Evaluation of small hydro power potential in three river basins of Mexico

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ABSTRACT

Technology was adapted and developed to evaluate systematically the hydro power potential in the Culiacán, Nautla and Tecolutla river basins covering some 30,000 km^2, with emphasis on power plants of 30 MW or less without reservoir. The basic hydro power potential of all stream reaches, with an average length close to 3 km, was evaluated. A distributed hydrologic model was applied and its output was compared to that of regional regression equations that were also developed. The frequency analysis of runoff series (flow duration curves) was carried. The optimized hydro power potential of feasible small, mini and micro power plants projects was evaluated, considering one or more penstocks per river reach. A complete geographic database with the results and context features was elaborated. The technology and experiences gained are applicable to other regions in Mexico and abroad.

Introduction

The Secretariat of Energy of Mexico has established policies encouraging the development of the hydro power potential (HPP) in the country, as a non pollutant and renewable resource, through the identification and assessment of small hydro power projects, to be developed either by the Federal Commission of Electricity (CFE) or by private investors.

For this reason, IMTA was solicited by CFE to develop and adapt technology for the systematic and exhaustive assessment of small, mini and micro hydro power potential projects that do not require a reservoir and have a mean annual capacity of up to 30 MWa (Trelles *et al.*, 2006a and 2006b). Three river basins were selected to carry a pilot study, including the Culiacán river basin (18,594 km^2), the Nautla river basin (2,804 km^2) and the Tecolutla river basin (7,861 km^2), which together represent 1.5% of the country area (Figure 1).

Figure 1 Culiacán, Nautla and Tecolutla river basins

Methodology

The methodology applied is analog in some aspects to that of a similar study for the United States of America (USDOE, 2004, 2006), with complements and adaptations to the Mexican context following guidelines by CFE. The Hydrotel technology (Fortin *et al.*, 2004) was adapted and applied for distributed hydrologic modeling. In addition, new technology was elaborated by IMTA for time series treatment, geographic procedures, 3D river network, and optimization of penstocks in hydro power projects. The hydro power projects were classified according to their capacity, hydraulic head and the applicable turbine technology (Table 1).

Table 1 Hydro power projects classification

<table>
<tr><th>Class</th><th>Power (P)</th><th>Head (h)</th><th>Technology (C, NC)</th></tr>
<tr><td>1</td><td colspan="3">Large (P>30 MW)</td></tr>
<tr><td>2</td><td rowspan="2">Small (1<P<30 MW)</td><td colspan="2">High (h>10 m)</td></tr>
<tr><td>3</td><td colspan="2">Low (h<10 m)</td></tr>
<tr><td>4</td><td rowspan="3">Mini (0.1<P<1 MW)</td><td colspan="2">High (h>10 m)</td></tr>
<tr><td>5</td><td rowspan="2">Low</td><td>Conventional (2.5<h<10 m)</td></tr>
<tr><td>6</td><td>Non conventional (h<2.5 m)</td></tr>
<tr><td>7</td><td colspan="3">Micro (0.01<P<0.1 MW)</td></tr>
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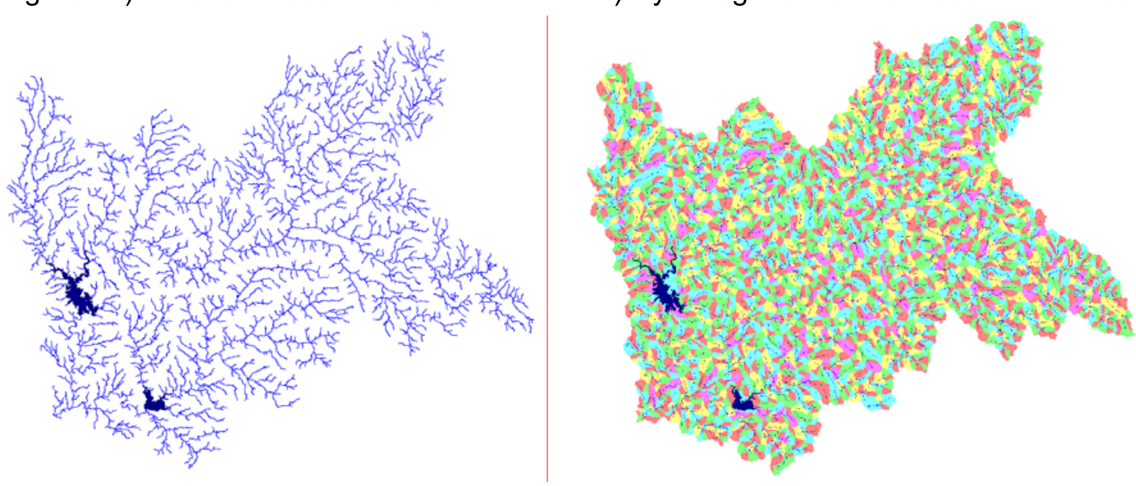
Physiography of river basins

