Haitian families use water at a gabion dam (HRC 2015)

COMMUNITY-SCALE FLASH FLOOD MITIGATION
Reference Guide to Optimizing Project Design

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1 INTRODUCTION AND BACKGROUND INFORMATION

Flash flooding remains the most deadly natural disaster, with the highest mortality rate; more than 5000 deaths worldwide every year on average. **Flash floods** are caused by moderate or heavy rainfall on ground with restricted permeability due to near saturation conditions or built impervious ground covers. The time of their formation is, generally, less than 6 hours. Flash floods are usually characterized by raging torrents that rip through river beds, urban streets, or mountain canyons. They can also occur even if no rain has fallen, for instance after a levee or dam has failed, or after a sudden release of water by a debris or ice jam.

In contrast, **seasonal floods** represent an overflow of water onto normally dry land; that is, the inundation of a normally dry area caused by rising water in an existing waterway, such as a river, stream, or drainage ditch. Flooding is a longer term event than flash flooding: it may last days or weeks. This distinction is very important when considering what mitigation strategies to implement. The guidance provided in this document refers to mitigation strategies for flash floods only.

Due to the highly variable nature of storm events, moderate or heavy rainfall can occur in any location. These storm events may cause **overbank flows** that exceed the capacity of constructed or natural storm drainage systems. The combination of overbank flows and their highly variable nature make adequate infrastructure investment cost prohibitive (despite the fact that several studies have shown that such infrastructure investment saves money when taking into account the cost of natural disaster response and reconstruction).

The ideal solution to flash flooding impact mitigation is to prohibit the construction of dwellings in high risk areas. Additionally, the most cost-effective solutions are non-structural including land use and urban planning, early warning systems, and household level changes. However, in many places these are not possible, due to a host of institutional, societal, and also financial shortcomings. In the absence of these solutions there are a number of mitigation strategies that can be accomplished and become effective at the local scale.

Along with occurring more quickly than seasonal floods, flash floods also have generally much smaller total volumes of water. It is this fact that allows small-scale projects to have significant impacts on flash flood wave propagation. Small-scale hydraulic works and revegetation campaigns can impact both the magnitude of peak flows and the time it takes for those peaks to arrive in downstream locations.
The goal of the present document is to provide guidance with regards to effective methodologies for flash-flood impact mitigation in small mountainous watersheds. The material presented is selected to facilitate the application of the methodologies to various watersheds of the type mentioned. These methodologies and the description of the tools they employ necessarily involve technical terms and hydrologic and hydraulic concepts, and are amenable to implementation by readers with some technical background in watershed hydrologic processes and their modeling, and in the hydraulics of open channel flow. The next section, however, is written in a way that all readers will be able to follow the salient features of the methodologies detailed in following sections.

2 METHODOLOGY AND APPLICABILITY

The goal of the strategies developed is to facilitate a quantitative understanding of the impact of various small-scale flash flood mitigation strategies. This goal can be achieved through the use of a personal computer with freely available software and the cooperation and collaboration between scientists and engineers, governmental and non-governmental agencies, and community partners that know the project area.

The software used herein is based on numerical representations of the physical relationships between moving water and the land surface. The physics of the relevant processes is well known; however, given the current state of technology, numerical modeling of those processes requires several simplifications, which infuse uncertainty in the computational results.

The accuracy, precision, and robustness (conditions under which results apply) of the numerical models is dramatically increased when accurate and detailed data is available. The resolution both in time and space of model representations should be linked to the available data. In many cases it will be necessary to extrapolate and interpolate missing data. It is very important to maintain statistical homogeneity when implementing these strategies.

The steps required to develop the quantitative sensitivity analyses described herein are outlined in Figure 2 and include:

Flash Floods and Climate Change

A team of scientists at the Potsdam Institute for Climate Impact Research implemented an advanced statistical analysis of rainfall data from the years 1901 to 2010 derived from thousands of weather stations around the globe. This analysis found that between 1980 and 2010 there were 12% more extreme rainfall events than expected in a stationary climate, or one without climate change. This study also found that in the last year of data, 2010, the increase was 26 percent.

