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Developing Low-Cost Inundation Maps for Dam Failures: Modeling and Analysis of a Potential Dam Failure for the Péligre Dam in Haiti

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1.0 Introduction

A dam by definition influences risk. It can reduce the risk of routine flooding downstream by managing water capacity in its reservoir. However, Dam also introduces significant risk to human lives, property, and the environment if they fail (Haddow, Bullock, & Coppola, 2008, 51).

Understanding the risk that a dam introduces is a critical component of mitigating it (Federal Regulatory Commission, 2016, 1-1). An inundation map is a crucial component to understand the impact of flooding that will occur in dam emergencies, including failures. No dam is fail-proof and the only feasible way to forecast the inundation caused by a dam failure is through computer simulation that produces inundation maps (Escuder-Bueno, Mazzaà, Morales-Torres, & Castillo-Rodríguez, 2016, 321).

An inundation map that provides water depths, velocity, and time of arrival is instrumental in developing evacuation plans, communicating risk, and making decisions for locations of temporary settlement and residential development. However, the problem is that developing these maps can be an expensive process with many technical requirements. The complexity and cost of developing inundation maps often means they are not prioritized and communities are left with unmitigated risks.

To specifically address the problem of dams and communities with no inundation maps, and therefore have unknown and unmitigated risks, the United States federal government has developed the DSS-WISE Lite System. The system is available free of charge and allows any emergency planning authority to produce high quality inundation maps for a scenario of their choosing (Altinakar et al. 2017). This system has been quite successful in increasing the percentage of dams across the United States that have created inundation maps and developed Emergency Action Plans (Jachimowicz, 2018, 7). There is no such system, however, available for developing countries where the need is even greater due to their vulnerabilities and lack of emergency management capabilities. Because the U.S. and other countries have invested significant resources and created a body of knowledge in mitigating dam risks, these investments and associated knowledge can and should be transferred to the developing world.

The purpose of this paper is to document a study that used an innovative process for producing inundation maps using the Péligre Dam in Haiti as a demonstration. The demonstration not only produces inundation maps for a specific area in Haiti, but it also demonstrates the potential for the production of low-cost yet accurate inundation maps for both dam and levee emergencies that can be applied in other developing countries. Here, we detail the team's innovative process that can be replicated elsewhere, as well as the specific results for a simulated dam failure at the Péligre Dam in Haiti.

The significance of this effort lies in the fact that the analysis was done remotely, requiring no field work, at low cost and provides strategic and tactical information that can be used in the emergency planning process. On a strategic level, the analysis provides an overall fatality and damage estimate which can serve to garner the attention of donors, decision makers, and policy makers. On a tactical level, this analysis provides the ability to provide forecasts of flooding for development of evacuation maps and can inform an individual household on their flood risk.

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2.0 Background

Haiti ranks 168th out of 189 countries on the United Nations 2018 Human Development Index (United Nations Development Programme, 2018). It is a developing country with weak physical infrastructure and low governmental capacity. Haiti is also disaster prone as evidenced by the devastating 2010 earthquake which was a national catastrophe, killing upwards of an estimated 220,000 people (World Bank, 2010, 5).

The Péligre Dam was opened in 1963 and is a large concrete gravity dam. It was built to provide flood control and power generation, with a power plant capable of generating 51 MW. There are two significant operational issues related to the Péligre Dam. The first is that the dam generates only an estimated 10% of the power it is capable of generating due to the lack of a matched distribution system. The second is that an extreme case of siltation has left the reservoir at only 40% of its original capacity (GLM Engineering, 2016, 9).

Figure 1: Downstream View of Péligre Dam (Source Haitiphotos.com)

The Artibonite river which starts from Lake Péligre in the central highlands of Haiti provides irrigation to fertilize the soil of one of Haiti's most productive agricultural areas. The construction of the Péligre Dam not only strongly impacted agriculture but also affected the movement of population as 3,000 ha of land were flooded. Additionally, the density of the population was 1 person per ha prior to the construction of the dam and 15 people per ha 20 years after the construction. (Howard, 1997, 7-8).

