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An Open Source Hydropower Feasibility Web Application for the Dominican Republic

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ABSTRACT

In countries with undeveloped waterpower potential, hydropower can be a cost-effective way to generate electricity while also utilizing the country’s renewal natural resources. The purpose of this paper is to present the design, development and testing of the Tethys HydroProspector web application developed to evaluate hydropower feasibility at a site from calculated Flow Duration Curves (FDCs) at specific sites. This project used data from the Instituto Nacional de Recursos Hidráulicos (INDHRI), the national water resource institute of the Dominican Republic. Using this data, FDC’s were calculated for four distinct watersheds in the Dominican Republic, and compared to previously developed curves. These curves were then used as input in the hydropower calculator. Using Darcy-Weisbach equations and hydraulic analysis, a feasibility tool was designed as a web application to calculate the hydropower potential of each of the four watersheds. This web application was able to calculate the hydropower potential and quickly analyze several distinct run-of-river hydropower options within the four watersheds.

Keywords
Flow duration curve, hydropower, Dominican Republic

1.0 Introduction

As a small island state, the Dominican Republic is heavily dependent on fossil fuel for energy generation, and has faced difficulties in the last 45 years in achieving reliable, efficient and sustainable energy production with negative consequences in socioeconomic development of the nation. The National Development Strategy (Estrategia Nacional de Desarrollo – END) (Ministerio de Economía, Planificación y Desarrollo, 2015) for the period 2010-2030, established the goal of diversifying energy generation placing emphasis on renewable energies. Information for the year 2015 had the following distribution of the National Interconnected Energy System: fuel (oil derived) 52%, natural gas 24%, carbon (coal) 12%, hydropower 9% wind 1.5%, bio-energy 1%, and solar 0.1% (Comisión Nacional de Energía, 2012).

Energy demand in the Dominican Republic was recorded at 1,516.5 kWhr per capita in 2013 (World Bank, 2015). As a comparison, the energy demand in the United States was recorded at 12,988.3 kWhr per capita in 2013. The population as of 2015 in the Dominican Republic is 9.44 million people, with 2.67 million households (United Nations, 2015). This means that the average energy use in the Dominican Republic is currently estimated to be approximately 5483 kWhr/household/year, or 2,001,295 kWhr/household/day. To put this in context, the average energy
use in the United States is 10,812 kWhr/household/year (U.S. Energy Information Administration, 2016).

While the installed capacity of hydropower was formerly about 15%, the lack of projects has reduced its contribution in recent years to only 9%. The goal defined in END by the National Energy Commission (Comision Nacional de Energia - CNE) is to follow a road map for renewable energy development (Agencia Internacional de Energias Renovables, 2016) that will increase hydropower to 16% by the year 2016, and to 20.6 by the year 2030, as reported by the International Renewable Energy Agency - IRENA. Several hydropower projects have been identified and profiled in the IRENA report in order to achieve this goal. Hydropower can provide cheap, clean, renewable electricity to communities in the Dominican Republic, and is a dependable form of energy that could consistently provide power to communities that regularly are without power. While some large hydropower plants exist in the Dominican Republic, many small hydropower plants could be built to bring power to small rural communities nearby that currently have limited power.

To estimate hydropower feasibility, a hydrologic analysis must be completed to determine the streamflow, the elevation change, and geographic characteristics of the site. These hydrologic studies require time, money, and engineering knowledge to accurately determine the streamflow, and the feasibility of constructing a small hydropower facility at the site. To address these issues, the Tethys Hydroprospector tool was developed as a web application on the Tethys platform. The purpose of this tool is to allow engineers to quickly and easily conduct a reconnaissance-level analysis, and determine whether the benefits of a hydropower facility at the specified location warrant a deeper and more costly investigation. The web application makes this analysis tool available through a thin client web browser so that it can be accessed and used by decision-makers who may not have a deep knowledge of the underlying modeling.