They also found that this record-breaking anomaly has distinct patterns across Earth’s continents with generally wet regions seeing an over-proportional increase and drier regions less so. In South East Asian countries the observed increase in record-breaking rainfall events is as high as 56 percent, in Europe 31 percent, in the central US 24 percent. In contrast, some regions experienced a significant decrease of record-breaking daily rainfall events. In the Mediterranean, the reduction is 27 percent, and in the Western US 21 percent. Both these regions are at risk of severe droughts.
1. The development of a \textit{Rainfall Time-Series}, spatially distributed, over the project area. This rainfall time series will be used as the main forcing for the hydrologic model.

2. A suitable \textit{Hydrologic Model} must be used to test the sensitivity of the project area to changes in land cover, such as revegetation campaigns, and/or urban development. This model will also be used to generate individual hydrographs to be routed through the river network including all tributaries.

3. A suitable \textit{Hydraulic Routing Model} must be constructed based on the geo-physical characteristics of the project area. This model will be used to test sensitivity to channel roughness and to the construction and configuration of gabion (or check) dams.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{flowchart}
\caption{Flow chart diagram of sensitivity analysis methodology for flash flood mitigation strategies.}
\end{figure}

\section{Design Storm Development}

Rainfall data comes from two sources primarily, either ground-based rain gauges, or satellite derived rainfall estimates. Each has advantages and disadvantages. Ideally, within the project site there are reliable rain gauge records going back 25 years. This is often not the case.

In the case where multiple rain gauges are in the vicinity of the project site, their time series can be matched up, then interpolated to cover the project site, and then used in an extreme value distribution analysis to obtain the volumes of rainfall of a given return period. In the case where multiple rain gauges exist, but their time series are not continuous, these time series can be appended only if the time-series come from similar probability distributions (the fitting parameters to the proper extreme value distribution have similar values).
Satellite rainfall estimates are produced globally by the National Oceanic and Atmospheric (NOAA) Office of Satellite and Product Operations. The Hydro-Estimator (HE) algorithm uses infrared (IR) brightness temperatures to identify regions of rainfall and retrieve rainfall rate, while using National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model fields to account for the effects of moisture availability, evaporation, orographic modulation, and thermodynamic profile effects.

The HE rainfall rate estimates are produced routinely every 15 minutes for the continental United States using the data from NOAA's Geostationary Operational Environmental Satellites (GOES). For the rest of the world the HE uses available geostationary data over Europe, Africa, and western Asia (METEOSAT), and eastern Asia (MTSAT). The global rainfall composite is then generated from those estimates from multiple satellites and updated every 30 minutes. The operational global HE products available include instantaneous rain rates and 1-hour, 3-hour, 6-hour, 24-hour and multi-day precipitation accumulations. HE product availability begins in 2006 and it is to the present. HE rainfall estimates are produced at a 4km X 4km spatial scale.

Both the rain gauge and HE rainfall time series should be used to develop Intensity-Duration-Frequency (IDF) curves representing storm maximum intensities over various durations for various return-period probabilities. These IDF curves are then used to develop design storms.

One strategy used to develop the design storms is to use the rainfall volume and duration for the desired return period to parameterize and scale an extreme value distribution to create a single peak hyetograph (rainfall time series) for the desired duration (see Inset). Another option is to search the time series available, if of sufficiently high temporal resolution, for observed events that match the desired intensity and duration for the volume-frequency storm to be simulated.

In many cases rain gauge data is daily, which is too coarse to capture storm temporal dynamics. In these cases it is possible to search the satellite rainfall record, which has a much finer temporal resolution. Figure 3 illustrates the strategy developed to use daily rain gauge and hourly satellite rainfall data to develop design storms that represent observed storm dynamics.