The physiography of the three river basins was analyzed with Physitel (Turcotte *et al.*, 2001) to determine the topology of the river network applying a specified density (Figure 2a). A 90 m resolution digital elevation model (USGS, 2005) was used as input, along with the corresponding vector map of the stream network and water bodies with a surface greater than 0.5 km^2 (INEGI).

Figure 2a) River and reservoirs network and 2b) Hydrologic units of Culiacán River Basin



The drainage areas were discretized in hundreds of relatively homogeneous hydrologic units (RHHU), with an average surface close to 5.5 km^2 (Figure 2b, Table 2). Then, for every RHHU the percent of each land use class present (INE, 2004), as well as of the predominant soil texture class were determined (INEGI, 2003).

The geographic database generated by Physitel was exported to the Hydrotel format, containing the following features: nodes, stream network reaches, water bodies, special points, hydrologic units, water divide, elevations, slopes, flow directions, hydraulic properties of soil percent of land use classes and predominant soil texture.

Table 2 Physiographic characteristics

River basin	River basin area (km^2)	Number of RHHU	Mean RHHU surface (km^2)	Mean reach length (km)
Culiacán	15,692	2,710	5.8	2.5
Nautla	2,785	423	6.6	3.5
Tecolutla	7,708	1,248	6.2	3.1

Determination of H and Q

The gross hydraulic head to be used in the power calculation and the drainage area for each river reach were determined using specially programmed procedures.

The mean annual historic daily flow over 20 years at the upper and lower nodes of every river reach was estimated by two methods: a) Hydrotel distributed hydrologic model, and b) Regional regression equation, explaining the mean annual flow as a function of drainage area, mean annual precipitation and mean annual temperature.

a) The distributed hydrologic model

The Hydrotel distributed hydrologic model generates multiyear mean daily runoff series in every RHHU and stream reach, along with other useful hydrologic variables. The model simulates direct, subsurface and base flows through six processes. It includes four vertical processes: interpolation of daily precipitation, minimum and maximum temperatures; snow accumulation and snowmelt; potential and actual evapotranspiration; and vertical water balance in three soil layers. As well as two horizontal processes: overland runoff; and river network and reservoir routing.

Each of these processes can be simulated by several alternative algorithms depending on the availability of data. There are 18 parameters to be calibrated for the six processes of Hydrotel, of which five are the most important: the depth of layers 1, 2 and 3, the scale factor of PET and the coefficient of recession (Fig. 3).

The output of the model includes daily simulated runoff series at each confluence in the river network as well as other useful time series. Additionally, the model generates different thematic maps, graphs and tables that can be exported.

Model calibration

The model was calibrated, first manually then with an automatic procedure, for several watersheds in each river basin with respect to four year runoff series at selected gauging stations. The criteria were to maximize the Nash Sutcliffe efficiency index and to minimize the volume difference between observed and simulated runoff accumulated during the calibration period (Fig. 4).

