Association of Cuban-American Engineers
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Cuban-American Association of Civil Engineers

2019 CUBA INFRASTRUCTURE SCHOLARSHIP COMPETITION

Participation Form

Team Name:

JJRC

University:

Brigham Young University

Faculty Advisor:

Dr. Rollin H. Hotchkiss

Does the team already have a C-AACE/ACE Member Industry Advisor? **Yes** ☒ **No** ☐

If you selected "Yes" above, please enter your C-AACE/ACE Member Industry Advisor's name in the box below:

Erik Sibila

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Project Title:

Streamflow Prediction in Cuba

Project Abstract (*150 words max***):**

The ability to predict streamflow is pivotal to a developing Cuba. Competing water demands for agriculture, drinking water and municipal and industrial use plus the ability to reduce flooding all make it essential to know of upcoming streamflow rates. To help countries better manage their water resources, BYU has developed a web-based streamflow prediction tool. It processes a global runoff grid, mapping the water into streams to produce a 15-day streamflow forecast. This tool has been implemented in various locations across the world and can be expanded to include Cuba.

The data produced from this tool has various applications, such as flood forecasting and mapping, irrigation control, and reservoir management. Some of these applications have been implemented in the Dominican Republic, which can be used as a case study to show the potential for Cuba.

Team Member Contributions

Chris Edwards – Team Leader

- Set up the Streamflow Prediction Tool for Cuba
- Wrote sections on Hydrology, Streamflow Prediction Tool, Proposal and Recommendations

Riley Hales

- Principal writer, including sections on Streamflow Prediction Tool, Tethys, Applications in other countries, and Proposal

Jacob Lewis

- Researched existing condition of Cuba's hydrologic system
- Wrote section on the current state of Cuba

Other Contributions

Dr. Rollin Hotchkiss – Faculty Mentor

- Helped with obtaining relevant data, hydrology concepts, paper organization, and revision.

Erik Sibila – C-AACE/ACE Member Industry Advisor

- Revision and paper organization

Dr. Jim Nelson – BYU Civil Engineering Professor

- Helped with Streamflow Prediction Tool and Tethys information.

Corey Krewson – BYU Civil Engineering Master's Student

- Helped set up Streamflow Prediction Tool for Cuba.

Hart Henrichsen – BYU Civil Engineering Undergraduate Student

- Helped with preprocessing files for the Streamflow Prediction Tool in Cuba.

Predicting Streamflow in Cuba for Water Resource Management

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Brigham Young University

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Abstract

The appropriate management of water is vital to sustaining people, countries, and economies. Traditional methods for water forecasting, either by hand or with computer models, can be difficult to use where money, personnel, and infrastructure are insufficient. Technological advances including open source software and environmental and climate data from remote sensing equipment such as satellites facilitate wider access to tools that overcome these barriers. Tethys and the Streamflow Prediction Tool (SFPT), developed at Brigham Young University (BYU) by a team of civil engineers, implement these technologies in ways that are impactful to the countries that need them most. In the Dominican Republic, Tethys and the SFPT have successfully provided forecast data and web applications used by government officials in planning and flood preparation scenarios. They have been globally tested and refined before being adopted by international organizations including NASA, the United Nations, the World Bank, and the European Centre for Medium-Range Weather Forecasts (ECMWF). These tools can help Cuba further develop its water resource management capabilities.

Keywords: Streamflow Forecasting, Web Application, Hydrologic Modeling

Introduction

Water is a basic requirement of life on Earth. Appropriate management of water quantity and quality affects nearly every aspect of day-to-day life. The ability to appropriately manage water is pivotal to a developing Cuba. Competing water demands, including agriculture, drinking water, municipal needs and industrial needs, will continue to grow with time. Floods can cause extensive damage and affect the lives of many people. For example, in May 2018 tropical storm Alberto caused extensive flooding in the Zaza and Agabama rivers, leading to the evacuation of 3000 people (Pérez, 2018). The urgency in water management is only compounded by the looming risks of droughts or floods if appropriate management techniques are not in place.

