydro systems (<100kW) tend to be 60 to 80%efficient. If a water-to-wire efficiency of 70% is assumed for the whole system, then the above equation approximates to:

$$P(kW) = 7Qh$$

Estimating the SHP size

The scheme size can be estimated from the design flow and the capacity factor[24]. It is assumed that each SHP would be designed on the basis of mean flow Q_{mean}. The design of a SHP scheme, specifically its installed capacity and the capacity factor, will depend on the amount of flow available to it and the time it will be permitted to operate. An initial estimate of how capacity factor varies with design flow is shown in the British Hydropower Association's guide:

Table 4: Design flow against capacity factor

Design Flow	*Capacity Factor (%)*
Q_{mean}	40
0.75 Q_{mean}	50
0.5 Q_{mean}	60

[23] "A guide to UK mini-hydro developments" (British Hydropower Association, January 2005), http://www.british-hydro.org/mini-hydro/download.pdf.
[24] The Capacity Factor (CF) is a measure of the amount of energy that a power conversion system generates relative to its rated installed capacity. Usually the CF is defined as the amount of energy generated over one year expressed as a percentage of the theoretical output from the same system assuming it operated continuously at its rated output.

0.33 Q_{mean}	70

Whilst the increasing capacity factor for a lower design flow may at first seem counter-intuitive, it makes sense. Hydropower systems which are designed for a lower average flow will produce an output over a larger proportion of the year, so the capacity factor will be higher; however, the total output over the year will be lower. This is analogous to the wind turbine which is designed for low wind-speeds, which will deliver output for more hours but at a lower power level than a 'standard' wind turbine.

The rated power for each site can be estimated from the design flow which is set at $0.75Q_{mean}$ for the purposes of this study and head H:

$$\mathbf{P}(\text{kW}) = 7 \times 0.75\mathbf{Q}_{mean}(\text{m}^3/\text{s}) \times \mathbf{H}(\text{m})$$

Once the rated power of each SHP location has been estimated the annual energy output can be estimated assuming a capacity factor of 50% for the following example (a figure of 50% is chosen as being at the lower end of the 50-70% range[25] that would typically be considered to provide an adequate return on investment).

$$\text{Energy (kWh/year)} = \mathbf{P}\ (\text{kW}) \times 50\% \times 8{,}760 \text{ hours/year}$$

Estimating the SHP cost.

ESHA has provided a range of capital costs (CAPEX) for SHP for different EU countries. A further refinement has been applied based on the rated power of each SHP site assuming that cost per unit of installed capacity increases with decreasing size. For the example presented here the following values have been used.

Table 5: Investment cost of hydro installation

Turbine output	*Investment cost bands (€/kW)*	*O&M as % of CAPEX*
<500 kW	1,500	2%
500-1000 kW	1,250	2%
>1000 kW	1,000	1.2%

Theoretical Potential in the example Catchment

For chosen example catchment there Theoretical Potential identified is 5,361MWe of SHP hydro capacity. The methodology described in this section can only provide an approximation of the gross SHP Technical Potential, as it suffers from two main uncertainties. One component of the methodology overestimates the realistic potential of the main drains as it assumes that a plant would be built at every node and make full use of the available head from the previous node. It also does not consider the distances between the nodes and how this might affect the capital cost of the scheme. It is difficult to quantify how much the methodology over estimates capacity and this will be specific to the catchment and terrain.

Another component underestimates the potential as there is no flow information in ECRINS for the tributaries (which could provide a significant share of the total potential). As shown in Table 3, of the identified catchment capacity using ECRINS

[25] "A guide to UK mini-hydro developments" (British Hydropower Association, January 2005), http://www.british-hydro.org/mini-hydro/download.pdf.- States that Capacity factors >50% are typical.

data, the contribution from tributaries represents around 35% of the overall capacity; this capacity is not accounted for the above methodology.

It should be noted that there could be options for refining the methodology – this may include seeking higher resolution data on the topography to help identify likely locations for siting SHP plant and the hydraulic heads that they would use. A full evaluation of Theoretical Potential also requires information on the proximity of the electricity grid and access for construction. Nevertheless the next section looks at how environmental constraints can be factored into the methodology to allow Technical Potential to be translated into environmentally compatible potentials.

Methodology to calculate the resource cost curve

For the example catchment, a resource-cost curve has been plotted by applying the following steps:

- The rated power P for each SHP site based on the $0.75Q_{mean}$ flow and the vertical height H is calculated.
- Calculate the capital cost of each SHP site based on its rated power.
- Calculate the annual energy output for each site assuming a 50% capacity factor.
- For each SHP site within the catchment area the unit cost of energy in € cents/kWh is calculated using a discounted cash flow analysis. For indicative purposes we have assumed that each SHP site would take a year to build and have a technical life of 40 years, it is also assumed that 20% of the original CAPEX is required for refurbishment of mechanical elements after 20 years of operation (capital cost breakdowns vary enormously, the United Nations Environmental Programme (UNEP) estimate 45% of SSH capital costs are associated with equipment costs[26]). A discount rate of 10% has been used in the cost analysis.
- The final stage is to plot a cumulative resource cost curve which shows a progression from the most economically attractive sites to less favourable sites (Figure 10).