**Example Matlab® Code to generate single peak extreme value distribution with desired peak and length.**

```
Peak=1.7; %Peak Value
Length=1200; %Number of Time Steps desired
rng default; % For reproducibility
xMaxima = max(randn(600,300), [], 2);
paramEstsMaxima = evfit(-xMaxima);
y = linspace(1.5,5,Length);
p = evpdf(-y,paramEstsMaxima(1),paramEstsMaxima(2));
Hydr_In=p*Peak/1.0884; %Variable is the desired time series
```

**Figure 3.** Design storm development strategy to combine daily rain gauge and hourly satellite rainfall data.
2.2 Assessing the Impacts of Land Cover Change

The rainfall-runoff relationship in any given catchment is unique to the conditions in that location. The primary variables that control this relationship are the basin geometry (e.g. slope steepness, length:width ratio, size), soil type and depth, and vegetation and land use. In general, the size of natural stream channels is related to the size of the storm and resultant flow that carries most of the sediment in the long run. This flow is known as bankfull flow, and it is found to have return periods from a little over 1 year in wet regimes to 3-5 years in drier regimes. As conditions in the watershed change, these relationships also change, which results in changes to channel geometry, peak discharge, and the time for those peaks to travel downstream.

In its most simple conceptual representation, a watershed can be considered a leaky bucket, where all of the variables mentioned control both the size of the bucket and the rate of the leak. Conversion of natural landscapes to agricultural and municipal uses can dramatically reduce the ability of watershed hillslopes to capture, infiltrate, and slow down water falling on the landscape. These changes result in a quicker watershed response leading to larger peak flows and faster peak travel times. The challenge for those seeking to mitigate those impacts is to assess the quantitative impact of mitigation measures, so that impacts can be assessed relative to other mitigation options.

A hydrologic model is a numerical model that uses a conceptual representation of the rainfall-runoff relationship to translate precipitation inputs (hyetograph) to watershed runoff (hydrograph). In locations with multiple sub-watersheds, the output of individual watersheds must be routed downstream to the project area outlet. There are many commercially available hydrologic models with various capabilities to represent the rainfall-runoff relationship and hydraulic routing to different degrees of sophistication.

Regardless of what hydrologic model is used, the first step in completing this task is to define the watershed boundaries and their parameters (i.e. geographic characteristics). The process of defining watershed boundaries is done through the use of Geographic Information Systems (GIS) software. A Digital Elevation Model (DEM) represents the terrain elevation in a grid. This information may be obtained from global databases (see Section 4.1.1.), or may be created from survey data obtained for the site of interest by modern-day digital cameras on remotely piloted drones. Grids may be of different spatial scales. Each GIS software package will have a tool for watershed delineation, regardless of which one is chosen, it is incumbent on the user to validate the watershed boundaries defined by using other data sources such as aerial imagery and stream channel data.

Figure 4. Watershed boundaries of Ravine Millet (HRC).
Upon defining watershed boundaries, other modeling parameters can be determined such as slopes, soils, and vegetation. Ideally, there will also be runoff or flow data available that can be used with the precipitation data to calibrate the hydrologic/hydraulic models. In many cases this data is not available, and therefore results of sensitivity analyses should be considered as relative to some nominal state which is not verifiable.

Lastly, the design storms developed need to be distributed over the project area, as different size watersheds receive different amounts of rain. Additionally, when spatially distributed data is available, such as satellite rainfall, and the project area is larger than the 4km X 4km grid, it should be used to determine the spatial distribution of rainfall over the site through spatial interpolation techniques, as higher elevations and wind-ward slopes tend to receive more rainfall.

The final important consideration when developing a hydrologic modelling representation of a project area is to consider whether to use a distributed or lumped representation of the system. A lumped hydrologic model represents each of the model parameters as one integrated value for the entire watershed. In contrast, a distributed hydrologic model represents the model parameters in a grid overlaying the watershed, where different grid cells have unique characteristics. The choice of which model representation to use should be based on the available data and the goals and objectives of the project.

Once the model is built, with the appropriate structure, parameters, and precipitation forcing, various sensitivity analyses can be performed by altering model parameters to represent changes to land use due to urban expansion, to vegetation due to planting campaigns, or to local slopes due to contour terracing construction. It is highly encouraged that sensitivity analyses should be constrained by the site conditions. For example, a total conversion of the landscape to a complex multi-layered forest will likely be unattainable both due to the time it takes for such a forest type to grow, but also due to competing land uses that limit revegetation projects.