These issues are not unique to Cuba. For example, billions of dollars of property damage and thousands of lives are lost annually from flooding (Snow, 2016). Floods and other water-related disasters account for 70 per cent of all deaths related to natural disasters (United Nations, 2018). Additionally, the world population projections continually outpace current global trends in water storage and sanitation capacity. Water scarcity affects more than 40 per cent of the global population and is projected to rise. Over 1.7 billion people are currently living in river basins where water use exceeds recharge (United Nations, 2018). In response to a global need for sustainability and responsible preparation, a 2015 United Nations assembly developed seventeen Sustainable Development Goals (SDG). These goals include plans to reach acceptable sustainable growth or infrastructure on topics such as health, economics, basic human rights, food, water, and energy. Of the seventeen SDG, at least ten of them directly depend on water resources to be achieved (United Nations, 2018). Thus, it is imperative that improvements be made in water resource management strategies in order to maintain a sustainable world. The technologies discussed in this paper are aligned with these goals.

The purpose of this paper is to show how adopting the latest hydrologic methods, including streamflow prediction, will enable Cuba to better manage their water and thus save lives, money, and time. The paper will first discuss the current state of water management in Cuba. Then, the traditional methods of hydrology and hydraulics will be compared to the newest methods and technologies made possible technological expansions. Next, the SFPT and Tethys will be discussed as specific methods for improving Cuba's ability to sustainably manage their water infrastructure. Examples from the nearby Dominican Republic will be presented. Finally, a proposal with specific implementation recommendations will be made.

Current State of Water in Cuba

As an island nation, Cuba has to carefully monitor and protect its limited water resource. In 2016, the Instituto Nacional de Recursos Hidráulicos (INRH) released a document called *Principales Indicadores y Datos de Infraestructura Hidrálica* (Fernández, 2018) that outlined the current state of hydraulic infrastructure in the country. According to the INRH, Cuba uses approximately 3.88 billion cubic meters of surface freshwater per year. This surface water, found in reservoirs, streams and rivers, accounts for 75% of the freshwater on the island. This water is used for drinking supply, agriculture, manufacturing, and other industries (Oficina Nacional de Estadística e Información, 2018). Because of its relatively high population and small land area, it is vitally important that Cuba closely monitor this system to ensure that reservoirs and rivers are being sufficiently recharged. A vast system of nearly 2000 rainfall gauges measures the amount of precipitation that the island receives. These gauges are monitored by over 1000 volunteers (Fernández, 2018). Wells are used to monitor the levels of subterranean aquifers. River flows are also monitored, and surface elevations are taken regularly. These measurements are also taken by hand and sent to various government agencies. Reservoir levels are checked regularly, as well as reservoir water quality. Using this system, INRH and other agencies manage water distribution to the best of their ability. However, as stated, the current system relies heavily on volunteers to take measurements, which allows for the possibility of human error.

Cuba also uses these measurements in its domestic disaster management (Fernández, 2018). As a tropical island, Cuba regularly suffers from hurricanes, tropical storms, and floods. However, many organizations have praised Cuba's emergency preparedness and have used its disaster management model for other countries. Cuba is able to use their hydrologic network to obtain water level data and safely evacuate cities and towns before major flooding occurs. By issuing early advisories 96 hours in advance, citizens can begin to prepare for said evacuations. By increasing the accuracy of water level data, these advisories can become more focused and assist the government in further preventing the loss of life and property in natural disasters.

Advances in Hydrology

Flow routing is the process of predicting how water flow rates over land or in a channel change with time. It is done using various methods including Kinematic Wave, the Inventory Equation, and the Muskingum Method. Traditionally, these methods have been performed on a local scale. The engineer or hydrologist would use rain gauge measurements to interpolate the precipitation over a single watershed. Then, using equations to predict runoff from rainfall, they would appropriately calibrate flow routing models and choose values for parameters (e.g. the Muskingum parameters K, storage time constant, and c (or x), the weighting factor). Using these values, they could predict the streamflow at points of interest.

With an increase in the quality and availability of satellite data, there has been a shift toward hydrology on a global scale. Instead of modelling a single watershed at a time, the hydrology of whole countries and continents can be modeled. Elevation, terrain, land use, soil parameters, and weather patterns are examples of data that can be measured through satellites. For example, the SFPT is based on a land surface model produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Rainfall, infiltration, and other land-surface characteristics are combined to generate a runoff forecast, represented on a global grid.