[26] http://www.unep.fr/energy/information/publications/factsheets/pdf/hydro.PDF

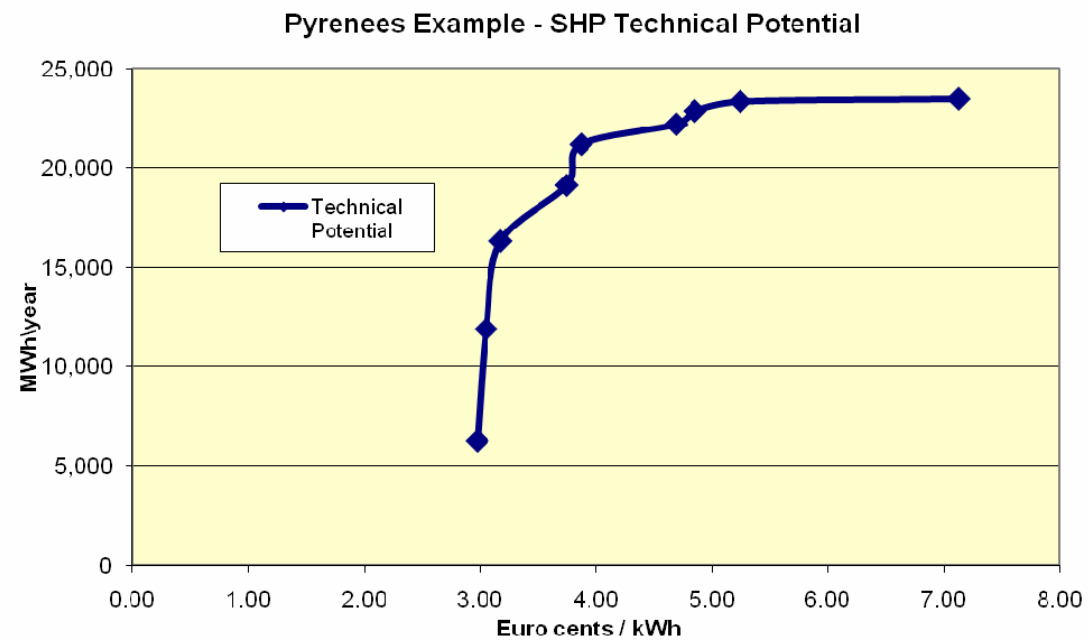


Figure 10: **Technical Potential cumulative resource cost curve for the Pyrenees example catchment area, assuming that a SHP scheme is placed at every node of the catchment's main drain making use of the full head**

Looking at the results, although, we see that the costs estimates are quite low when compared to current and foreseen electricity wholesale prices. So even with the limitations mentioned before, which could bring down the costs even more, there seems to be a financially attractive Technical Potential which can be exploited. In case of a European wide assessment the costs could be grouped in attractive potential (30% or more below the whole sale prices), plausible potential (-30% up to + 30% of the foreseen whole sale prices) and limited Technical Potential (up to electricity prices paid by consumers including tax, i.e. 20 Eurocent/kWh).

3.3 Factoring in the Environmentally Compatible Potential

Whist it can be seen that there is scope for the methodology to be refined for evaluation of the Technical Potential; it is worth considering an environmental proxy in parallel to demonstrate how the methodology would work in full and the potential impact of environmental constraints on the cost of energy from hydro installations.

As previously stated there are a number of different elements which can be applied within individual catchments and entire regions. At this stage two elements have been considered to demonstrate the potential impact of an environmental constraint (as from the stakeholder workshop held on 27th November 2009 these elements are most affected by environmental constraints):

3. Reduced design flow – considering the design flow is reduced from $0.75Q_{mean}$ to $0.33Q_{mean}$ to simulate the impact of restricted abstraction, which would allow a greater flow of water through the water body.

4. Increases capital costs - the CAPEX has also been increased by a third to simulate the added cost of environmental mitigation measures, such as fish ladders, eel ladders, and installation of low-impact turbines.

Due to the reduced flow the installed capacity of each SHP site is reduced, along with its annual energy output. In the example catchment the due to the reduced design flow rate, the Technical Potential is reduced by 44% to an Environmentally Compatible Potential of 2,359kWe. This is reduction is without considering which SHP sites might not be economically attractive any longer and therefore unattractive to develop, hence further reducing the Environmentally Compatible Potential.

The effect of the increased capital cost and reduced SHP capacity can be seen in Figure 11 where the two resource-cost curves are presented. From this it can be seen that the resource cost curve shifts to the right and down, representing that both the generation potential is lower, and the cost of energy generated is more expensive. The reduction in the amount of energy generated is simply created by the limit on the water than can be abstracted from the watercourse and passed through the SHP system and the reduced capacity of the hydro plant. The increase in the cost of energy generated is however caused by the increase cost of the plants capital cost an also as hydro plant is more expensive at smaller scales (as shown in Table 5).

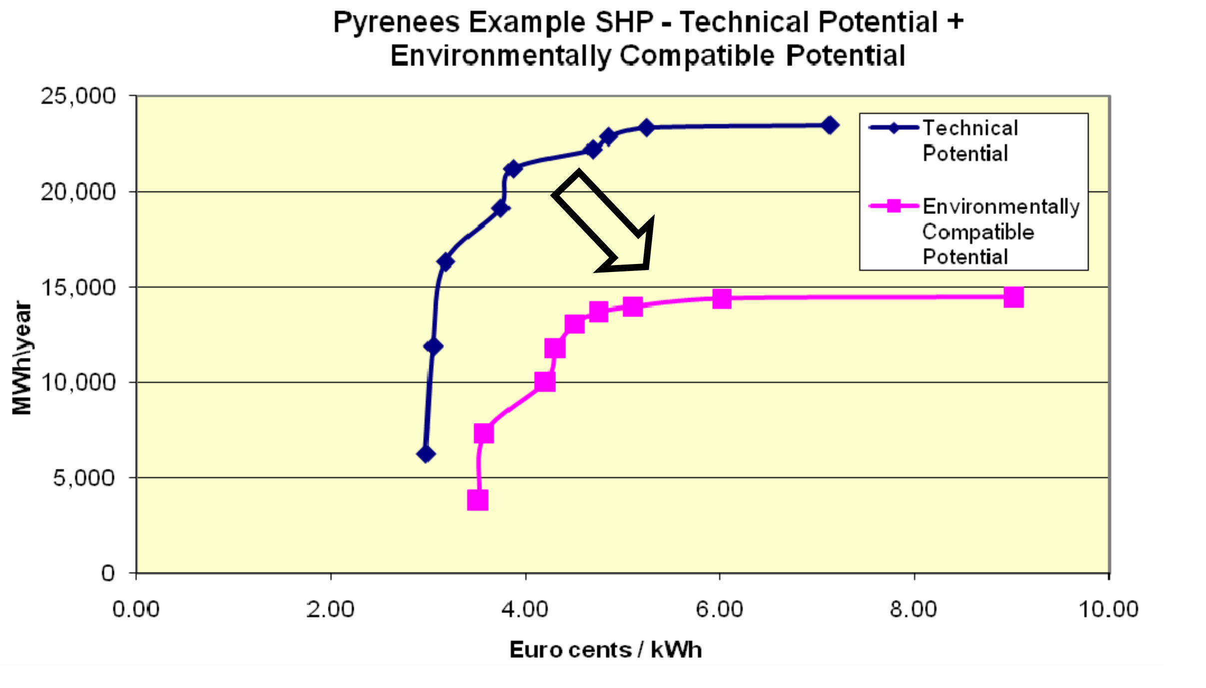


Figure 11: **Comparative resource cost curves for technical and environmentally compatible potential for the Pyrenees example catchment area**

The next stage of the methodology is to model the impact of other factors that will affect the environmentally compatible potential; these were investigated as part of the stakeholder workshop held on 27th November 2009 and are detailed in the previous report[27], but would require further clarity around the specific impacts of different constraints. Key factors to consider further include:

[27] “Small-scale hydropower: how to reconcile electricity generation and environmental protection goals?”, ETC/ACC Technical Paper 2009/13, December 2009

- Abstraction rate restrictions to maintain residual flow and good ecological potential under different scenarios/designations.
- Fish deterrence / passage and associated capital costs.
- The allowable deployment density of SHP developments in a catchment or group of catchments.
- Exclusion from certain designated areas. There are many different types of designated areas and restrictions could vary considerably from one type to another.