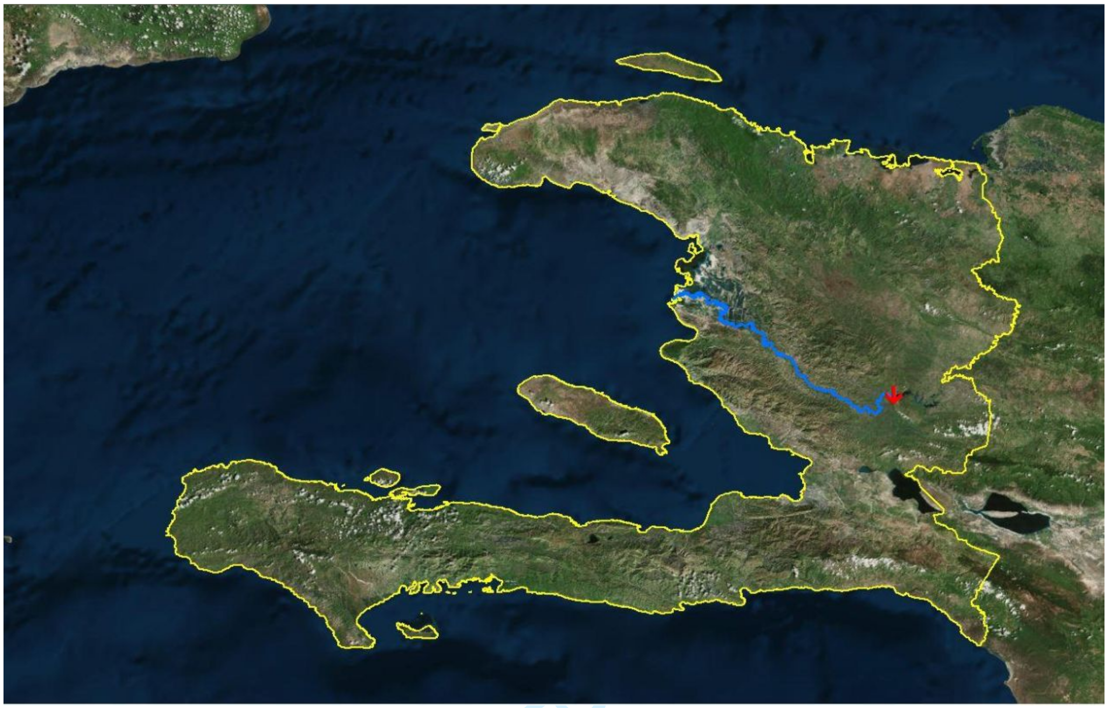

Figure 2: Location of Péligre Dam and Artibonite River

Though an American Society of Civil Engineers post-earthquake infrastructure analysis report claims that they received second-hand evidence that the dam sustained no damage from the 2010 magnitude 7.0 M_w earthquake, our research team was unable to find evidence of any structural analysis of the dam at any point after the Earthquake (American Society of Civil Engineers, 2012, 35).

Haiti's civil infrastructure is relatively weak overall, but does include a disaster response authority at both the regional and national level (Fordyce, Sadiq, and Chikoto, 2012, 8). However, our research team was unable to find evidence that any authority has conducted any analysis of a potential dam failure or any emergency planning whatsoever in Haiti. Additionally, there is little evidence of any research considering the effect of a failure at the Péligre Dam on the surrounding environment.