This satellite-generated runoff can be routed into streams, as described above. In the case of the SFPT a routing model known as the Routing Application for Parallel computation of Discharge (RAPID) is used. RAPID is based on a matrix version of the Muskingum Method and calculates a flowrate for each stream segment. To run RAPID, a stream network and three additional datasets are needed. The first is river connectivity information, which includes each river ID, the downstream River ID, the number of upstream rivers, and the ID for each upstream river. Next the inflow of water into the network is needed; this is where the gridded runoff forecast mentioned above is used. Finally, RAPID requires Muskingum parameters for each stream reach. The final product of the model is a flowrate over time at the mouth of each stream in the network of interest.

The use of satellite data and global models reduces the time and resources required to predict runoff using hydrologic models. While there still will be circumstances that require precise local models, global models make hydrologic information more accessible. This is especially important in areas where limited historical data and limitations in technology and resources make it difficult to build and maintain hydrologic models. If engineers and scientists in these areas can access the results of a global model, they can spend more of their time and money focusing on decision making and planning.

The Streamflow Prediction Tool and Tethys

The Streamflow Prediction Tool (SFPT) is a resource for forecasting streamflow for any river in the world. It was developed at Brigham Young University over the last few years with funding and collaboration with the United Nations GEOGLOWS (Group on Earth Observations GLObal Water Sustainability) project and the NASA SERVIR team. Both groups promote using remote sensing equipment like satellites as well as stream or precipitation gauges (or "Earth Observations") to help use water resources more sustainably across the globe. The tool relies on preprocessing files created using GIS tools, the ECMWF runoff forecast, and the RAPID routing model.

The files necessary for the model are created using GIS tools. The first step is to generate the stream network from a Digital Elevation Model (DEM). The stream network for Cuba is shown in Figure 1. Next, the river connectivity information is determined and stored in a csv file. This information, for each stream, contains the River ID, the Downstream River ID, the number of Upstream Rivers, and the ID for each Upstream River. The Muskingum parameters for routing the water downstream are calculated for each stream and stored in csv files. Once all of the files are created, the final step is to route the overland runoff to streams using the RAPID method described earlier.

The computed flow rates are shown as a hydrograph for each stream. The ECMWF runoff is an ensemble forecast, meaning the model produces 51 different forecasts for each day, known all together as an ensemble. The hydrograph produced by the SFPT displays the mean, the standard deviation, and the maximum and minimum flows, as shown in **Error! Reference source not found.**Figure 2.

Figure 1: Cuba stream network delineation.