It can be seen that the restricted flow and increased capital costs assumed above have a significant impact on the resource cost curve. If a reference energy generation cost of €0.06/kWh is taken, the potential is reduced by some 40%. On a wider basis the potential energy generation would be reduced yet further if some of the sites were located in designated areas where restrictions applied.

At this stage of the project the results above are only indicative. They demonstrate that meaningful calculations can be made of the Environmentally Compatible Potential if the data on which to base the initial Technical Potentials exist, and if reasonable assumptions can be made on the impacts of the environmental constraints. Both of these elements need to be developed further if a holistic methodology is to be created.

4 Further Development of the Methodology

4.1 Refinement of the SHP Technical Potential

4.1.1 Correlation with other data

The example catchment calculation of the previous section takes the theoretical potential evaluated from the ECRINS data, and applies some general factors for ‘water to wire’ efficiency, and takes the Design Flow as a fraction of the average. As discussed earlier, this is not expected to give a very realistic estimate for individual sites because it cannot reflect detailed local factors. This is likely to be particularly true for the lowest capacity sites. For catchments with high Theoretical Potential, it is likely that this can be tapped through large scale installations, and there may indeed be existing schemes that harness a significant fraction of the potential. This needs to be investigated more fully, but for the moment three initial pilot comparisons with ‘other’ data sources have been carried out to give some indication of how well - or badly - the ‘top-down’ approach works.

- Comparing Theoretical Potential for selected ‘high potential’ catchments with actual large scale installations
- Comparing ECRINS node data on elevation with actual head at existing dams and weirs. This should give some measure of how well the local data at the nodes can be mapped to the real world.
- Comparing the Technical Potential at the nearest ECRINS node to data from existing or planned SHP installations on actual design flow and hydropower capacity.

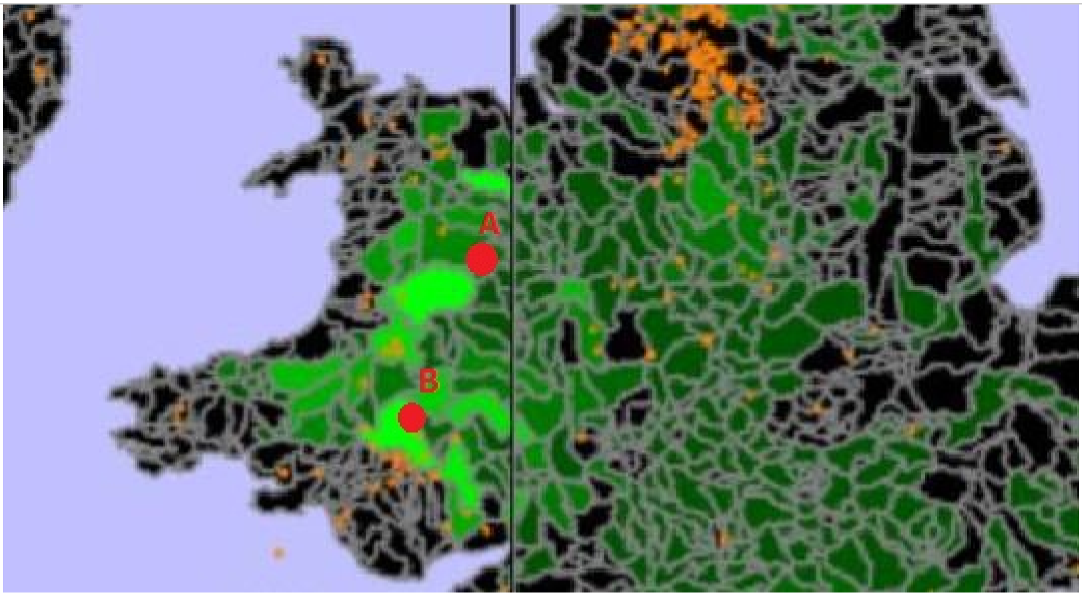
Comparing Theoretical potential for selected ‘high potential’ catchments with actual large scale installations

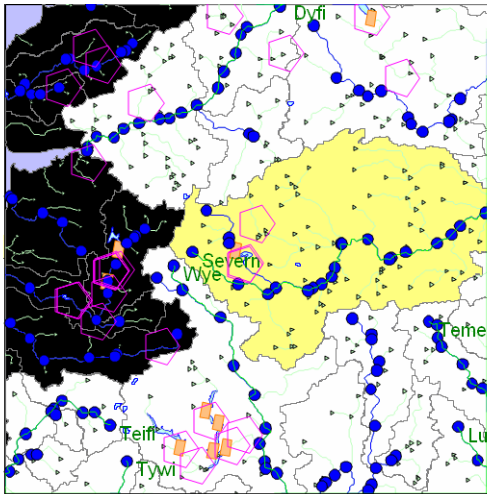
Figure 5showed clear areas of high Theoretical Potential (>40MW). As discussed above, these areas may be more suitable for large scale hydro, with either very high head or very high flow. While this is really outside the scope of this study, it is useful for this initial investigation, to give some insight into the reliability of the calculations at the high end. This will give some indication whether the potential for small scale hydro is being estimated in a reasonable manner.

Three regions were chosen because they had a concentration of ‘high potential’ catchments, and also had orange icons showing the site of a dam in some of the relevant catchments. Catchments were chosen by inspection which had one or two ‘dam’ icons, so that an internet search could be performed on the dam name to find any matching hydropower scheme. When all of the dams had a matching scheme then the catchment was accepted. After a few iterations, two acceptable catchments were found for each region.