3.0 Methodology

This study used innovative process in the development of inundation maps. The overall process has four steps as described by the below figure:

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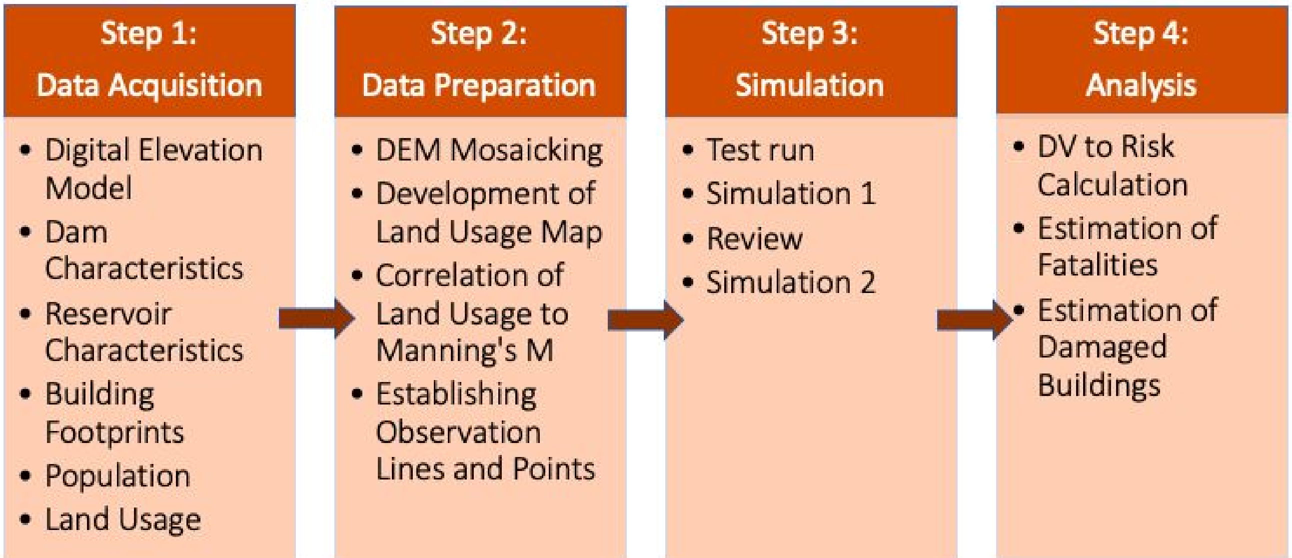

3.1 Data Acquisition

An objective and constraint of this study was to complete it without any field work. Thus the biggest challenge was finding a high resolution Digital Elevation Model that could be used for the simulation. A general search was undertaken with an aim of finding a dataset that covered the area of the dam, reservoir, and watershed that had around a 1/3 arc-second resolution. The dataset was found on a public site, Haitidata.org. It is an open-source platform funded by the World Bank and managed by the Haitian government. Most importantly it contains a dataset from a Lidar sensor on an aircraft that covers the entire country at 1.5-meter resolution (World Bank, n.d.).

Other required data included ram & reservoir characteristics which were found on several publicly available reports but the most credible was the *Topo-Bathymetric and Geophysical Study of Sediments, Péligre Reservoir, Haiti* conducted in 2016 for operational and maintenance requirements of the dam. A land use map is a requirement for the simulation, specifically for the purpose of correlating a mannings m cooeficiant. Building footprints and population data was acquired from the open street maps platform. Lastly, imagery from google earth was used to establish locations of bridges and observations points and lines. Table 1(below) provides a summary of the required data and notes on their acquisition and preparation.

3.2 Data Preparation

Significant data preparation must take place in order for the simulation to be successful. two of the most significant data sets needing preparation, lidar tail mosaicing and land use map development will be discussed in detail below.

Required Data	Acquisition	Preparation

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Digital Elevation Model (DEM)	Located on a public site and downloaded	Downloaded in 17 separate sections that required stitching together
Dam characteristics	Various open-source reports	N/A
Reservoir characteristics	A 2016 Inter-American Development Bank-funded sedimentation study	Bathymetric Model created by the NCCHE based off Lidar data and reservoir characteristics
Building footprints	Located on openstreetmaps.org	Cropping of selected area using Artibonite river mask
Land use map	Created based on open-source imagery	Performed a supervised classification
Locations of bridges and other obstructions	Located based on open-source imagery	A shapefile was manually created .
Observation points and lines	Created based off open-source imagery	A shapefile was manually created .
Breach scenario	Developed based on consultation with subject matter experts	N/A

Table 1. Required data and notes on their acquisition and preparation.