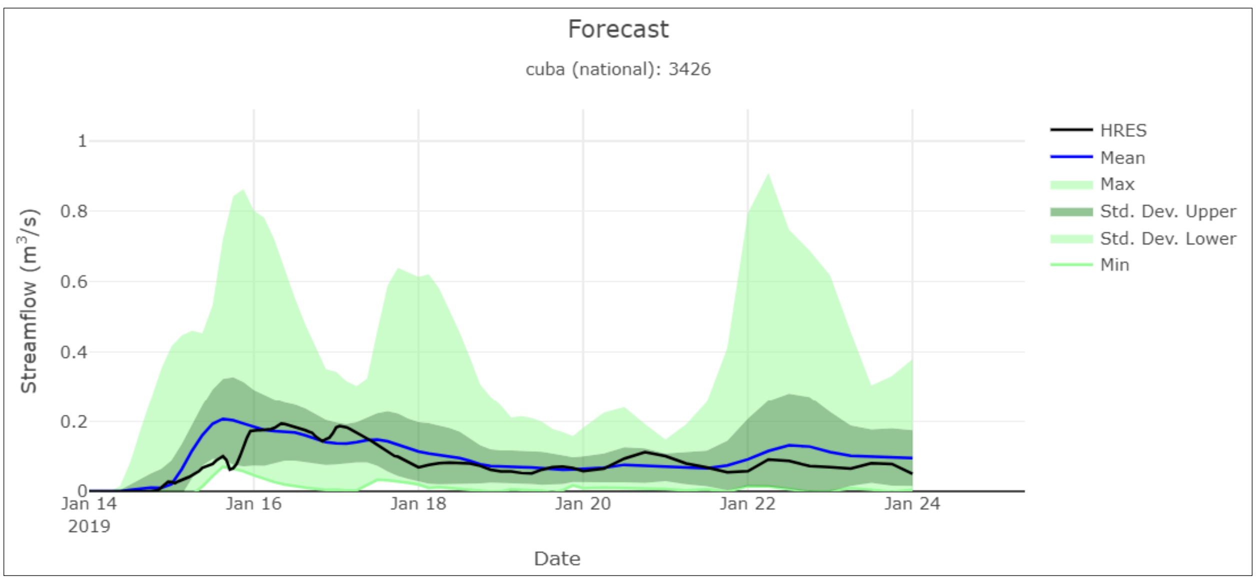

Figure 2: Example forecast hydrograph for a stream in Cuba.

To add context to the forecasted flowrates, a historical simulation is created. ECMWF has used historical meteorological data to produce 35 years of simulated runoff grids, known as the ERA-Interim dataset. For each day from 1980 -2014, a separate simulated runoff grid is produced. These grids are processed using RAPID, like the forecasted runoff grids, which generates a simulated 35-year time series of flow at each stream (see Figure 3). From this record, return periods and daily averages are computed. The context provided by this historical simulation can be a valuable resource where stream monitoring stations have not been established or have ceased functionality.

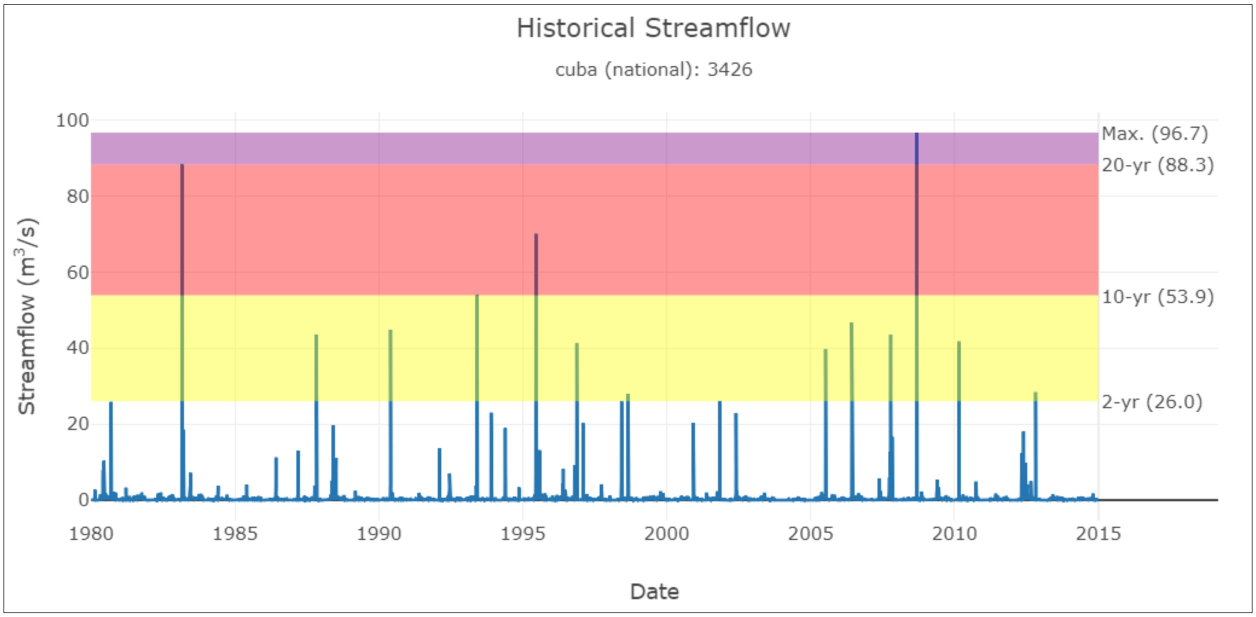

Figure 3: Historically simulated streamflow for a stream in Cuba.

The ECMWF forecasts have been widely tested, and improvements are consistently being made to increase accuracy (Perez, 2016). In areas with in-situ measurements, the forecast performance at a local scale can be validated. To understand exactly how well the SFPT works in Cuba, it would be helpful to compare the forecasts with local stream gauge data.