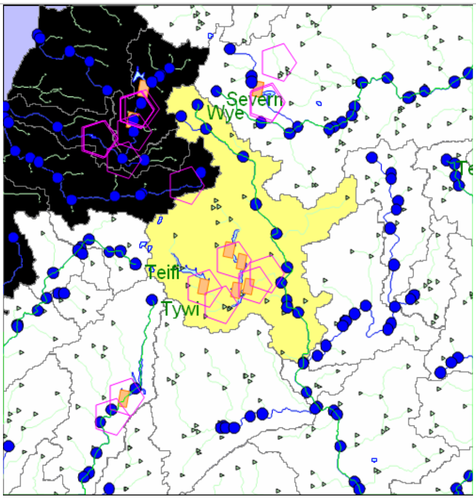
In general, the installed capacity was roughly equivalent to the calculated theoretical potential, which is encouraging. Because large scale hydro schemes can involve significant alteration of flows in surrounding catchments it is not too surprising that in one case (D) the installed capacity is greater than the theoretical potential. For catchments A and B in Wales it is possible that the low percentage does indeed represent low uptake of available potential, water abstraction from the reservoirs or environmental constraints.

Site	*Installed Capacity (MWe)*	*Theoretical Potential (MWe)*	*Percentage Exploited*
A	1.17	56.5	2 %
B	8.15	32.4	25 %
C	125.0	258.4	50 %
D	68	48.5	140 %
E	32	87.5	37 %
F	354	444	80 %





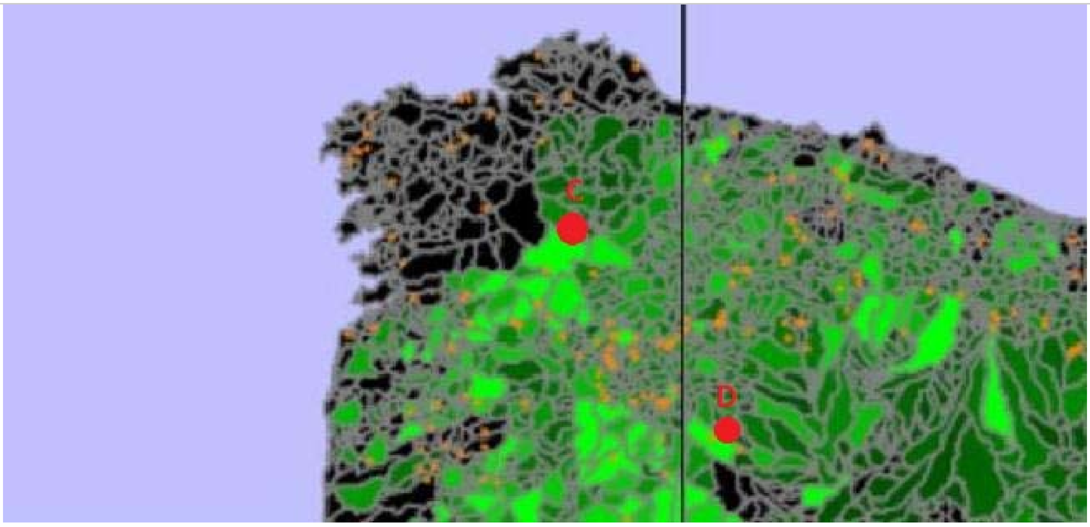
Site	A	
XY	3,403,009	3,350,400
LongLat	-3.605169	52.48696
CatchmentID	9726	B030001206
Theoretical Potential	56.5MW	
Actual Installed capacity at Dams	Dam Trannon 0.3MW, Clywedog A,E 0.7MW, Clywedog Phase 2 0.17MW	
Total Current Installed Capacity	1.17 MW (2% of theoretical potential)	

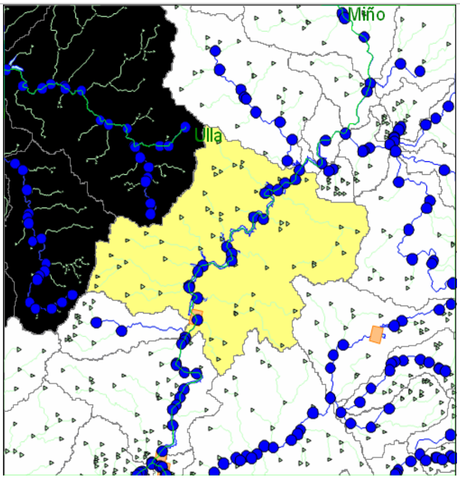


Site	B	
XY	3,399,145	3,330,550
LongLat	-3.605169	52.48696
CatchmentID	9744	B030001238
Theoretical Potential	32.4 MW	
Actual Installed capacity at Dams	Caban Coch 0.95MW, Elan Valley 3.1 MW, Elan Valley 2 3.1MW, Claerwen 1.0MW, Clyn Hydro 0.006MW	
Total Current Installed Capacity	8.15 MW (25% of theoretical potential)	