3.2.1 Lidar Tile Mosaicking

Due to a data downloading limitation, the DEM was downloaded in 17 separate files and then merged together. The merged DEM covered the Artibonite River area and Péligre Dam Reservoir. Because that DEM has the highest and lowest elevation value, the two values of mosaicked DEM should be the same as before. To ensure the mosaicked DEM contained the same minimum and maximum value, the algorithm was designed to merge the DEM and check if the mosaicked version contained the correct value.

The algorithm found the highest and lowest elevation value before mosaicking, and after mosaicking it compared if the highest and lowest value of the merged DEM remained the same. All processes was implemented using the Python programming language. The benefit of using Python is its ability to handle large DEM data volume, and the reusability of Python script.

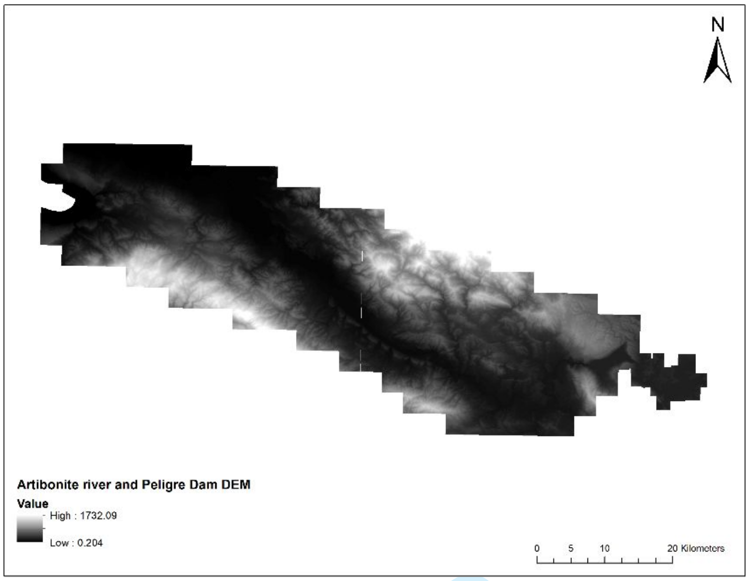

Figure 3: Mosaiced DEM

3.2.2 Land Use Map Development

To complete the simulation, a land cover map of the Artibonite River area was generated. For this study, one Landsat 8 OLI/TIRS C1 Level-1 multispectral image with 30 x 30 meters resolution from August 15, 2018 covering the study area was acquired through USGS EarthExplorer. After preprocessing, the image was clipped by a 10km buffer vector of the river.

The supervised classification method was used for land cover classification since the classes have been pre-established. The five classes included in the study were residential, cropland, mixed vegetation, bare land, and water bodies (Jensen, 2005, 338). The maximum likelihood algorithm was used because it is more effective when the number of training sites per class is large (Jensen, 2005, 374-379). The total accuracy assessment of the supervised image classification was 82.2%. Though not over 85%, it was good enough for this classification since the spectrum of vegetation along the coast area were highly similar to croplands. Finally, the land cover raster image was transferred into vector format by ArcGIS for further simulation.

The land use map was then used to correlate a manning's roughness coefficient for the different land covers. The coefficient is a measure of friction that the land cover imparts of the water flow of an open channel.