Accessing the SFPT

A web application for the SFPT is available that provides a graphical interface for viewing the watersheds and model results. The main page of the application displays the stream network, as shown in Figure 4. The different colored triangles represent streams with a forecast in a 2-, 10-, or 20-year return period. Clicking on a stream segment brings up a menu that contains the forecast hydrograph, historical simulation, daily averages (see Figure 5), and options for data download. Free access to the tool is available at tethys.byu.edu where there are also links to find the original source code and installation support.

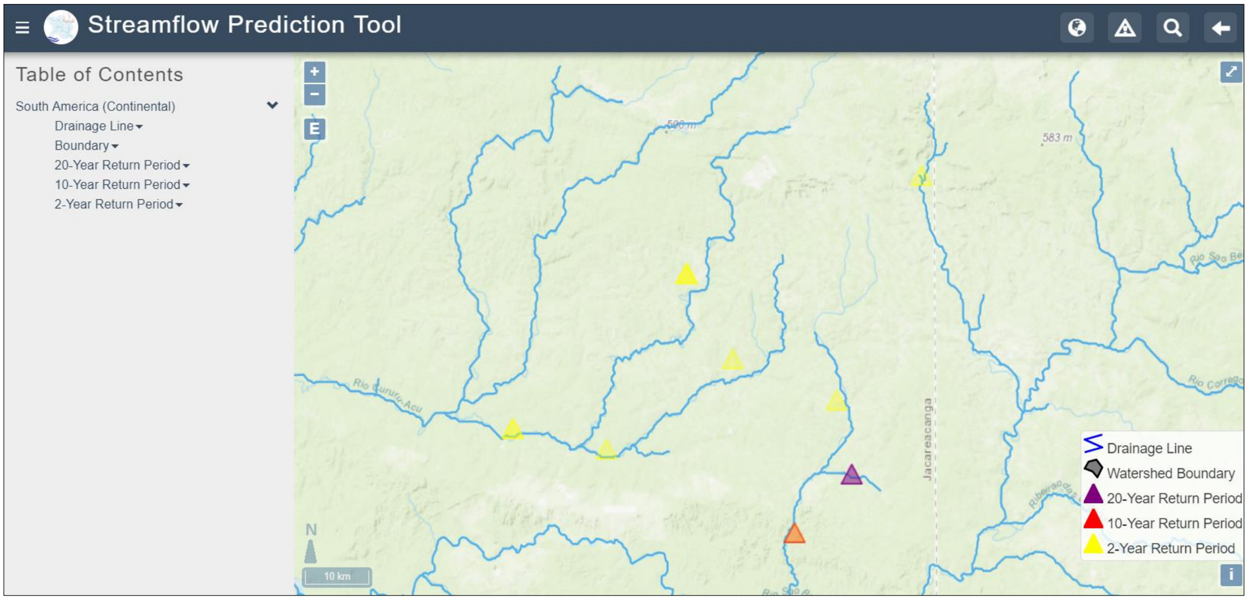

Figure 4: Streamflow Prediction Tool graphical interface for South America.