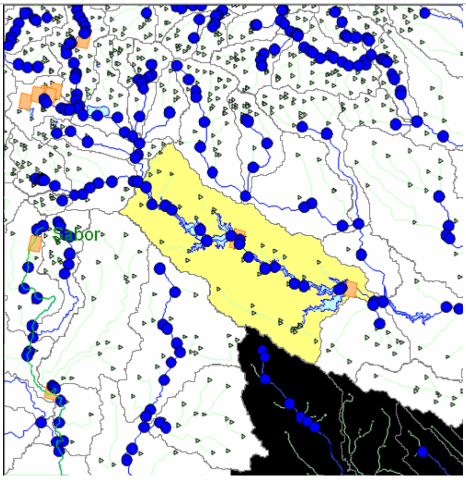
Figure 12: Selected catchments in Wales

Note – the open pentagons show the location of known Hydro sites in the UK



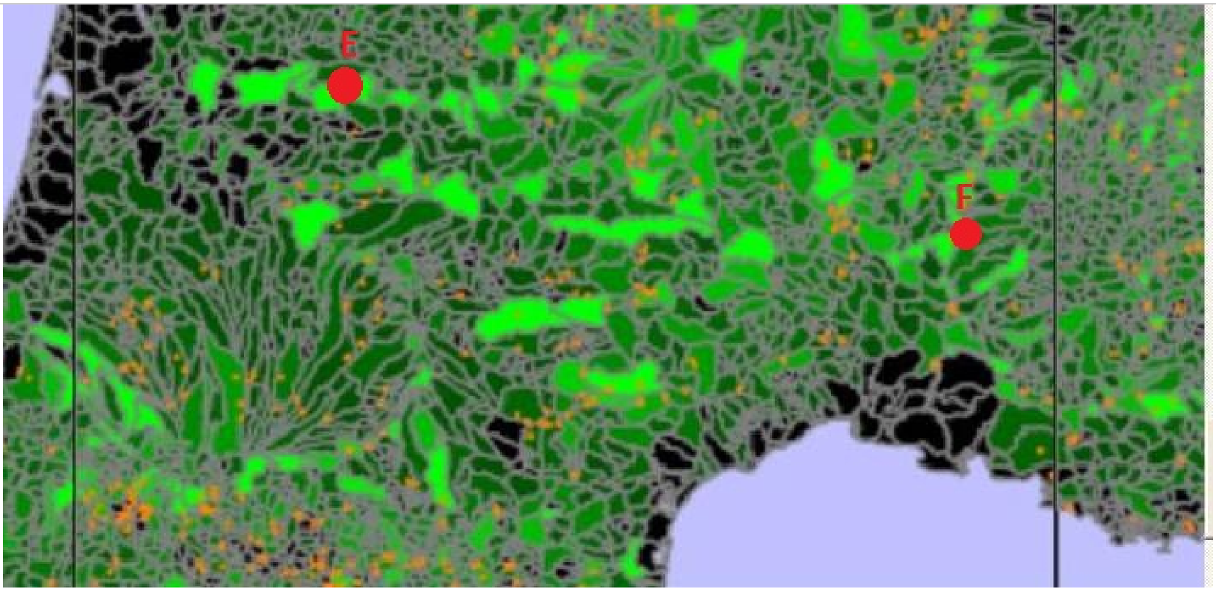


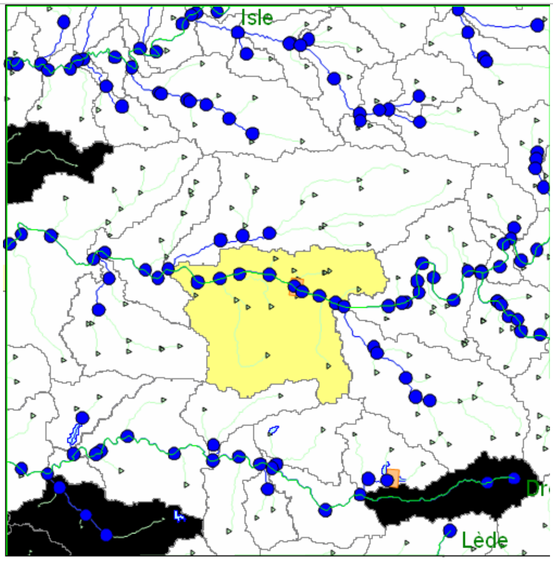
Site	C



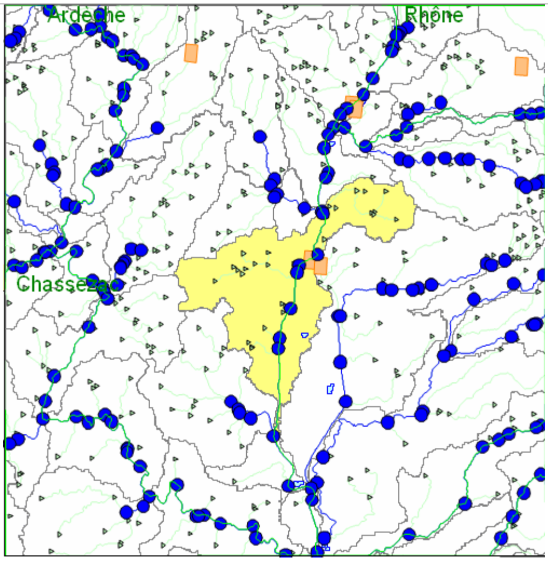
Site	D	
XY	2,964,572	2,250,150
LongLat	-6.464667	42.0145
CatchmentID	30850	E030147421
Theoretical Potential	48.5MW	
Actual Installed capacity at Dams	Cernadilla unknown, Valparaiso 2 x 34 MW	
Total Current Installed Capacity	>68 MW (>140% of theoretical potential)	

Figure 13: Selected catchments in North West Spain





Site	E	
XY	3,578,565	2,460,200
LongLat	0.6000058	44.83207
CatchmentID	24516	D030210976
Theoretical Potential	87.5MW	
Actual Installed capacity at Dams	Tuiliere 32MW	
Total Current Installed Capacity	32MW (37% of Technical Potential)	



Site	F	
XY	3, 893,341	2,382,550
LongLat	4.636132	44.4156
CatchmentID	25158	D030211614
Theoretical Potential	444.6MW	
Actual Installed capacity at Dams	Donzere 354 MW	
Total Current Installed Capacity	354MW (80% of Technical Potential)	

Figure 14: Selected catchments in France

4.1.2 Comparing the Technical Potential at the nearest ECRINS node to data from existing or planned SHP installations on actual design flow and hydropower capacity.

As part of this project, desk research was undertaken which identified 546 actual or planned hydropower installations in the UK. These have been compared to the estimated theoretical potential at the nearest ECRINS node. It should be noted that the amount of data available is constantly improving. In the months since the Desk Research exercise was undertaken an IEA website has gone live which has a list of 1200 planned sites in the UK[28].

The theory was that a good correlation could be used to derive an empirical factor to apply to the Theoretical Potential for individual nodes (or the catchment as a whole) to give a ‘first-level’ ‘top-down’ estimate of the Technical Potential. This could then be compared to results from discrete test cases run with a localised site level model (such as HydroBot) to derive a further empirical factor showing how much of the ‘first-level’ Technical Potential is likely to be realistically exploitable.

294 out of the 546 sites were close enough to nodes that had flow data for a comparison to be made. Following the approach adopted to the head comparison above, Figure 15 and Figure 16 below show the correlation between actual and predicted Theoretical capacity for two distances between node and actual site. In the first of each pair of plots the axes have been limited to 10MW because this is the area of interest for SHP schemes.