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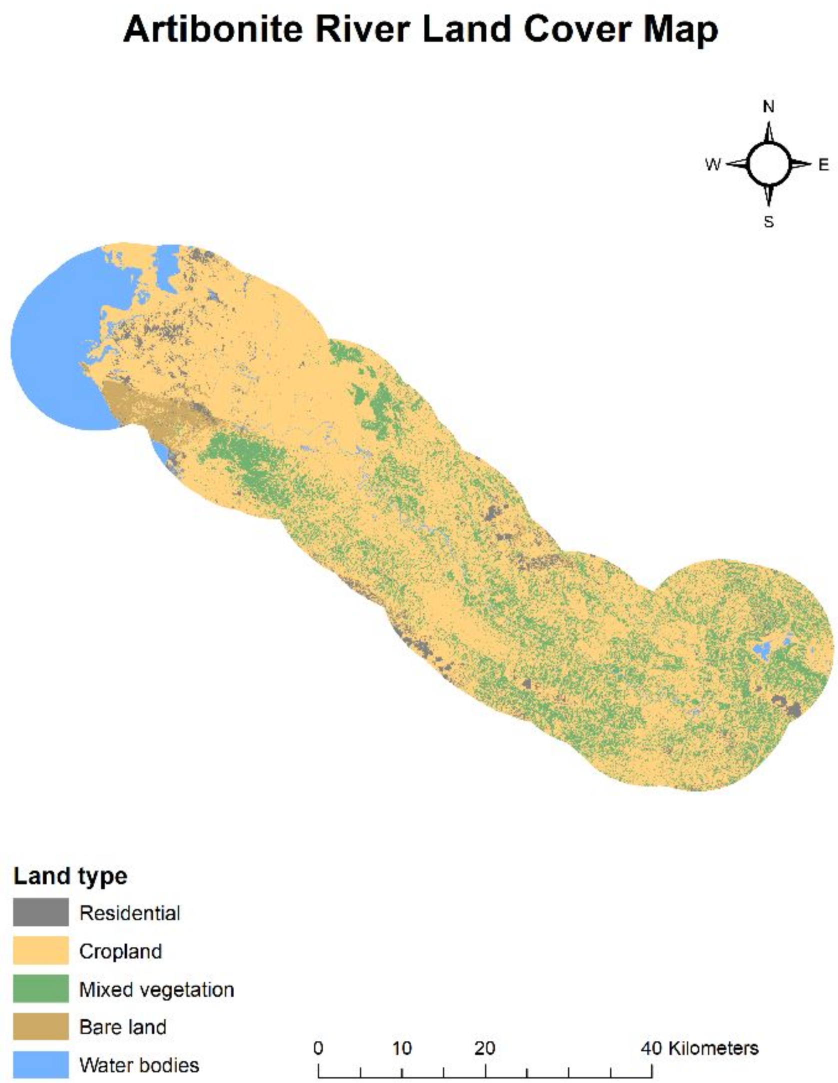

Figure 4. Land cover map that was developed based on imagery using supervised classification

3.3 Simulation:

Using the prepared data, the National Center for Computational Hydroscience and Engineering (NCCHE) performed two simulations using their proprietary DSS-WISE dam failure modeling platform. The center has a long history of performing complex hydrological simulations and specializes in dam and levee failures. The first simulation, Max Normal Discharge, was based on a maximum normal discharge scenario. For a period of 48 hours the discharge was 605 m^3 per second which represents the maximum water flow if all three gates are fully opened. The second simulation, Breach Scenario, was a moderate breach of 100 meters that developed over one hour. This scenario produced a maximum discharge from the dam of 2097m^3 per second and a cumulative discharge of $6.97 \times 10^8 m^3$.

For each scenario, several files were provided to include shape files for time of arrival, maximum depth and maximum Depth-Velocity (DV) value. The DV value represents the value of depth multiplied by velocity. Both depth and velocity are important in determining fatality rates (Federal Emergency Management Agency, 2018, 9).