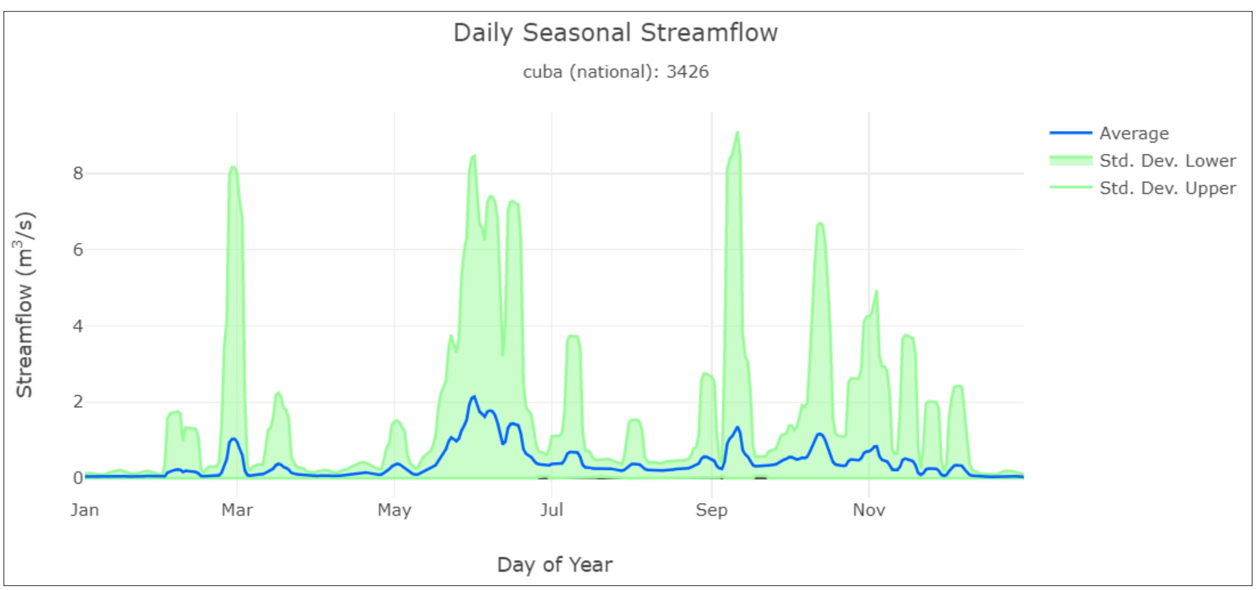

Figure 5: Example daily average plot for a stream in Cuba.

The application was developed using a software package, called Tethys, developed at BYU. Tethys was built by civil engineers seeking to lower the technical barriers that inhibit engineers from showing the results of their computations and analysis (Alcantara, 2017). Since its inception, the software, especially the SFPT, has been adopted by engineers with NASA SERVIR, the UN GEOGLOWS teams, and the ECMWF. The source code for the application, is available online and is free to use. Tethys enables quick and standardized methods of sharing data. Importantly, this makes the SFPT more valuable because the forecast data are also available to other programs, websites, and people. The Tethys platform facilitates this sharing with a programmatic data access procedure known as an application programming interface, or API. Tethys, including the graphical and API access to data from the SFPT, enables stakeholders anywhere to use global models and resources to enhance their local water management and analysis capabilities.

Within weeks, the SFPT will move from being operated at research lab to ECMWF headquarters. Their super-computing infrastructure will improve the speed and reliability of access to the tool. The DEM and historical data preprocessing work to get SFPT predictions on Cuban streams has already been prepared by this team and made available to ECMWF.

Applications of Tethys and SFPT in the Dominican Republic

The national water agency in the nearby Dominican Republic, El Instituto Nacional de Recursos Hidráulicos (INDRHI), has already adopted the use of streamflow prediction and Tethys. Like Cuba and many island nations, the Dominican Republic relies heavily on streams and reservoirs for their fresh water. Each week, representatives from INDRHI and other branches of government meet to allocate available water to the national demands. At these meetings, they make decisions for water use based on the current water levels and forecasted changes based on the SFPT and derivative applications. One such application is a Reservoir Management application (Figure 6, shown below). It was developed by teams of Civil Engineering students emphasizing in a water resources at Brigham Young University with minimal coding experience. The app shows historical water usage and allows for simulation of future water usage by using the streamflow estimates of the SFPT and the estimates of water usage. This application generates reports showing results of the simulations. These reports are taken to the weekly meetings where they can be used as a reference by government officials making water management decisions.