The power generation capacity of each hydropower plant is dependent on the streamflow, potential head, and overall economic resources available at each given site. To accurately determine the hydropower capability of a location, an accurate Flow Duration Curve (FDC) is necessary. FDCs have been traditionally applied in hydrology to hydroelectric planning, river and reservoir sedimentation studies, habitat suitability, and low-flow augmentation (Vogel & Fennessey, Flow-Duration Curves I: New interpretation and confidence intervals, 1994). New applications of FDCs include water allocation, waste load allocation, river and wetland inundation mapping, and the economic selection of a water-resource project (Vogel & Fennessey, 1995). An FDC is created by ordering the flows in a river and calculating what percentage of the time the river experiences a discharge or higher. The discharges of most interest in a hydropower application are those that can be reliable and generally are flows that would be equaled or exceeded 80% or 85% of the time. The 80th percentile represents a balance between the times of higher discharge when the storage is filling, and the times of flows lower than the 80th percentile (e.g. the 85th 73 percentile) when the outflow must be supplemented with water from reservoir storage to deliver sufficient hydropower. See Figure 1 for an example of flow duration curves. Historical data of streamflow is needed to create the FDC, but in the Dominican Republic there is limited and sporadic stream gauge data that can be used to evaluation the FDC, so many methods have been developed to obtain FDCs at ungauged sites (Booker & Snelder, 2012). One approach is to estimate the FDCs of the ungauged site using the FDCs of a nearby site, and then transform the known FDC by comparing the watershed properties of both the gaged and ungauged sites. GIS is then to determine and estimate the properties of the watershed that would influence streamflow characteristics the most. The use of tools in ArcGIS to search for exploitable hydropower sites has been demonstrated and tested in Switzerland where there are large number of hydroelectric schemes in operation in both mountainous and gently sloped areas (Félix & Dubas, 2010). GIS-based computational programs, like “hydropot”, have been applied to identify potential sites along the drainage network in a hydropower-developed basin in Brazil based on remote sensing and regional streamflow data (Larentis, Collischonn, Olivera, & Tucci, 2010).

The web application presented here builds on a previous work that developed a methodology to evaluate the potential of small hydroelectric power projects (SHEPs) in rural communities in the Dominican Republic (Buehler, 2011). This SHEP tool uses GIS to estimate the FDCs for the sites selected on a map, based on regression equations that are dependent on variables like watershed area, slope, and average precipitation.

2.0 Methods

2.1 Flow Duration Curves
2.1.1 Recorded Data

The most likely predictor of the future is a sound understanding of what has happened in the past, and the most reliable method for developing a FDC is to use daily observed discharge values that have been recorded for several years. The more observed values that have been recorded, the more likely the curve will be able to predict the future. The challenge faced in most cases in countries that are still developing their waterpower potential, such as the Dominican Republic, is the availability of recorded data in multiple locations. The discharge values were evaluated in general accordance with the Weibull method (Wanielista, Kersten, & Eaglin, 1997). That is, discharge values are sorted from highest to lowest and assigned a number (1, 2, 3…). This assigned number is then divided by the highest number (or the total number of observed values included in the analysis) plus one. These results, multiplied by one hundred, represent the percentages of the time the corresponding flows are met or exceeded. These values are plotted as shown in Figure 1. The FDC created from the recorded data is the basis used for comparison in this study. Both surrogate methods explored for this project failed to predict the FDC created using recorded data. However, current research is exploring improvements to these methods to improve accuracy. Specifically, there is potential that the curves created by the simulated data exhibit a consistent bias that may be adjusted so that the curves created by observed data are more accurately represented.

2.1.2 Simulated Data

This project used simulated ERA Interim data (Dee, et al., 2011) gathered from the Tethys platform Streamflow Prediction Tool (2016). This online application generates a surrogate 35-year time series of discharge data by modeling the retrospective meteorological data in a land surface model using a modeling method called RAPID that downscales ECMWF forecast results to individual stream reaches. Resulting data has the potential to substitute for observed data in locations where none have been recorded. The simulated data had fewer spikes in the flow, which led to a more uniform flow and a flatter curve along the higher percentiles. It would appear the simulated flow does not account for base flow very well and many erroneous zero values were removed before the FDC was used.

Figure 1. Comparison of Flow Duration Curve methods.
2.1.3 ArcGIS Tools

The second surrogate method explored for this project was a set of geoprocessing workflows developed in ArcGIS. The different tools use the watershed shapefile, the annual precipitation for the area, the soil types and land uses for the watershed, and the elevation shapefile to calculate discharge values for the watershed. The tools were only considered accurate for these higher values. Rather than producing a time series as data, the output of these tools was a table of discharge values for approximately every five percent. These values could then be directly plotted as an FDC.