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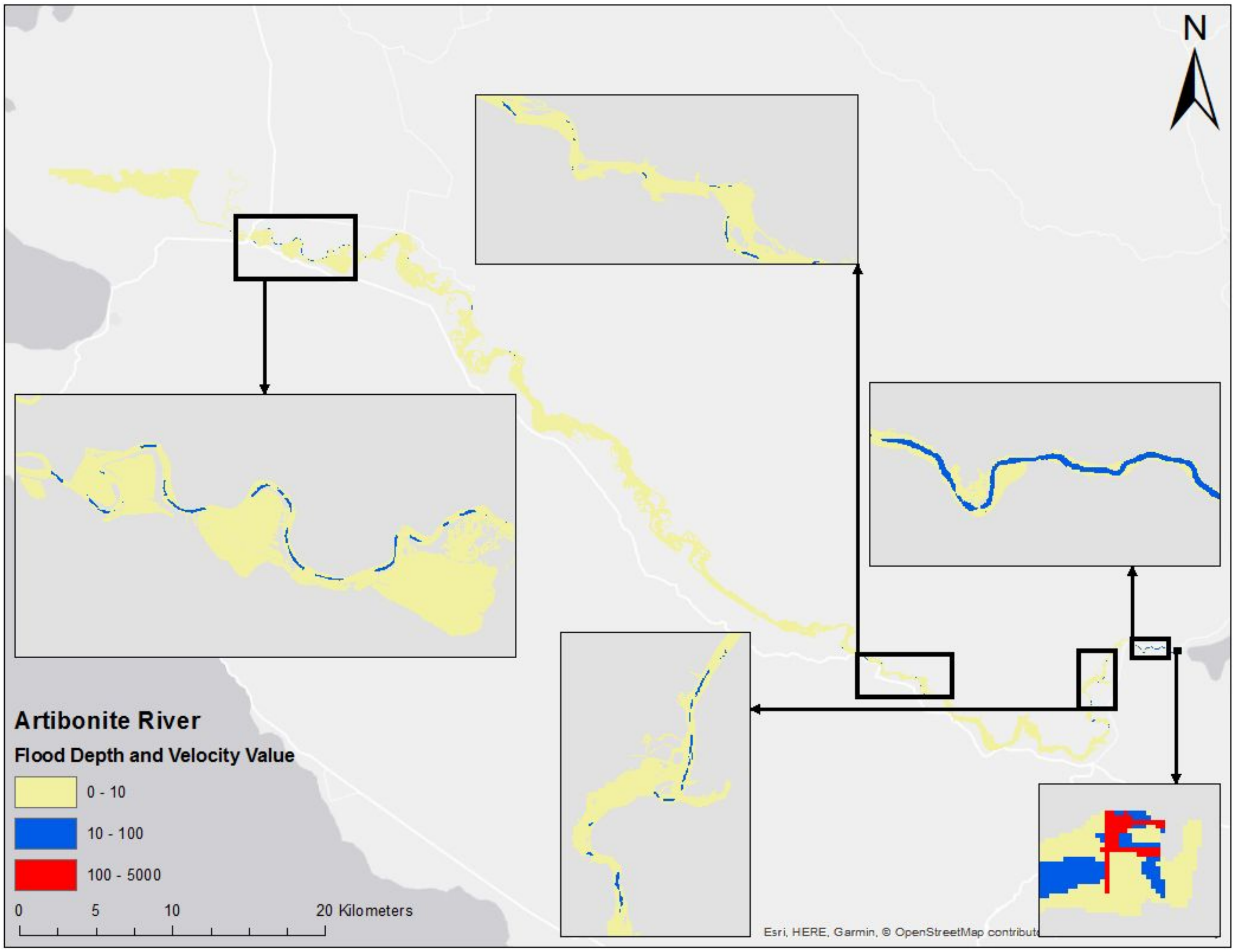

Figure 5: Flood Depth and Velocity

3.4 Analysis

The goals of the analysis were to estimate a total fatality rate and total buildings damage for the Breach Scenario. To accomplish this, we developed a risk layer based on the DV layer. The data were grouped into three categories as described in Table 2.