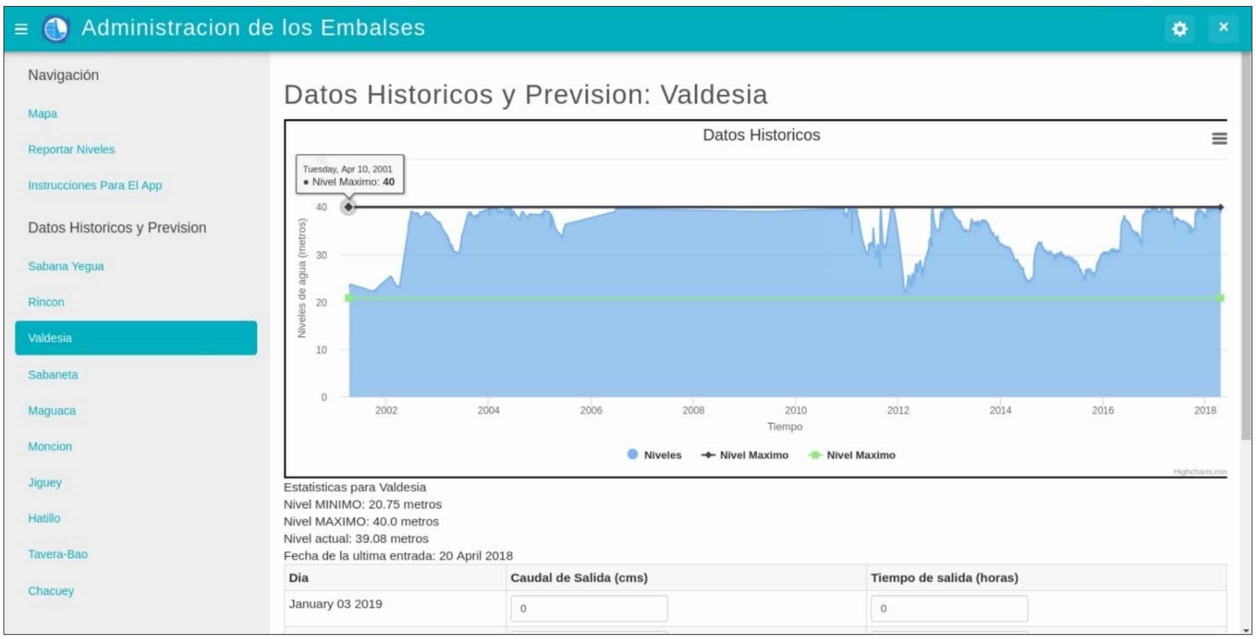

Figure 6: Simulation of the Valdesia Reservoir in the Reservoir Management app

Additionally, BYU is currently working in collaboration with INDRHI of the Dominican Republic to develop Tethys applications that enhance their local flood warning and mapping capabilities. For flood mapping, the application will use forecast streamflow data from the SFPT and its statistical analysis of historical data to identify watersheds likely to experience flooding.

This app produces maps of the areas forecasted to be inundated, as shown in Figure 7. The results are graphically animated over time and show a statistical analysis of their probability and risk. One application of the maps and statistical analysis is to identify the areas most likely to flood and the forecasted flood depths. Emergency response teams can prepare the at-risk regions and provide possible evacuation notices as many as 15 days in advance.

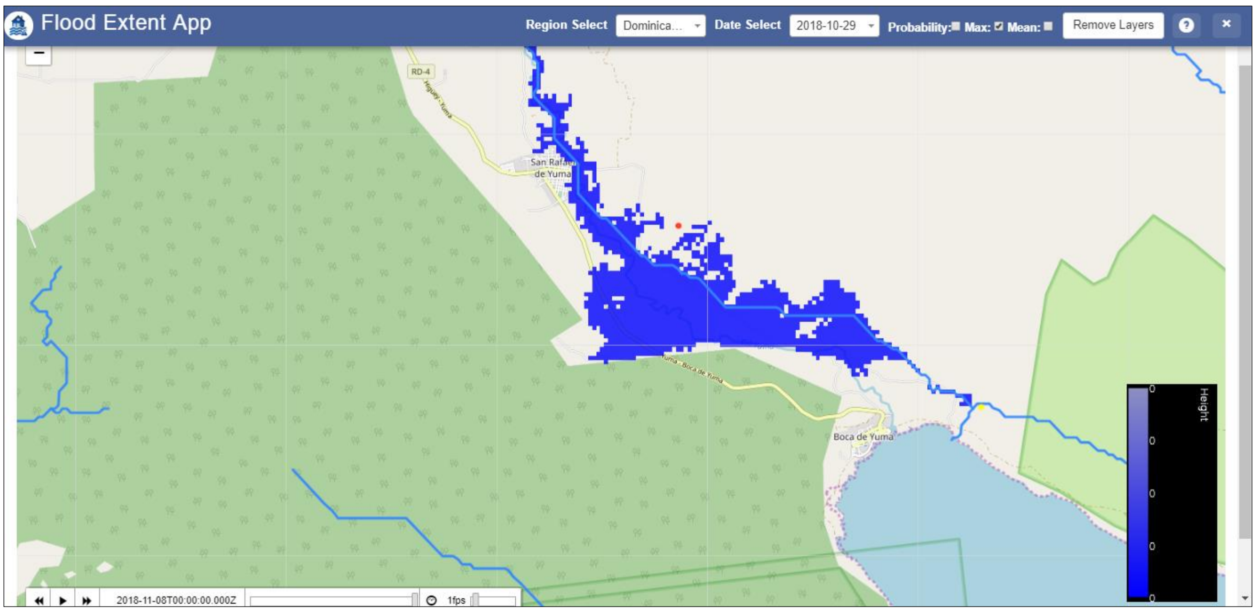

Figure 7: Example flood extent map in the Dominican Republic.