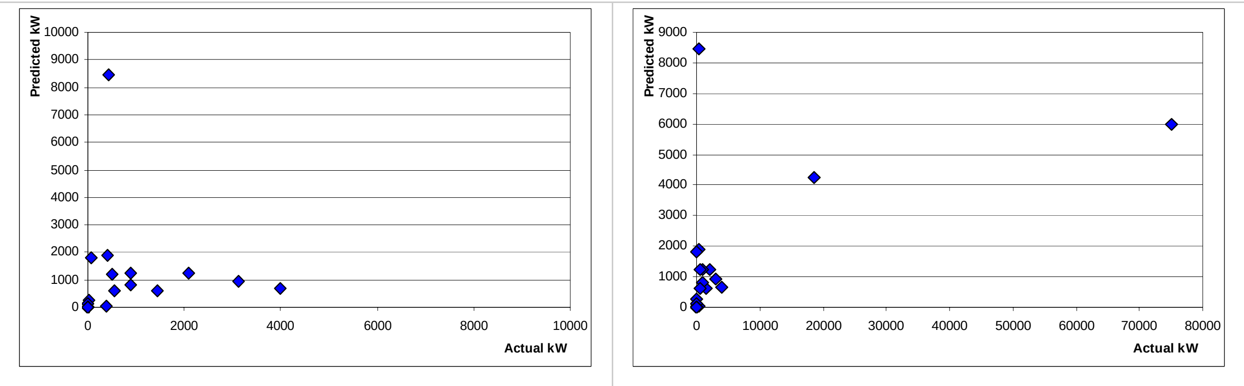


Figure 15: **Correlation between calculated Theoretical Potential at nearest node and actual capacity of scheme: nodes within 200 metres of scheme**

[28] http://www.small-hydro.com/

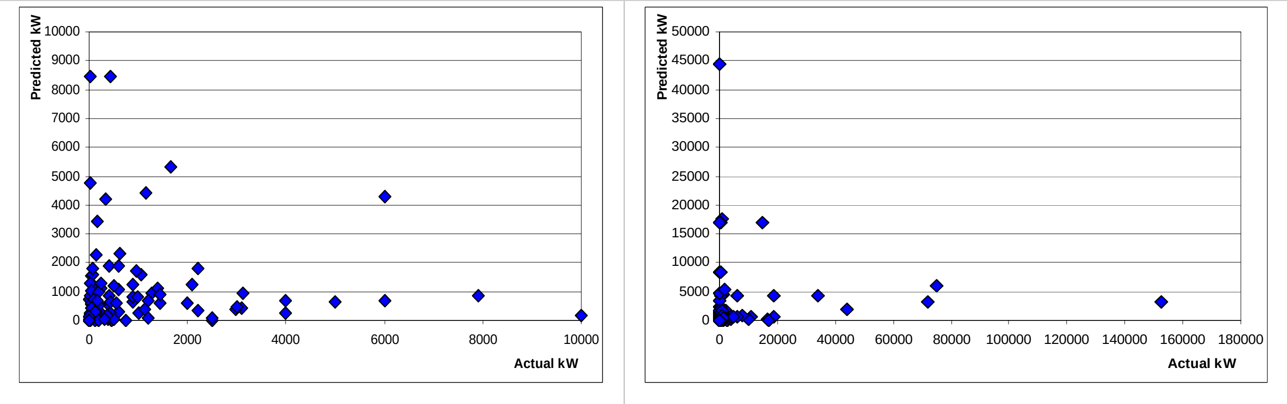


Figure 16: **Correlation between calculated Theoretical potential at nearest node and actual capacity of scheme: nodes within 1000 metres of scheme**

Again, this appears to be random scatter, which again suggests that the Theoretical Potential calculation for individual ECRINS nodes does not map well onto the real world. This reflects the fact that there a range of complex issues within the development of hydropower projects which affect their deployment which has not been captured by the ECRINS model.

4.1.3 Environmental Compatibility – Natura 2000

The Natura 2000 network is one of the key instruments for promoting biodiversity and conservation. It is thus an important resource for evaluating the environmentally compatible potential. It is very well described by text from the Belgian Coordination website:

“The nature conservation policy of the European Union is essentially made up of two directives, the 1979 "Birds Directive" and the 1992 "Habitats Directive". They form the framework for protecting and conserving Europe's wildlife and habitats. At the centre of this nature conservation policy is the creation of a network of special areas of conservation across the European Union. This network is known as Natura 2000.”

The main objective of Natura 2000 is to contribute to the preservation of biological diversity on the territory of the European Union, while taking into account socio-economic parameters. In this way, Natura 2000 does not prohibit human use of land or resources within the sites proposed, nor does the Habitats Directive require them to have a particular legal protection status. However, the requirement is that the favourable conservation status of the habitats and species must be maintained and ideally, improved.

The practical implementation of Natura 2000 is left to the Member States. The network is made up of:

- Special Protection Areas (SPAs) to conserve the 187 bird species and sub-species listed in Annex I of the Birds Directive as well as migratory birds and
- Special Areas of Conservation (SACs) to conserve the 253 habitat types, 200 animal and 434 plant species listed under the Habitats Directive.”

The Natura 2000 website includes links to national websites and source of information (http://www.natura.org/national_links.html). By following these links we were quickly able to download ESRI shape files giving geographic information on the SPAs and SACs, for the UK and for Spain. The plots of Figure 14 below show examples of this data overlaid on the theoretical potential calculated as in Figure 5.

For the purposes of this pilot exercise it is enough to note that algorithms could easily be written to identify for each catchment whether there were any SACs or SPAs contained within, and this could be used to apply a scaling factor to the hydro potential, or to eliminate the catchment from consideration completely (scaling factor =0). Note – the Natura 2000 data from Spain alone was downloaded, hence the lack of overlay in Portugal.

In terms of understanding the quantative effect on SHP projects of being located in or nearby environmental constraints further consultation with the hydro community would be required to understand the additional costs of being in a designated area such as a SPA or SAC. Using this it would then be possible to define the Environmentally Compatible Potential.