Flood Risk Category	m^3 /sec	Fatality Rate
Low	0-20	0.01
Medium	20-40	0.1
High	> 40	0.8

Table 2: Correlation of Risk Category to Fatality Rate

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Fatality rates were derived from the Bureau of Reclamations Reclamation Consequence Estimating Methodology where a fatality curve is offered for no notice dam failures based on historical case studies. The research team used the curve and adjusted for local factors to determine the rates as shown in Table 2.

The next step was to integrate population data and building footprint data. Each building that lay within the specified risk zone was assigned both a fatality rate and building occupancy estimate based on parameters shown in Table 3. The building occupancy estimate was derived as the total population in the study area 70,000 divided by the number of buildings (Open Street Map, n.d.).

Risk Area	# of Buildings within	Estimated # of Occupants
Low	690,183	62816
Medium	540,381	4918
High	248,832	2265

Table 3: Building and Occupancy Rate

4.0 Results

In total two simulations were conducted. The first was a scenario that saw the three gates of the dam opened at maximum water capacity for a period of 48 hours. This represented the maximum discharge from the dam without a breach. For this scenario, inundation maps were produced but the impact analysis was not conducted due to an obvious lack of flooding in residential areas based on visual observations.

The second scenario was a moderate breach of 100 meters that developed over 1 hour. In addition to producing inundation maps, a further impact analysis was conducted. Based on the analysis, it was estimated that 65 fatalities would occur and 202 buildings would be destroyed.

The implication lies in the fact that this analysis provides justification and specific information for emergency planning purposes. Specifically, the study can be the basis for development of evacuation maps, plans, and early warning systems. Due to the high resolution imagery and analysis, the inundation and risk maps produced can inform not only communities but also individual properties on their risk for flooding. Most importantly, time of arrival by using the map estimates can provide a basis for evacuation planning. On the other hand, inundation maps can be used for land use planning and development decisions by informing the extent and severity of flooding. It is especially significant in Haiti to understand the extent of flooding because of fragile construction methods and presence of temporary settlements along rivers. Furthermore, it is critical to note that fragile construction and temporary settlements are common in Haiti.

Lastly, the overall significance of this study is that by using our methodology, the cost of producing inundation maps and conducting the associated analysis is a fraction of traditional methods. The cost of this study was approximately $5,500 USD. The research team estimates that a comparable study by a private sector engineering consulting firm would be well over $50,000.

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5.0 Conclusions and Future Work

This work outlines how we were able to produce low-cost inundation maps using an innovative process that can be replicated anywhere in the world. We demonstrate a means of generating data that can be the basis for inundation and evacuation maps created using computer simulations. The biggest issue for future efforts will certainly be data availability and specifically that of the DEM. Had the Lidar data set not been available, the research team would have collected their own imagery using small drones and using photogrammetric techniques, producing a low-cost DEM with equivalent resolutions to the Lidar DEM that was used.

The limitations of this study nonetheless exist. The two main limitations of the study lie in the scope of the analysis and the lack of field verification. In terms of the scope, only two scenarios were chosen out of an infinite possibility. A conservative high release scenario and a catastrophic failure scenario were chosen to represent the range the case that is most likely to occur to least likely to occur. Additionally, due to intensive computing and time requirements for the simulation processing, two scenarios were the maximum that could be feasibly run for this study. The other limitation is that there was no field verification performed. For example, accuracy and precision could be determined through sampling field locations and establishing whether predicted impacts are plausible. Although the study would have benefited from conducting such analysis and verification, it was not achieved due to lack of funding.

Future work can be broken up into two areas: continuing research on the Péligre Dam and similar research for other dams. In regards to the Péligre Dam, a field study would be the logical next step to perform ground verification of the inundation maps, assess the current state of preparedness of downstream residents, and gain feedback on evacuation maps that would be derived from the study. Secondly, this methodology could be applied to other dams in developing countries with the goal of further reducing costs of developing inundation and evacuation maps. This research represents an attempt to apply knowledge and investments made in the developed world to the developing countries to have the potential to greatly mitigate disaster risk and save lives.