Another application used by INDRHI helps agricultural decision makers meet the water needs of farms. This app works in conjunction with both the SFPT and the Reservoir Management Tethys apps. The application performs hydrologic computations of the water needs of farms based on the type and amount of crop being grown. Then, using forecasted stream flows and reservoir information, the app determines if there is enough water to meet agricultural demand and helps the user simulate how to regulate flow from the reservoirs to best meet that need.

Using Tethys and the SFPT, the Dominican Republic enhanced its water management capabilities leading to a more sustainable water use nation-wide. These applications have enabled a small, island nation, similar to Cuba, to expand their water resources infrastructure with minimal additional work. Because the source code to Tethys and these applications is publicly available, Cuba has years of work and many applications ready to be applied to their infrastructure and water needs.

Proposal and Recommendations

We recommend that Cuban officials, engineers, and scientists consider adopting the use of the SFPT and Tethys to enhance their current water management and forecasting capabilities. These applications can help manage water usage and prepare for flood events. To accomplish this goal, they should consider expanding their stream monitoring network and connect with the researchers at BYU and their partners. Both recommendations are briefly discussed.

Expansion of Stream Monitoring Network

Expanding the stream gauge network will better allow Cuba to take advantage of the exciting benefits of global streamflow predictions. The results of the SFPT can be compared to local stream gauges to see how the forecasts perform locally. As necessary, forecasts and computer models can be tailored to better represent the local conditions that affect runoff. The gauges are additionally beneficial for other hydrologic monitoring purposes. Stations for measuring streamflow can also measure environmental variables such as temperature and dissolved oxygen content. These stations could monitor sediment transport for rivers that flow into reservoirs.

Research of the limited publicly available data about the Cuban stream monitoring infrastructure suggests that it is disorganized and does not cover the entire country. With further information on the actual state of the Cuban stream network, our team can consult on appropriate ways to improve the existing stream gauges. An appropriately improved stream monitoring system could be consistently available and at minimum cover the major rivers in the country. This will likely be the only monetary cost related to implementing the SFPT and Tethys app paradigm for Cuban needs.

Collaboration with BYU and International Communities

We recommend working in collaboration with BYU and in turn their partners at NASA, the UN, and the World Bank. Appropriate water resource leaders in Cuba can contact the BYU Hydroinformatics lab by email at *worldwater@byu.edu* and visit the website *worldwater.byu.edu* for more information on their global modeling mission. The professors and students there are principally responsible for the creation of Tethys and the SFPT. They are eager to apply their tools to countries in need. They can connect Cuban officials with the broader international community involved in this project and teams of student engineers eager to work alongside Cuban teams of engineers. The engineers and researchers with these groups have libraries of instructions and example applications, and a community of supporters. The work in the Dominican Republic is readily transferable to Cuba given the similarities of location, climate, and needs. Appropriate personnel can be trained and work in collaboration with this community to apply existing tools and develop additional applications to fulfill specific needs of the Cuban government and people. BYU and the international community are eager to form new, mutually-beneficial partnerships that positively impact the world.

Economic Impact

Ultimately, using the SFPT can help Cuba save precious resources including time, money, and people. While improving the stream gauge network for validation purposes would increase costs, the benefits of implementation are far reaching. Without the need to create a local streamflow forecasting model, Cuban officials and engineers can instead focus their time and money on developing solutions to water resource challenges. Additionally, the web-application format allows for efficient data sharing. Better irrigation practices can lead to more production. Improved residential and industrial water management can lead to an increased quality of life. Better flood preparation can save lives and infrastructure. Ultimately, the SFPT serves as a tool to help Cuba prepare for a more sustainable future.

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