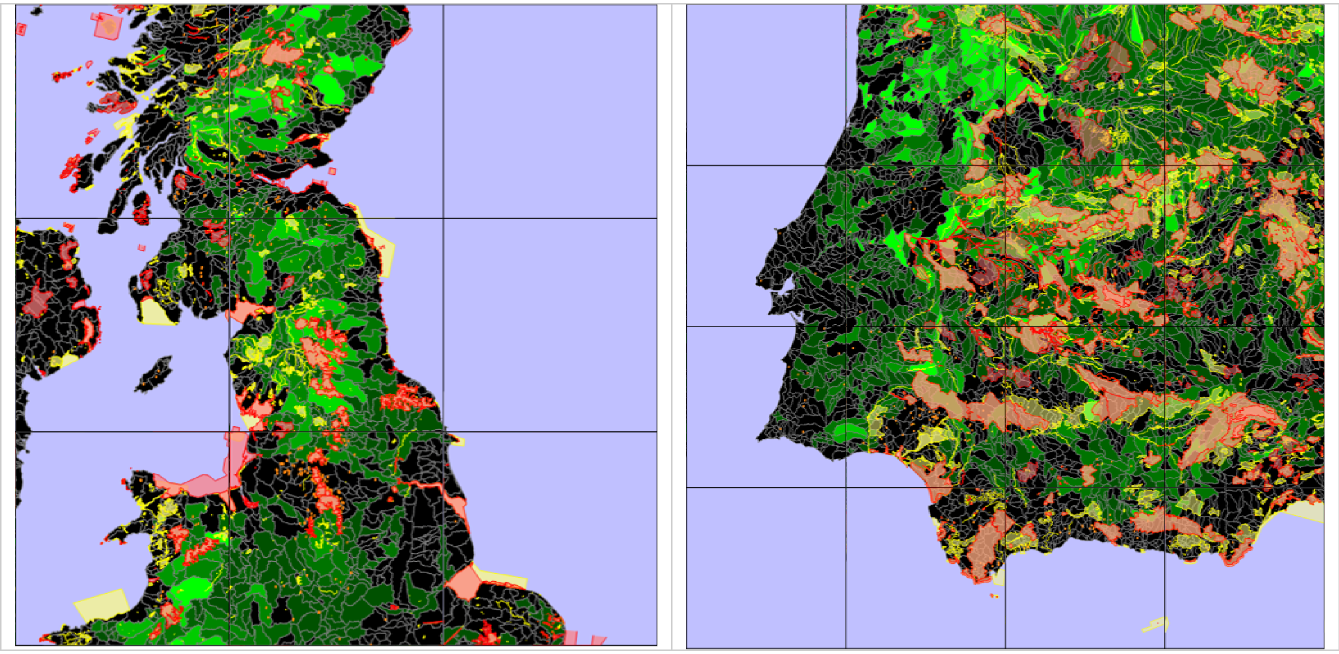


Figure 17: Examples of Natura 2000 areas overlaid on plots of theoretical potential, for part of the UK (left) and Spain (right). SACs (habitat, animals, and plants) are shown in yellow, SPAs (birds) are shown in red

5 Conclusions

The key conclusions from this study are as follows:

- ECRINS contains a range of data on river networks; such as elevation, dam/weir head, co-ordinates and monthly flow linked to main drain line segments. Assessment of the initial data available identifies some initial limitations, these include:
- Main Drain flow data – Currently this covers less than 50% of the main drains across Europe.
- Tributary flow data - An important point is that no flow data is supplied directly on the flow for Tributaries. For this study an estimate will be calculated based on the length of tributaries and the increase in flow between given nodes
- Elevation data - Is only available at the nodes, in some cases there can be a significant distance between these, resulting in poor granular resolution.
- Dams data – The data available for dams is limited, only c.4,600 structures are contained in the database, however based on a recent UK study[29], this could be expected to represent in the region of c.3% of the total number of river barriers/structures.

- It was possible to make an assessment of the SHP Theoretical Potential for countries where flow data was available. This Theoretical Potential calculated from ECRINS has been compared to a similar potential value calculated for 8 Scottish catchments as part of the Scottish Hydropower Resource Study[30]. The average variation between the potential calculated in this report and the Scottish calculation methodology was 10%, which indicates overall the different methods broadly agree for the catchments evaluated, although the methodology used in this report tended to somewhat lower potential estimates.
- A rigorous evaluation of Technical Potential is significantly more complicated than estimating the Theoretical Potential and would have to predict the location, turbine type, turbine capacity, head exploited, flow fraction exploited, for individual turbine installations. In order to get an accurate result the exercise would start to become an 'individual site' approach rather than 'catchment-wide' and thus much more complex and costly.
- On initial inspection, ECRINS would not appear to be a good starting point for such a rigorous evaluation of Technical Potential. In ECRINS, Main Drain and Tributary nodes are defined purely by looking at merging of flows, and may be separated by tens of kilometres. The information at any ECRINS node is very local and may not be representative of the surrounding topography – detailed information that is needed for any realistic evaluation of a possible SHP site. ECRINS nodes also may not be located close to key locations, in particular existing dams and weirs.

[29] "Mapping hydropower opportunities and sensitivities in England and Wales (technical report)" (Environment Agency, February 2010), http://www.environment-agency.gov.uk/shell/hydropowerswf.html.
[30] 'Scottish Hydropower Resource Study' August 2008, Nick Forrest Associates, SISTech and Black & Veatch, http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf

- Despite the granular nature of the data an example catchment was analysed in the Pyrenees was reviewed, this assumed that a hydropower system would be installed at each node, making use of the flow at the previous node and the head differential. From estimation of the installed capacity and the capital and operating costs a resource cost curve was then generated for the catchment. Whilst this demonstrates an approach, the methodology is crude and requires refining through the obtaining better resolution elevation data and algorithms to define the placement of potential SHP. Local information such as the distance to grid connection and roads is also required.

- Whilst it can be seen that there is scope for the methodology to be refined for evaluation of the Technical Potential. It was felt worthwhile to consider an environmental proxy in parallel to demonstrate how the methodology would work in full and the potential impact of environmental constraints on the cost of energy from hydro installations.

- An initial assessment of the effect of environmental constraints, two elements have been considered to demonstrate the potential impact of an environmental constraint (as from the stakeholder workshop held on 27th November 2009 these elements are most affected by environmental constraints):

- Reduced design flow – resulting in a smaller installed capacity and energy generation.

- Increases capital costs - the CAPEX has also been increased by a third to simulate the added cost of environmental mitigation measures.

- For the example catchment, due to the reduced flow (imposed by the environmental constraints) the installed capacity of each SHP site is reduced, along with its annual energy output. In the example catchment the due to the reduced design flow rate, the Technical Potential is reduced by 44% to an Environmentally Compatible Potential of 2,359kWe. This is reduction is without considering which SHP sites might not be economically attractive any longer and therefore unattractive to develop, hence further reducing the Environmentally Compatible Potential.

- It can be seen that whilst the overall methodology would seem to allow the end goal of defining Europe's environmentally compatible SHP potential to be identified, there are some significant challenges in actually technically delivering this using the ECRIN database alone; these challenges are mainly are based on the granular resolution of the data available in ECRINS.

- It was found that the Theoretical Potential can be defined using the methodology described in this work, and yields comparative results when tested against similar studies in limited catchments (such as HydroBot). However, evaluating Technical Potential is much more complex requiring both a higher resolution of data and also a wider range of data than contained in ECRINS.

- The identification of the Environmentally Compatible Potential seems like could be achievable, if the challenges presented in identifying the Technical Potential can be overcome. Although to define the impact of different environmental designations / constraints would require consultation and consensus with the hydro and environmental community to establish both the impact on development of SHP in these areas, and also the impact on the capital cost.

- If the evaluation of Europe's environmentally compatible SHP potential is to be pursued using the ECRINS data, a more robust estimate of Technical Potential would need to be defined. This would need to be done though identifying additional data sources, refining the methodology and then testing the results (possibly against another method such as HydroBot) across a limited area. If this could be demonstrated to be successful and replicable across Europe then it would be worth further developing the final step of the methodology to define the Environmentally Compatible Potential.