2.3 Assessing the Impact of Channel Roughness Changes

Flows in stream channels propagate downstream under the action of earth’s gravity, where additional flows may be added laterally throughout a section of channel and when a catchment outlet or tributary flows are combined with flows in the main channel. Flow depth is controlled by the geometry of the stream including its width, length, side slopes, and downstream slope, along with the roughness of the
stream channel bed. Changes to any of these channel characteristics will change how flows propagate downstream.

Where the strategies outlined in Section 2.2 will result in hydrographs from each of the project sub-catchments, these hydrographs represent the flows at their respective sub-catchment outlet and therefore cannot be used as input to a river routing model representing water flowing down the same sub-catchment stream channel, as the flow begins at the top of the stream and is added to as it continues down the catchment.

One way to ameliorate the discrepancy between the hydrologic model output at the sub-catchment mouth and the desire to route the flood wave through the entire sub-catchment tributary stream, is to set hydrologic modelling parameters to represent a nearly immediate response to rainfall inputs, thereby minimizing the impact of travel time through the watershed. The hydrographs derived from this strategy can then be used in a routing model to represent flood wave propagation downstream.

The propagation of a flood wave downstream is controlled by the basic physical laws including the conservation of water mass, energy, and momentum. These laws were combined to create a set of hyperbolic partial differential equations known as the Saint (St.) Venant Equations. River routing models use some solution to this set of equations with various simplifications, depending on the sophistication of the model being used and the terrain morphology.

For the most common cases associated with flash flooding and the relatively small and steep catchments prone to flash flooding, the options to represent flood propagation are limited. Many commercially available river routing models were developed for large slow moving rivers and are not appropriate to the steep terrain and narrow channels found in these locations. The Kinematic Routing Model (KRM), appropriate for steep and narrow channels, is one of the tools that may be used (e.g., Georgakakos and Posner, 2015). Inputs to the KRM are the channel geometry including channel width and side slopes, downstream slope, and channel lengths including the locations where tributaries join the main channel. The other necessary parameter to model flood wave propagation represents the channel bed roughness.

Channel bed roughness is an important determinant for flood water depth and propagation velocity. Intuition tells us that as bed roughness increases, flow velocities are reduced. If flow velocity is reduced, but the same amount of water is in the channel, flow depth increases. It is very important for project managers and designers to understand the potential impact of mitigation efforts, as increasing channel bed roughness through planting or placement of rocks or logs will slow the approaching flood wave, it will also increase the depth of that flood wave. Therefore, any increases to channel bed roughness should only be considered in those locations where an increase in flood depth will not put more people at risk of flooding.
The numerical channel-water routing model facilitates the implementation of a sensitivity analysis on channel bed roughness. Using the KRM to simulate different roughness values in different locations throughout the watershed stream channel network, provides quantifiable understanding of the impact of those changes. These changes can then be compared to other possible mitigation strategies and their impact to flood depths and times of arrival of downstream flooding.

2.4 Assessing the Impact of Gabion Dams

Gabion dams are relatively simple and low-cost structures, which can often be built with local materials and minimal training. These small dams act to temporarily impound water behind them, the volume of which is determined by the height of the dam, the width of the channel, and the stream bottom slope. Due to the potentially large flow events associated with severe storms, the structural integrity of the dams is paramount, as their failure can be catastrophic sending large flood waves full of sediment and debris downstream.

The strategy developed to use numerical modeling to assess the impact of dams in a project site is an extension of the previously discussed impact assessments. Successful implementation of the gabion dam impact assessment is incumbent on developing the models and model inputs previously described including: design storms, hydrologic model, and the channel routing model.