Figure 3 Vertical and horizontal processes of Hydrotel

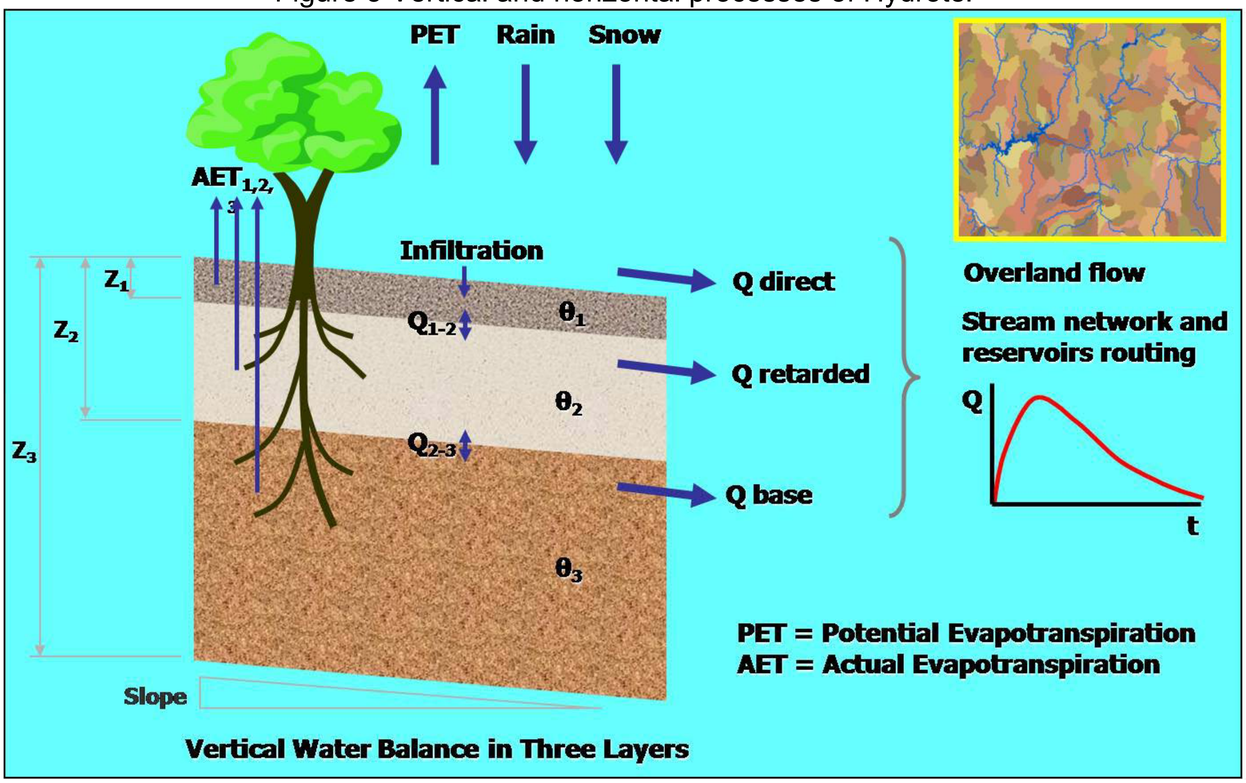
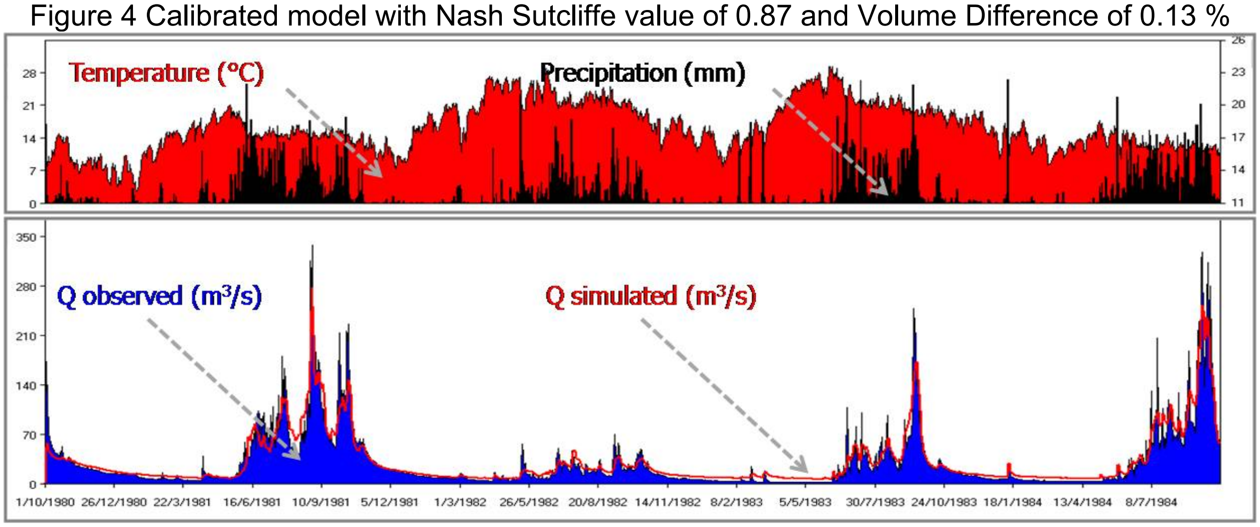


Figure 4 Calibrated model with Nash Sutcliffe value of 0.87 and Volume Difference of 0.13 %



b) Regional regression equation

This method allows the estimation of mean historic runoff for every stream reach as a function of area, mean precipitation and mean temperature. The parameters of a regression equation were determined from simultaneous meteorological and runoff records at selected gauging stations:

$$\mathbf{Q = e^{a}\, A^{b}\, P^{c} T^{d}}$$

where:

Q = Mean annual runoff (m^3/s)
A = Drainage area (km^2)
P = Mean annual precipitation over the drainage area (mm)
T = Mean annual temperature over the drainage area (°C)
e = Base of natural logarithms
a, b, c, d = Empiric regression parameters

Special procedures were programmed and used along with the Hydrotel model to interpolate daily multiannual series of precipitation and temperature, then average over the corresponding drainage areas for every stream reach, as inputs for the regional regression method. The same to calculate the mean historic runoff for every stream reach.