Linear regression analysis was used to develop the water flow prediction equations in the SHEP tool (Buehler, 2011). INDRHI provided the hydrologic data for 13 different watersheds sites and also the basin properties such as drainage areas, average precipitation, curve numbers (CNs), and slopes. The flow prediction equations were estimated using ordinary least squares (OLS) analysis and manual numerical search for least square error (MNS). This resulted in sets of equations for flows with specific percentages of exceedance: 99, 95, 90, 85, 80, 75, 70, 60, 50, 40, 30, 20, 10, and 1. Figure 1 shows an example of the observed, 35-year simulated and GIS140 derived FDCs for a watershed in the Dominican Republic.

The results mirrored the slope of the curve from the recorded values more accurately than the results of the simulated data. However, the regression equations consistently underestimated the available discharges.

2.2 Hydropower

2.2.1 Data and Calculations

To calculate the hydropower potential at a site requires specific data. Elevation data, hydraulic infrastructure parameters, and watershed characteristics must all be calculated. Using the FDCs discussed above, and these specific parameters, the flow through a hydroelectric generator could then be determined.

Hydropower generation is dependent on the amount of head, or energy available at the turbine. The amount of head available is dependent on the initial energy, the friction loss in the pipe, and any losses that occur from bends, connections, or other geometry in the pipe. Using the Darcy-Weisbach equation, and Darcy-Weisbach roughness values for different types of pipes the friction losses can be calculated. The Darcy-Weisbach equation is shown below in Equation 1.

\[
\Delta h = L f_D \frac{V^2}{2g D}
\]

The Darcy-Weisbach equation calculates the head loss, or the change in energy in a pipe due to the length of the pipe, the friction coefficient, the overall velocity in the pipe and the diameter. As the length of the pipe increases, the friction losses increase as well. As the diameter in the pipe increases, the friction losses decrease. The largest factor in friction losses is the velocity in the pipe, which is related to the overall flow in the pipe. The faster the flow in the pipe, the more energy is lost due to friction. Head loss is also impacted by what are known as minor losses. Minor losses are the changes in energy caused by the hydraulic structures involved in the hydropower generation process. As water enters or exits a pipe, energy is lost as the water contracts or expands.

Similarly, as the water runs over pipe connections, or along bends, the water loses speed energy which decreases the overall head. These types of hydraulic structure losses are defined by the following equation.

\[
\Delta h = K \frac{V^2}{2g}
\]

The K is the minor loss coefficient for the specific hydraulic structure, and are distinct for entry, exits, connections and different types of bends (Young, Munson, Okiishi, & Huebsch, 2011).
After the different head losses from the friction loss and any minor losses were calculated, they were summed and subtracted from the initial elevation of the pipe. The remaining head, or energy was then used to calculate the power generated by the turbine. The power generated by the turbine is calculated using the universal power equation shown below.

\[ P = \frac{\gamma Q h \eta}{550} \]

The \( \gamma \) term represents the specific weight of water, which can be specified by the user depending on the temperature of the water. The \( \eta \) term represents the efficiency of the turbine. The head loss calculations and the power calculation were made using an Excel sheet that was later converted to a web application using Tethys (Swain, et al., 2016). Within the spreadsheet, different hydraulic characteristics of the penstock or pipe were calculated. The average velocity, Reynold's Number, laminar or turbulent flow, and a friction factor were determined based on the inputs the user specified. The efficiency of the turbine was also a user input, and was set at 53% by INDRHI for the Dominican Republic sites, to account for poor construction and turbine quality.

Each level of flow from the FDC was used as an input in the spreadsheet to generate the capacity at each level of flow. These were then graphed in Excel to create flow-capacity curves for each site. The 80th 189 percentile flow was used as an overall estimate of the capacity of each site.

The program was then used at each specific site given by INDRHI. Flow-capacity curves were then generated and used to analyze the most efficient hydropower option at each site. These are discussed in greater detail in the Results section of this report.

2.2.2 Automation

Once the hydropower calculator was created and tested in Excel, the tool was then reprogrammed as a web based application in the Tethys platform (Souffront & Jackson, 2016). The programs originally written in VBA were translated into Python, and using JavaScript were published to the Tethys platform as an independent application. The flow duration curves for each of the four watersheds were hardwired into the application but the hydraulic parameters (pipe material, length, elevation, diameter, etc.) were left as user inputs. The Hydro Power application can be seen below in Figure 2.