Quantitative assessment of the impact to flows gabion dams have may be done with models such as KRM. Gabion dams can be considered as standard contracted weirs. These weirs are common in irrigation systems and the equations that define flow over their spillways is well validated. The geometry required, beyond the description of the stream channel system, is the height of the dam \( h \) and the width of the spillway \( L \), assumed centered on the dam width. The height of the side gabions of the dam that constrict the weir is assumed to be equal to the height of 1 gabion for better stability to high flows.
Models such as the KRM allow the user to define the stream channel as a series of segments. Each segment has unique characteristics including the segment length, bottom slope, bottom width, side slope, and roughness. Each segment is broken into subdivisions for the purpose of solving the differential equations. The number of subdivisions required for the solver to converge with minimal losses will depend on the conditions of the project area (e.g., Georgakakos and Posner, 2015). The number of subdivisions in a segment also controls where gabion dams can be placed for simulation. Gabion dams can be located at the end of any subdivision within any segment. Sensitivity analyses on the location, the number, the height and width of spillways, can all be performed using numerical models such as the KRM.

### 2.5 Translating Changes in Flow to Inundation Area

The methodology described thus far will allow investigators to assess the potential impact of hillslope revegetation, channel revegetation, and gabion dam construction on the peak discharge at the project area catchment outlet and the time it takes for that peak discharge to arrive downstream. In many cases, the exact locations where inundation is likely to occur and the degree to which changes in discharge are translated to changes in inundation area are important in the decision making process.

In order to assess the inundation area of a particular discharge value in a particular location, the US Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (HEC-RAS) can be used. HEC-RAS is a river hydraulics model, the software allows the user to perform one-dimensional steady flow, unsteady flow calculations, sediment transport/mobile bed computations, and water temperature modeling. For the purposes of determining inundation area, a steady flow computation is sufficient, where that flow value represents the peak discharge output from either the hydrologic model or a model such as the KRM.

![Figure 8. Schematic of Gabion Dam illustrating the geometric variables that define flow over the dam spillway (HRC).](image)

![Figure 9. HEC-RAS geometric variables, including cross-sections, bank lines, left, center, and right flow paths, defined in ESRI ArcMap using the HEC-GeoRAS plugin.](image)
HEC-RAS essentially solves the same equations used to derive the KRM but without some of the simplifications. This additional generality in formulation also restricts the HEC-RAS application in the steep ravines associated with flash flooding, as the gradients are too large and the model cannot converge to a stable solution. The inability to converge to a solution is especially true when trying to simulate unsteady flow, or the propagation of a flood wave through the domain. However, the use of a discharge produced by a different model more suitable for the steep ravine environment at a given segment of river allows the application of the HEC-RAS to provide realistic solutions for inundation extent.

Model geometry required to create and implement a HEC-RAS model include detailed cross-sections containing the elevation of points across the area of interest. These cross-sections can be most easily attained when hi-resolution elevation data is available in the form of a DEM. Hi-resolution DEM contain geo-referenced elevation data in a digital format that can be loaded in to GIS software, where geometric variables such as cross-section station/elevation pairs can be extracted. The HEC built the HEC-GeoRAS plugin for ESRI ArcMap to facilitate the extraction of required data. However, other GIS software can also be used, albeit with more manual steps required.

Output generated by the HEC-RAS steady flow simulation is the Top Width of the water level at each cross section. By knowing the Top Width of two cross-sections and the distance between cross sections, the formula for area of a trapezoid can be used to determine the inundation area between those two cross-sections. This can then be done for subsequent cross-sections to determine the total inundation area.

Additionally, the water surface elevation of each cross section is also output from the HEC-RAS model. These points can be exported from the HEC-RAS model and imported into a GIS, where they can be used to develop a polygon representing the inundation extent for various discharge values. These polygons can then be loaded in to a variety of mapping platforms including GIS software, online map servers, and Google Earth Pro (freely available) and used by disaster response and risk management and planning to reduce threats associated with these events. It is noted, however, that the HEC-RAS computations are essentially for one-dimensional flow down the river and will not account for any local secondary flow components that may be generated by obstacles. Thus, the results obtained using the methodologies described above should be used with allowances for possibly greater local inundations.
2.6 **SUMMARY OF METHODOLOGICAL STEPS**

In this section we develop a table of the methodological steps and numerical tools required to apply the methodology discussed in the previous sections.