The mean annual runoff for every stream reach, gauged and ungauged, of the river basin was then estimated by means of the resulting regional regression equations, as follows:

Culiacán river basin: $\mathbf{Q = e^{-23.2639}\, A^{1.3186}\, P^{1.7918}\, T^{1.1527}}$

Nautla river basin: $\mathbf{Q = e^{-13.8546}\, A^{1.0997}\, P^{0.4649}\, T^{2.2645}}$

Tecolutla river basin: $\mathbf{Q = e^{-21.1736}\, A^{0.8949}\, P^{2.4047}\, T^{0.2090}}$

c) Comparison of methods

A comparison was made of the observed runoff and the estimated or simulated flows by both methods. The error was calculated over the calibration period for the selected gauging stations.

$$\boldsymbol{\varepsilon = (\Sigma Qe_i - \Sigma Qo_i)/\Sigma Qo_i}$$

where:

ε = Runoff estimation error (%)
Qe_i = Estimated mean annual runoff (m^3/s)
Qo_i = Observed mean annual runoff (m^3/s)
i = Year index

The Hydrotel distributed hydrologic model was chosen for the rest of the study because of its greater precision and for the clear advantage of having multiannual daily runoff series at any confluence of the drainage networks. This in turn allows the runoff frequency analysis (flow duration curves).

Assessment of the basic hydro power potential

a) Basic HPP

The basic or gross HPP of the three river basins was estimated as the addition of the mean annual power of all river reaches with a value greater than 10 kWa. The calculation was done considering a global efficiency of (81.5%) with the following equation:

$$\mathbf{P = \eta \rho g H Q / 1{,}000}$$

where:

P = Mean annual electric power (kWa)
η = Global efficiency, normally from 75 to 88 (%)
ρ = Density of water, 1,000 (kg/m^3)
g = Gravity acceleration, normally 9.81 (m/s^2)
Q = Mean annual historic runoff at the center of the reach (m^3/s)
H = Hydraulic head in the stream reach (m)

b) Available basic HPP

The available basic HPP was calculated by subtracting from the total basic HPP the added HPP of those river reaches already developed, that is with an existing hydro power plant, and of those laying in a conditioned or exclusion zone. The units for the mean annual power are MWa.

$$\mathbf{P_{bd} = P_b - P_d - P_c}$$

where:

P_{bd} = Available Basic HPP (MWa)
P_b = Basic HPP (MWa)
P_d = Developed HPP (MWa)
P_c = Conditioned or excluded HPP (MWa)

The developed HPP corresponds to the set of existing hydro power centrals in each river basin, belonging to CFE, LyFC (public company for the central region) or to private owners, according to the records of the Energy Regulatory Commission. It was calculated as follows:

$$P_d \text{ (MWa)} = \text{Mean annual generation (MWh)} / 8{,}760 \text{ h}$$

The conditioned or excluded HPP corresponds to those river reaches that coincide partially with zones under legal or administrative restriction to be developed, such as urban zones, irrigated areas, natural protected areas and archeological zones. To this end specially programmed geographic procedures in Visual Basic for ArcMap were applied.

c) Feasible basic HPP

The feasible basic HPP in each river basin was determined by subtracting from the available basic HPP the added HPP of those river reaches that are more distant than specified values from connection points to the electric grid or from access features. The considered connection points are: urban areas greater than 2,500 inhabitants, transmission lines, power plants and electric substations. The considered access features are: urban areas, roads and railroads. To this end specially programmed geographic procedures in Visual Basic for ArcMap were applied. The feasible basic HPP was calculated with the following equation:

$$\mathbf{P_f = P_{bd} - P_{da} - P_{dc}}$$

where:

$\mathbf{P_f}$ = Feasible basic HPP
$\mathbf{P_{bd}}$ = Available basic HPP
$\mathbf{P_{da}}$ = Available basic HPP in streams far from access features
$\mathbf{P_{dc}}$ = Available basic HPP in streams far from connection points

The successive stages of the basic HPP assessment were calculated for the three river basins (Table 3).