Please note that a data folder can be found at https://____________- containing all data relevant to this study.

Reference List

Altinakar, Mustafa, Marcus McGrath, Vijay Ramalingam, and James Demby. n.d. "Two-Dimensional Levee Failure Flood Simulation using DSS-WISE™ Lite." https://www.floods.org/Files/Conf2017_ppts/F6_Altinakar.pdf

American Society of Civil Engineers. (2012). *Haiti M_w 7.0 Earthquake of January 12, 2010: Lifeline Performance.* Edited by Curtis L. Edwards. https://ascelibrary.org/doi/book/10.1061/9780784412404

Escuder-Bueno, Ignacio, Mazzaà Guido, Morales-Torres Adrián, and Castillo-Rodríguez Jesica T. August 1, 2016. *Computational Aspects of Dam Risk Analysis: Findings and Challenges.* Retrieved from https://doi.org/10.1016/J.ENG.2016.03.005

DRAFT MANUSCRIPT

Federal Energy Regulatory Commission. March 2016. "Introduction to Risk-Informed Decision Making." *Risk-Informed Decision Making Guidelines.* https://www.ferc.gov/industries/hydropower/safety/guidelines/ridm/risk-guide/chapter-1.pdf

Fordyce, Erin, Abdul-Akeem Sadiq, and Grace Chikoto. 2012. *Haiti's Emergency Management: A Case of Regional Support, Challenges, Opportunities, and Recommendations for the Future.* http://hdl.handle.net/1805/3385

GLM Engineering. (May 2016). *DRAFT #2 Topo-Bathymetric and Geophysical Study of Sediments, Péligre Reservoir, Haiti.*

Haddow, G., Bullock, J., & Coppola, D. 2008. Introduction to Emergency Management (3rd ed.). Amsterdam ;: Elsevier/Butterworth-Heinemann.

Homeland Security Dams Sector. September 2011. *Estimating Loss of Life for Dam Failure Scenarios*. https://damsafety.org/sites/default/files/files/DamsSectorConsequenceEstimation_LossOfLife.pdf

Jachimowicz, Adam. Spring 2018. "National Dam and Levee Failure Simulation Tool for Emergency Managers." *The Buzz.* https://silverjackets.nfrmp.us/Portals/0/doc/newsletter/The_Buzz_Spring_2018.pdf

Jensen, John R. 2005. *Introductory Digital Image Processing: A Remote Sensing Perspective* 3rd Edition. Upper Saddle River, New Jersey: Prentice Hall.

Quiñones, Maya, William Gould, and Carlos Rodríguez-Pedraza. (February 2007). *Geospatial Data Availability for Haiti: An Aid in the Development of GIS-Based Natural Resource Assessments for Conservation Planning*.

United Nations. May 4, 2011. *Final Report of the Independent Panel of Experts on the Cholera Outbreak in Haiti*. Accessed January 2019. https://www.un.org/News/dh/infocus/haiti/UN-cholera-report-final.pdf

United Nations Development Programme. 2018. "Human Development Indicators." *Human Development Reports.* Accessed May 24, 2019. http://hdr.undp.org/en/countries/profiles/HTI

U.S. Department of Interior Bureau of Reclamation. July 31, 2015. "Reclamation Consequence Estimating Methodology: Guidelines for Estimating Life Loss for Dam Safety Risk Analysis." *Reclamation: Managing Water in the West.* https://www.usbr.gov/ssle/damsafety/documents/RCEM-Methodology2015.pdf

World Bank. 2010. *Haiti Earthquake PDNA: Assessment of Damage, Losses, General and Sectoral Needs.* http://documents.worldbank.org/curated/en/355571468251125062/pdf/701020ESW0P1190R0Haiti0PD NA020100EN.pdf

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