**METHODOLOGICAL STEPS FOR APPLICATION TO A PARTICULAR SMALL WATERSHED IN STEEP TERRAIN**

<table>
<thead>
<tr>
<th>STEP</th>
<th>DESCRIPTION</th>
<th>TOOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Development of design-storm precipitation input with storm volume of a given return period and with spatial distribution reflecting historical observed storms</td>
<td>Extreme value analysis of gauge data and spatial analysis of satellite data.</td>
</tr>
<tr>
<td>2</td>
<td>Development of tributary-watershed GIS mapping, spatial databases of digital terrain elevation data, soils, and land-use and land-cover data for the application watershed</td>
<td>Global databases and/or local surveys using drones and GIS software.</td>
</tr>
<tr>
<td>3</td>
<td>Development of tributary and main-stem channel topology, and database development for channel cross-sectional data, roughness data, and potential gabion dam site data</td>
<td>Ground surveys and/or high-resolution digital images from drones.</td>
</tr>
<tr>
<td>4</td>
<td>Parameter estimation of spatially-distributed hydrologic model for each tributary watershed based on available data</td>
<td>HEC-HMS</td>
</tr>
<tr>
<td>5</td>
<td>Parameter estimation of high-resolution kinematic routing model for each channel segment</td>
<td>KRM</td>
</tr>
<tr>
<td>6</td>
<td>Use of spatially distributed hydrologic model to produce inflow hydrographs along the channel segments using a given design-storm precipitation hyetograph with a given spatial distribution over the catchment</td>
<td>HEC-HMS</td>
</tr>
<tr>
<td>7</td>
<td>Use of kinematic routing model along with the inflows of the previous step to produce discharge-hydrograph estimates for each segment of the channel network</td>
<td>KRM</td>
</tr>
<tr>
<td>8</td>
<td>Use of the peak discharge estimates from the channel flow hydrographs for the channel segments in populated areas to produce inundation mapping</td>
<td>HEC-RAS</td>
</tr>
</tbody>
</table>

**NOTE: STEPS 4-8 PRODUCE A BASELINE RESULT WHICH WILL BE COMPARED TO PERTURBED-PARAMETER SOLUTIONS FOR THE ASSESSMENT OF THE IMPACT OF PROPOSED IMPROVEMENTS**

<table>
<thead>
<tr>
<th>STEP</th>
<th>DESCRIPTION</th>
<th>TOOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Change the watershed land-use/land-cover to conform to realistic future replanting or reforestation development, repeat steps 4-8, and assess the significant differences in inundation and discharge hydrographs (including peak discharge and timing) from the baseline run.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Change the channel roughness parameters conforming to realistic future channel revegetation, repeat steps 5, 7, and 8, and assess the significant differences in inundation and discharge hydrographs from the baseline run.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Develop a series of potential gabion dam configurations (number, sites, and sizes of dams), for each one repeat steps 7 and 8, and assess the significant differences in inundation and discharge hydrographs from the baseline run.</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE: THE SENSITIVITY ANALYSES IMPLIED BY METHODOLOGICAL STEPS 9-11 MAY BE AUGMENTED AS NECESSARY TO INCORPORATE SIMULTANEOUS CHANGES IN WATERSHED LAND COVER, CHANNEL VEGETATION AND GABION SITING.**
3  EXAMPLE OF THE APPLICATION OF THE METHODOLOGY

The methodology outlined above was applied to a ravine in Haiti in collaboration with partners at the International Organization for Migration (IOM) near Port-au-Prince, Haiti. The Ravine Millet watershed was identified by IOM and the US Agency for International Development (USAID) as the source of significant downstream flooding and to possess potential to implement various strategies to mitigate that flooding.