Table 3 Basic HPP of river reaches assessment

River basin	Basic HPP (MWa)	Developed HPP (MWa)	Excluded basic HPP (MWa)	Available basic HPP (MWa)	Feasible basic HPP (MWa)
Culiacán	1,001.9	28.9	68.8	933.1	274.0
Nautla	543.5	15.5	123.7	419.8	297.9
Tecolutla	1,546.1	171.7	242.4	1,303.7	1,004.7

Assessment of the feasible hydro power projects potential

The potential of feasible hydro power projects without reservoirs was assessed. This was carried by optimizing within each river reach the location and length of one or more penstocks. To this end, two applications were developed.

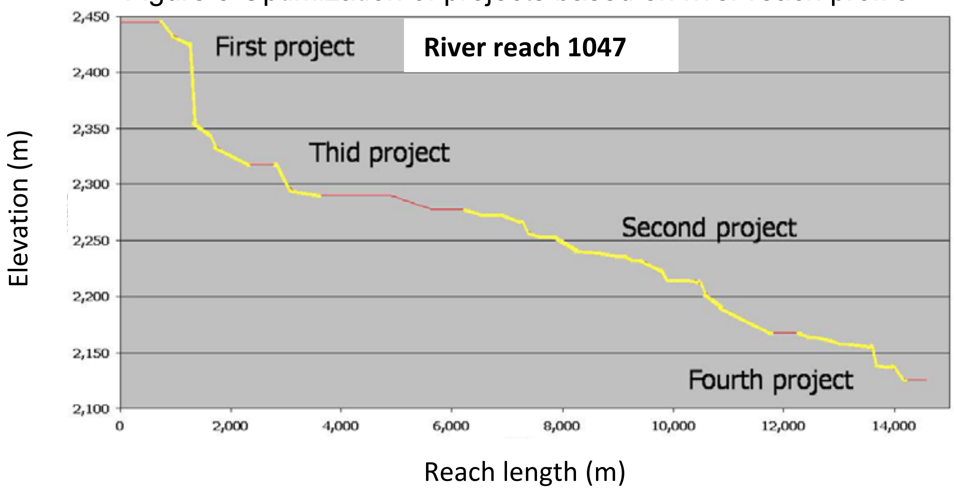
3D network analysis and penstock optimization

The first application produces a file for each river basin with the X, Y and Z coordinates of a set of points that segment every river reach at specified intervals, in this case 90 meters. The second application is a Visual BASIC application with functions shown hereafter. The numbers in parentheses show the values used in this study.

- Interpolates the runoff at the starting point of a proposed penstock location, taking into account the length and the gross hydraulic head for every river reach.

- Locates multiple penstocks projects in a stream reach that satisfy specified criteria on maximum penstock length (5,000 m) and minimum power (10 kW), considering a project flow based on a selected frequency (65%) and a specified global efficiency (81.5%).
- From the segment with maximum Power/Length the penstock grows by segments until it gets to a flat zone with minimum slope specified (0.02), unless the flat zone is shorter than a threshold distance (150 m).
- Generates output files of stream reaches and projects with geometric and hydropower characteristics.
- Generates thematic georeferenced vector maps of the river network and the optimized penstock projects.

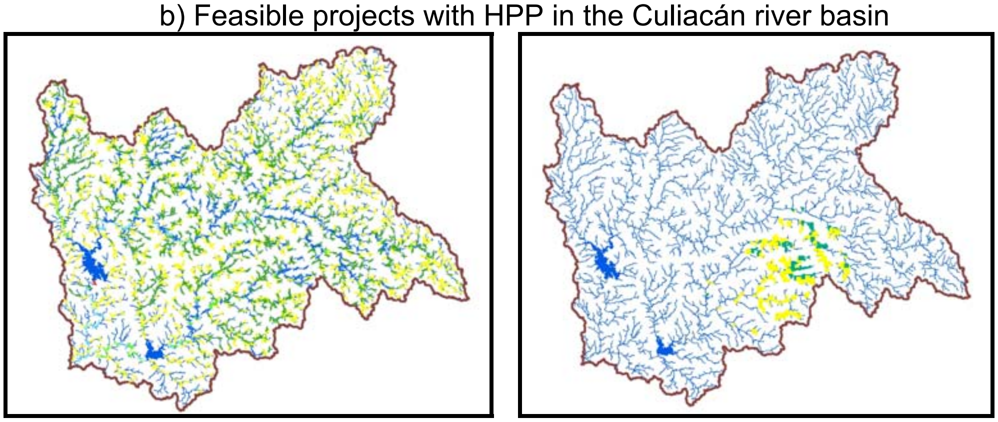
Figure 5 Optimization of projects based on river reach profile



Elaboration of site and context maps

A geographic database (geodatabase) with metadata was elaborated for each river basin, with features in vector and raster formats in ArcMap. It is homogeneous in Lambert Conic Conformal projection, with official Mexican parameters. The geodatabases include: river reaches with basic HPP by classes (Fig. 6a), sites of feasible projects with HPP by classes (Fig. 6b).