6

7 Literature

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red.

8 Appendix 1: Technical Potential – a suggested individual site approach

The comparisons in the bulk of the report suggest that ECRINS nodes are not well suited to an individual site approach to calculating the Technical Potential. However, there is one possible enhancement that could be applied to ECRINS data that might overcome this. ECRINS contains binary geographical 'shape' information on the river segments which implicitly defines x-y coordinates for 'sub-nodes' along that segment (these lie between the Main Drain or Tributary nodes that form the termini of the segment). These 'sub-nodes' describe 'sub-segments' of the river segment that should be more descriptive of the local topography. Within the resolution of ECRINS, there is effectively an implicit sub-node at every point where there is a significant change in the direction of the watercourse. This may be sufficient to make better assessments of realistic, exploitable, head and flow, which can be used to derive a more sophisticated estimate of hydropower potential and costs. It should be possible to find a sub-node that is very close to each dam and known hydropower site, which will hopefully improve the correlation.

There are significant drawbacks to this approach. ECRINS does not have elevation or flow information at these implicit 'sub-nodes', and so these values would have to be derived by some estimation method, or by reference to another, more detailed data source. However, it may be an informative exercise to follow this approach for a few selected catchments with known installations or planned schemes, and correlate the revised estimates

The ECRINS 'sub-node' individual site approach to evaluating Technical Potential within a catchment can be summarised by the following steps, which are described in further detail below:

- Take each line segment in the catchment
- Split the line segment into a number of discrete 'stretches'
- Derive the actual head and flow for each stretch (see the definition of actual head below)
- Derive the 'useful' head and flow for each stretch (see the definition of useful head below)
- Assign turbine type and capacity for each stretch based on useful head and flow

There are a number of issues to be resolved at each step:

- *Take each line segment in a catchment* – to avoid unnecessary calculation, filter out line segments which do not have flow data – leaving the main drains with measured flow data and tributaries associated with them where flow can be estimated or calculated from the main drain flows.

- *Split the line segment into a number of 'stretches'* – using only the geometry inherent in ECRINS gives three possible scales for defining stretches:
  - a) the entire line segment – this has elevation data defined at each end.
  - b) the elemental 'subnode' segments defined as lines joining the vertexes encoded in the 'shape' field for that line segment – these do not have separate elevation data and this would have to be estimated from the geometry, or abstracted from other data sources.
  - c) a collection of one or more contiguous subnode segments – this would imply an iterative approach evaluating all possible combinations of contiguous elemental subnode segments, and then selecting the most cost effective option, eliminating the options that include subnode segments allocated to that option, and then iterating.
  - d) match elemental subnode segments to existing dams or weirs in ECRINS. These are special cases because the head at each dam or weir is known, and the capital costs of installations will be greatly reduced because there is an existing barrier and infrastructure. The main concern for this is the low coverage of the ECRINS data – only 5,000 sites which is estimated to be of the order of 1% of the sites in Europe.
- *Derive the actual head and flow for each stretch* – for options (a) and (d) above this data are directly available in ECRINS; for options (b) and they would have to be estimated from the geometry or abstracted from other data sources.
- *Derive the 'useful' head and flow for each stretch*
  - the useful head is the fraction of the actual drop in elevation along the stretch that can be exploited for engineering/economic considerations. The suggested possible approaches are:
    - Evaluate the fraction on an individual basis from detailed topographic data and a model of the costs for different topographies
    - Assign a fraction on a semi-empirical basis from a lookup table where stretches are grouped by some geometric criteria – e.g. length and head and angle between subnode segments for multiples
    - Take the entire head for the stretch.
  - The useful flow is the fraction of the average flow on the stretch that will be used by the turbine(s) assigned to that stretch. This involves a number of issues:
    - Variability of flow along the stretch.
    - Maximum fraction allowed because of environmental or other constraints (known as the reserve flow).
    - Costs associated with exploiting that fraction, e.g. capital and operating cost, connection to power grid, manpower and logistics for supporting turbine(s) of that size at that location.
- *Assign turbine type and capacity for each stretch based on useful head and flow* – methodologies exist for assigning optimal turbine design to particular head and flow regimes, illustrated by the diagram in Figure 18.

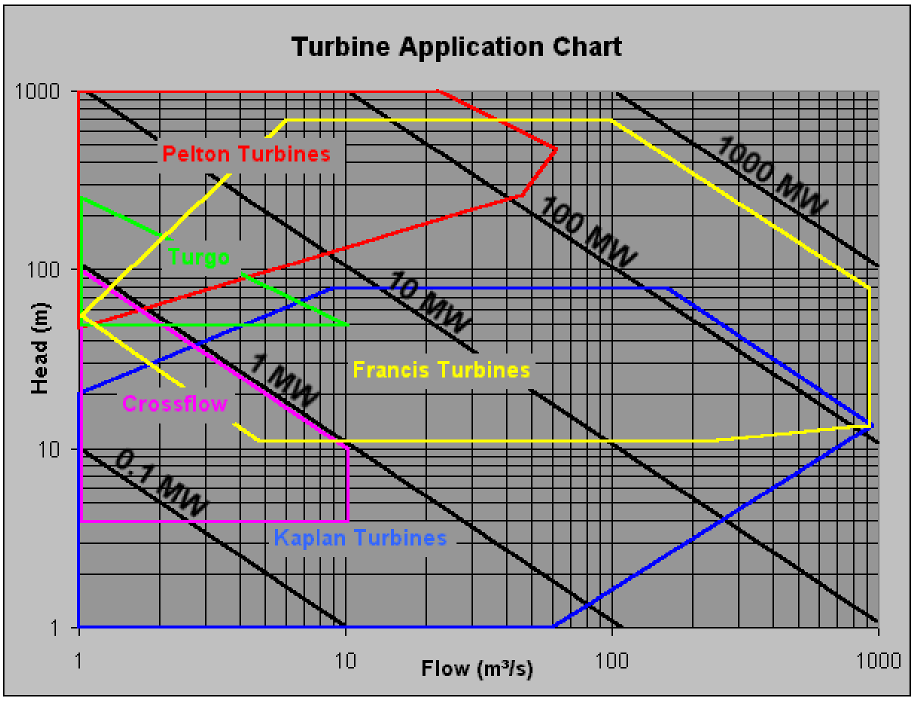

Figure 18: Flow and head regime for different turbine types

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