3.1  STUDY AREA

The Ravine Millet watershed is located approximately 9.5 kilometers south south-east of Port-au-Prince, Haiti (Figure 12). At the outlet of the watershed at Bois Moquette the entire catchment area is approximately 6.7 sq. km. with the Ravine Millet stream traversing the watershed for 6.4 kilometers. In addition, there are 4 tributaries that include 4.6 km of stream length (Figure 11). The area is characterized by very steep terrain (Table 1). The land uses across the site are a mix of housing, second or third-growth scrublands that return after deforestation, with the majority of the area covered by small-scale agriculture.

According to USAID, the small-scale agriculture located on Haiti’s steep slopes does not represent a sustainable solution to the country’s nutritional needs or economic future. According to their research, “There is no evidence that either the Haitian state or donors can afford the high investments required to make hillside agriculture productive on a sustainable basis...most Haitian landscapes will never consist of an ideal of hillside farms meeting high standards of soil and water conservation, mixing perennial and annual crops, benefitting from profitable marketing strategies, attaining adequate rural incomes, and providing equitably for upstream and downstream users alike.”

Table 1. Ravine Millet System Catchment Sub-basin properties.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (sq. km.)</th>
<th>Average Slope (°)</th>
<th>% Dense Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>W400</td>
<td>0.87</td>
<td>17.5</td>
<td>2.75</td>
</tr>
<tr>
<td>W410</td>
<td>0.7</td>
<td>19.7</td>
<td>5.52</td>
</tr>
<tr>
<td>W440</td>
<td>0.76</td>
<td>22.0</td>
<td>3.76</td>
</tr>
<tr>
<td>W450</td>
<td>0.82</td>
<td>19.9</td>
<td>8.88</td>
</tr>
<tr>
<td>W510</td>
<td>0.62</td>
<td>15.3</td>
<td>8.43</td>
</tr>
<tr>
<td>W560</td>
<td>1.74</td>
<td>13.6</td>
<td>7.17</td>
</tr>
<tr>
<td>W570</td>
<td>1.19</td>
<td>12.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The study area consists of dense urban population at the watershed outlet and dispersed but growing population centers near the top of the watershed. This distribution is in part due to the severely steep terrain in the remainder of the project area, whose slopes prohibit dwelling construction.
The Ravine Millet watershed became a serious area of concern when after two hours of rain on 2 May 2012, the width of Ravine Millet nearly doubled in size, taking with it 11 houses and placing at imminent risk at least 20 more. This same rain event caused the near collapse of one of the bridges in the area as well. In response to this event, IOM made three recommendations:

1. Continue dredging of canals.
   a. This refers to the severe deposition occurring in downstream locations where constructed storm water channels have lost nearly all their conveyance capacity due to filling by deposited sediment.

2. Riverbank reinforcement
   a. Employ the use of gabion baskets, stone and concrete retaining walls to prevent further widening of the channel.

3. Emergency Erosion Control in the mountains
   a. Through the construction of small trenches, rock walls and/or gabions in small rows. The idea behind the construction of these small structures is to capture sediment being eroded from the hillsides and upstream areas before it can reach and compromise downstream reaches. Construction of these small structures will also act to slow water down locally, increasing infiltration and reducing the erosive potential.

Figure 11. Ravine Millet sub-catchments and tributaries. Note that catchment W570 has no distinct stream channel.
3.2 Defining Design Storms

Working with partners at IOM and through online searches, records were obtained from three rain gauges in the vicinity of the project site (Table 2). In addition, the NOAA Global Hydro-Estimator satellite rainfall data available at HRC were used. The project area is covered by four grid cells with a temporal coverage from 2006 to the present (Figure 12). These two data sets were used to make Intensity-Duration-Frequency curves (Figure 13). The return period values from these curves were compared to other return period intensities from around the region (Table 3). The regional estimates for comparison were found through online searches. As can be seen from Table 3, an excellent source for this information is international airports in the project region.

Using the strategy outlined in Figure 3, design storms were developed representing the intensity and duration of different return period events (Figure 14). The result of identifying observed storm events to represent the temporal distribution of rainfall results in a series of design storms of different lengths with unique shapes, where some storms have the characteristic single peak, other storms have multiple peaks of similar magnitudes, and yet other storms have multiple peaks with different magnitudes.