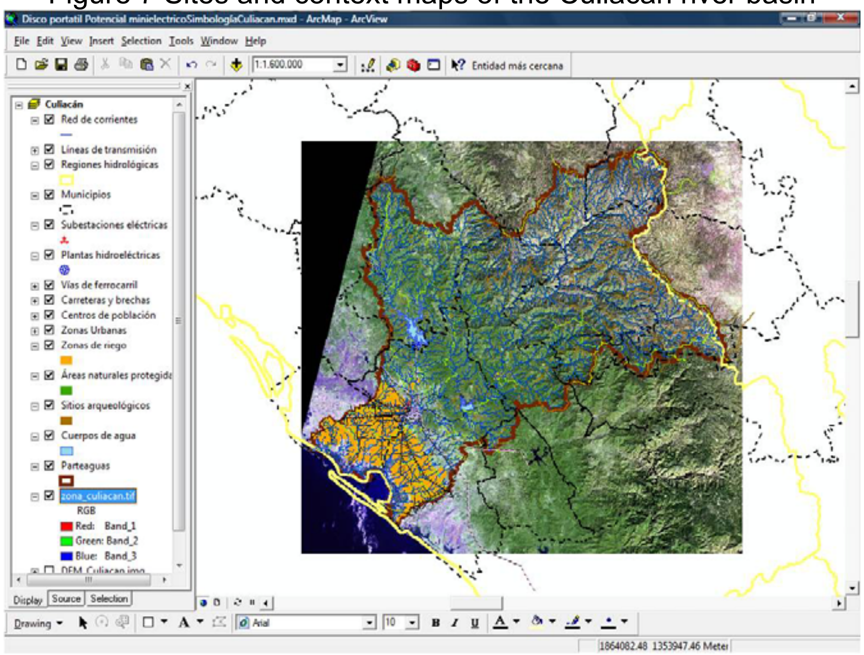
Figure 6 a) River reaches with basic HPP and
b) Feasible projects with HPP in the Culiacán river basin



Context maps

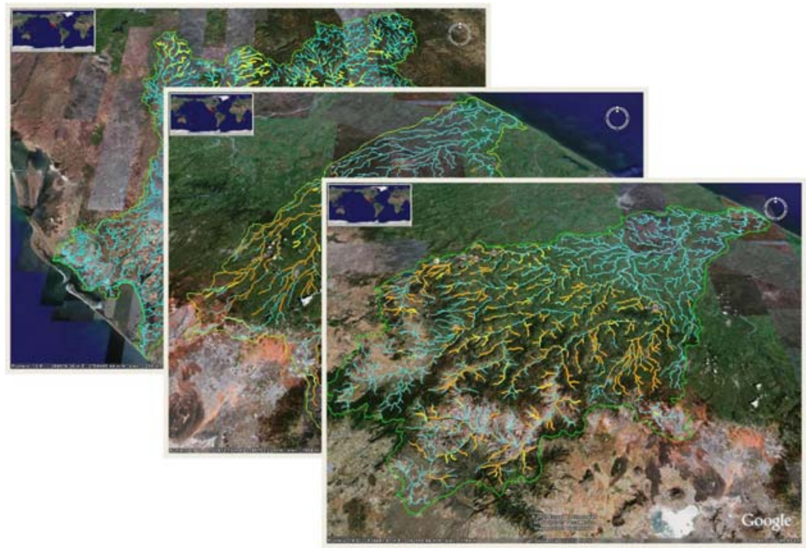
The geodatabases include as well context features: electric infrastructure, exclusion zones, ways of access, political divisions, hydrography, monitoring networks, DEM and satellite image (Fig. 7).

Figure 7 Sites and context maps of the Culiacán river basin



Finally, selected features of the geodatabases were exported to the projection and format of GoogleEarth (Figure 8). This might allow diffusing the information once the official approval is granted.