![Hydro Power application](image)

**Figure 2.** Hydropower calculator Tethys app.
The application is designed to function according to specific user inputs. The analysis is run on a specific watershed which calls the hardwired FDC’s previously calculated and stored on the Tethys server. The pipe material, elevation and other hydraulic parameters are specified, and then the analysis is run by clicking the ‘Calculate Capacity” button. The application then generates the table of capacities and the flow-capacity graph for the specific watershed and hydraulic parameters. An example of this is shown below in Figure 3. The page shows all the values for the flow duration curve and the associated capacity. The curve is also displayed on the page, which can be exported as an image or a PDF file.

3.0 Results

The software and application were tested by comparing the FDCs to the existing historical data provided by INDRHI. The FDCs calculated for the four different watersheds were then hardwired into the application, and the capacity for each flow was generated. The elevation, diameter of the pipe, and length of the pipe was then changed to generate a design for each watershed. Options included a concrete dam, with an elevation specified by the user, or a run-of-river option with the elevation calculated from the natural elevation of the site. The results from the web application are summarized below. The different options were entered into the web application, and changed to result in the most effective design for either a dam or a run-of-river hydropower facility.

3.1 Manabao

Option 1 for Manabao is a dam projected to be 28 meters high, with a storage capacity of 45 million cubic meters. This data was provided by INDRHI, and was then analyzed using the hydroelectric capacities calculated and input into the hydropower application. The flow-capacity curve for a dam at Manabao is shown below in Figure 5. From this flow-capacity curve, it can be determined that at the 80th 236 percentile flow of 1.40 cms, a dam of that height could produce approximately 200 kW or 6,400 households. The curve also shows that if a greater flow were available, a greater generating capacity would result.

3.2 Option 2: Run-of-River, Steel Pipe
Using Google Maps, the elevation changes of the Manabao site were analyzed and the point of greatest head was determined. These points are shown above in Figure 4. The point of entry for the water is labeled as "A", while the ending point - or the point of the powerhouse - is labeled as "B". Using these two points, a pipe length of 297 meters and an elevation head of 27 meters were determined. Using the flow-duration curve, a flow-capacity curve was produced for the run-of-river plant. A 1-meter pipe was used as the standard pipe diameter. This is shown in Figure 6.

Using this curve, it can be determined that using the same 80th 249 percentile flow of 1.40 250 cms, a run-of-river project would produce only 181.2 kW and serve 5,800 households. The maximum capacity of the run-of-river project is 313.1 kW, which results from the 50th percentile flow. The decreasing capacity for increasing flow is a factor of the overall head loss for the pipe. The friction losses in the pipe are dependent on the velocity of the water, and the diameter of the pipe. If the pipe diameter was increased, the capacity for the flow would increase with increased flow. For economic purposes, the pipe diameter was limited to a 1-meter pipe. The ability to quickly change the pipe diameter and view the different flow-capacity curves is an important benefit of the application.

The economic factors of both of these options must be considered before deciding a viable hydropower plant. A run-of-river project is cheaper to construct, utilizes less materials, and usually takes less time to construct than a dam. A dam has a longer design life, has the added benefit of storing water, and power generation can be better controlled through a dam. These factors should be considered, along with the generation capacity of the site when choosing a hydropower option.

For Manabao, the highest capacity for this run-of-river option of 313.1 kW is greater than the 80th percentile capacity of the dam. However, this capacity is for the 50th percentile flow. To generate more power at the 80th percentile, the pipe diameter must be larger, which increases construction costs. To put these power capacities into context, and assuming that the generator operated 24 hours a day, the 181.2 kW generated from the run-of-river generator with a 1-meter pipe would provide electricity for 5,800 households. The 200 kW generated from a dam would provide electricity for 6400 households. This 10% increase in capacity should be weighed against the difference in economic value to determine the best option for the site.

Economic estimates for a run-of-river project compared to a dam project show that construction costs are much lower for a run-of-river. Cost estimates are roughly based on labor costs, mate-
Figure 5. Flow-capacity curve for Manabao dam

Figure 6. Flow-capacity curve for run-of-river project at Manabao.
rivial costs, and a general projection of the potential revenue generated. A more accurate cost analysis would include factors such as initial costs, inflation rates, and interest rates at the site.