Figure 8 Three pilot river basins in GoogleEarth



User interface

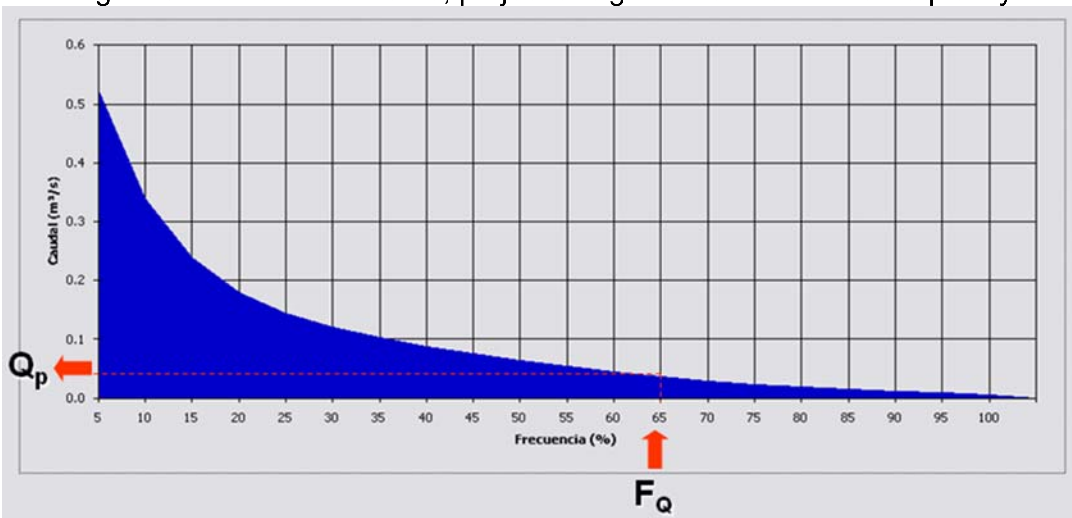
The geodatabases can be queried via a user interface, applying graphic and alphanumeric procedures in Visual Basic for ArcMap, to retrieve very detailed information regarding river reaches (Table 4).

Table 4 Query interface for river reach HPP

Topology	Basic HPP	Location and geometry	Exclusions	Hydrology	Distances to	Projects
Reach ID RHHU ID Upper node ID Lower node ID	Basic HPP class	Municipality State Stream Hydrologic region Watershed Upper node Elevation Lower node Elevation Hydraulic head 2D length 3D length Slope	Access feasibility Connection feasibility Exclusion zone Type of exclusion	Upper node mean flow Lower node mean flow Center point mean flow	*Access:* Roads Railroads Urban areas *Connection:* Transmission lines Power plant Substations	Number of projects *Sum of:* 3D lengths Heads Power *Percentage to develop of:* Lengths Heads Power