3.3 Salto de Jimenoa

For the Salto de Jimenoa site, only run-of-river options were considered. Using GIS data from INDRHI, the elevation head was analyzed using elevation data collected from Google Maps. The points for the run-of-project are shown in Figure 7.

The point of entry for the water is labeled as “A” and the powerhouse location is labeled as “B”. Two options were considered with a 1-meter diameter pipe and a 2-meter diameter pipe, respectively. For both options, a 739-meter commercial steel pipe with an elevation head of 135 meters was used. The flow-capacity curves for both options are shown below in Figure 8.

This flow-capacity curve shows the differences between a 1-meter pipe and a 2-meter pipe. These curves show the impact that pipe diameter has on generation capacity. The larger pipe allows the same flow to generate more power, because the head loss is not as large in the larger pipe. The different capacities are summarized below.

3.3.1 Option 1: Run-of-River 1 meter

For the 1-meter option, the 80th percentile flow results in a capacity of 1838 kW. The maximum capacity is the result of the 50th percentile flow, with a maximum capacity of 2450 kW.

3.3.2 Option 2: Run-of-River 2 meter

For the 2-meter option, the 80th percentile flow results in a capacity of 2016 kW. The maximum capacity is the result of the 20th percentile flow, with a maximum of 5348 kW. The increase in capacity is due to the larger pipe, but the benefits of the larger pipe may be offset by the economic costs.

3.6 Summary

As discussed earlier, the pipe diameter has a significant impact on the generation capacity. The 1-meter pipe 80th percentile flow resulted in a capacity of 1838 kW, while the 2-meter pipe resulted in a capacity of 2016 kW. To put this in perspective, and again assuming the generator operated 24 hours a day, the 1-meter option could provide power for 58,850 households while the 2-meter option could provide power for 64,550 households. This 10% increase in power could serve more households, however the economic factors of construction must also be considered.

Assuming steel costs at $300 USD/ton (Quandl, 2016), the 1-meter pipe would cost $3,000, and the 2-meter pipe would cost $6,000. This difference in cost would also extend to labor costs, installation costs, and any service costs. In conclusion, even though the 2-meter pipe would serve more households, the economic costs and benefits must be considered before implementing either of these options.

Only run-of-river options were considered at Salto Jimenoa due to the difficulty in implementing a dam at the site. The construction costs of such a dam would outweigh the generation capacity, and the benefits of water storage. Construction of a dam at the site would allow a certain level of power to be reliably generated, as well as allow water to be stored in the area. However, the site is difficult to access, and construction costs and trans-
Transportation costs would also add to the economic costs, and would make building a dam at the site unfeasible.

Several factors to consider in the analysis of these sites include the quality of the DEM file used and the existing water use in the watershed. The DEM data used to calculate the elevations of the run-of-river, as well as the quantity of water to be stored by the dam was provided by INDRHI. However, this DEM data does not account for any existing water uses in the watershed. For more accurate results, the water use within the watershed should be calculated both to provide an accurate FDC, but to also ensure that a hydropower project would not negatively impact the existing water use. As more data is added, the flow-duration curve equations can then be calibrated to result in a more accurate value of flow.

4.0 Conclusion

The Hydro Power web application allows engineers and designers to quickly make rough estimates of hydropower capacity based on a flow duration curve, elevation data, and other geographical parameters. Using a flow duration curve for a specific site allows the hydropower facility to be designed for any level of flow, and gives engineers a preliminary idea of how much flow to expect, and how large of a hydropower facility is most effective for the watershed.

The web application for the hydropower calculator makes it easier for communities looking to develop small hydropower facilities to quickly create a preliminary design, and adjust that design to meet the needs of the specific community. Parameters such as head loss, elevation change and pipe diameter are easily adjusted. Flow capacity curves can be produced to compare between options, and facilitate the sharing of information during the design process.

Future research in the development of flow duration curves includes developing web applications that will use the precipitation, slope and curve number or soil properties to develop flow duration curves. Future research into historical data and correlations between precipitation and runoff in specific areas will also help develop better applications that can calculate the flow duration curve effectively.
5.0 References