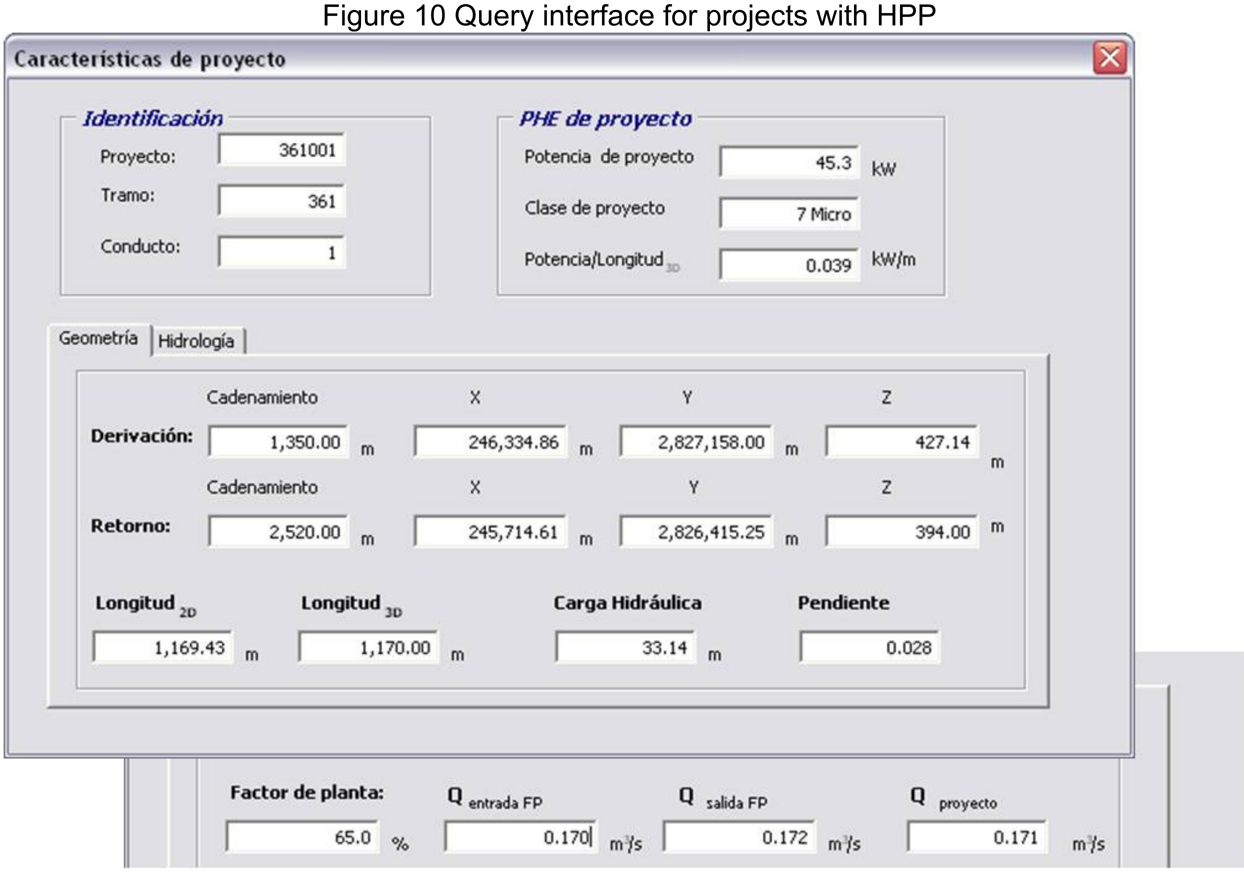
The Hydrology tab of the interface allows retrieving the flow duration curve at the upper and lower nodes of any river reach, based on a daily simulation of 20 years. This in turn permits to select the project design flow for a specified flow frequency (Fig. 9).

Figure 9 Flow duration curve, project design flow at a selected frequency



The geodatabases can also be queried regarding the optimized projects using a rich screen with an ID and a project HPP sections; plus two tabs, one for geometry and the other for hydrology (Fig. 10).

Figure 10 Query interface for projects with HPP



Summary of results

The Assessment of the feasible hydro power projects potential for the three river basins was carried, then summarized by project class (Table 5), as well as by river basin (Table 6).

Table 5 Classification of feasible projects HPP

Project Class		Culiacán		Nautla		Tecolutla	
		Feasible projects	Power (MW)	Feasible projects	Power (MW)	Feasible projects	Power (MW)
1	Large	0	0.0	0	0.0	0	0.0
2	High Small	2	2.8	22	48.5	27	70.9
3	Low Small	0	0.0	0	0.0	2	2.3
4	High Mini	70	18.7	82	29.8	139	42.9
5	Low Mini C	2	0.3	14	4.9	40	13.5
6	Low Mini NC	0	0.0	8	2.0	9	2.2
7	Micro	224	8.0	160	6.0	455	16.7
Total		298	29.8	286	91.1	672	148.5

Table 6 Feasible projects HPP by river basin

River basin	Total projects HPP (MW)	Excluded projects HPP (MW)	Non feasible projects HPP (MW)	Feasible projects HPP (MW)
Culiacán	116.6	10.8	76.0	29.8
Nautla	186.7	43.5	52.0	91.1
Tecolutla	296.7	76.5	71.7	148.5

Conclusions

Through this effort technology has been adapted and developed to evaluate in a systematic and exhaustive manner the hydro power potential of small, mini and micro projects without a reservoir.

The basic hydro power potential as well as that of optimized projects has been successfully evaluated for three pilot river basins.

A complete geodatabase has been elaborated for each river basin, allowing the communication of results.

The application of distributed hydrologic models improves the results with respect to the application of regional regression equations, because the first method generates multiyear daily runoff series at every confluence.

The possibility of identifying several optimized projects in every river reach represents advancement.

The experiences and technology described here are applicable with few adjustments to other river basins, both in Mexico and in other countries. This constitutes an opportunity towards the goal of sustainable water and energy resources management.

Recommendations

To evaluate the basic and optimized projects HPP of the entire country of Mexico.

To adapt and develop technology in order to complement the feasibility analysis of projects with HPP, considering economic variables.

To adapt and develop technology in order to evaluate the HPP, considering projects with reservoir.

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