<table>
<thead>
<tr>
<th>Rain Gauge</th>
<th>Length of Record (Years)</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petion Ville</td>
<td>4</td>
<td>2009-2013</td>
</tr>
<tr>
<td>Damien</td>
<td>12</td>
<td>2002-2014</td>
</tr>
<tr>
<td>Kenscoff</td>
<td>3</td>
<td>2010-2012</td>
</tr>
</tbody>
</table>

Figure 12. Rainfall data locations for the Ravine Millet project area, stars indicate rain gauges and dots indicate satellite grid centroids.
Figure 13. Intensity-Duration-Frequency curves for both (left) the average from three rain gauges, and (right) the average of the four satellite rainfall pixels that cover the project area.

Table 3. Magnitudes (mm/day) for different return period storms from around the Caribbean for comparison with those calculated from Haiti rain gauges in the vicinity of the project area.

<table>
<thead>
<tr>
<th>Location</th>
<th>1-yr</th>
<th>2-yr</th>
<th>5-yr</th>
<th>10-yr</th>
<th>20-yr</th>
<th>50-yr</th>
<th>100-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comerio, Puerto Rico</td>
<td>97</td>
<td>128</td>
<td>178</td>
<td>219</td>
<td>278</td>
<td>326</td>
<td>378</td>
</tr>
<tr>
<td>Cerrro Maravilla, PR</td>
<td>152.4</td>
<td>228.6</td>
<td>304.8</td>
<td>431.8</td>
<td>558.8</td>
<td>660.4</td>
<td></td>
</tr>
<tr>
<td>San Juan WSFO, PR</td>
<td>96.5</td>
<td>134.6</td>
<td>167.6</td>
<td>205.7</td>
<td>233.7</td>
<td>274.3</td>
<td></td>
</tr>
<tr>
<td>Pico del Este, PR</td>
<td>177.8</td>
<td>279.4</td>
<td>355.6</td>
<td>482.6</td>
<td>558.8</td>
<td>660.4</td>
<td></td>
</tr>
<tr>
<td>Caneel Bay Plantation, Virgin Islands</td>
<td>101.6</td>
<td>157.5</td>
<td>215.9</td>
<td>292.1</td>
<td>342.9</td>
<td>411.5</td>
<td></td>
</tr>
<tr>
<td>Homestead, FL</td>
<td>121.0</td>
<td>160.0</td>
<td>196.0</td>
<td>251.0</td>
<td>298.0</td>
<td>351.0</td>
<td></td>
</tr>
<tr>
<td>St. John, U.S. Virgin Islands</td>
<td>80.0</td>
<td>109.0</td>
<td>165.0</td>
<td>212.0</td>
<td>283.0</td>
<td>343.0</td>
<td>409.0</td>
</tr>
<tr>
<td>Vieques, Puerto Rico</td>
<td>88.0</td>
<td>117.0</td>
<td>168.0</td>
<td>208.0</td>
<td>267.0</td>
<td>314.0</td>
<td>365.0</td>
</tr>
<tr>
<td>Norman Manley International Airport (Kingston)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sangster International Airport, (Montego Bay)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE</td>
<td>88.33</td>
<td>125.42</td>
<td>169.91</td>
<td>215.73</td>
<td>283.20</td>
<td>336.40</td>
<td>394.64</td>
</tr>
<tr>
<td>Average Satellite Rainfall</td>
<td>81.64</td>
<td>141.9</td>
<td>196.9</td>
<td>233.3</td>
<td>268.3</td>
<td>313.5</td>
<td>347.4</td>
</tr>
<tr>
<td>Averaged Rain gauge Observations</td>
<td>41.8</td>
<td>122.7</td>
<td>196.5</td>
<td>245.4</td>
<td>292.3</td>
<td>353</td>
<td>398.5</td>
</tr>
</tbody>
</table>
3.3 Assessing Hillslope Revegetation Impacts

In order to carry out a sensitivity analysis of changes to hillslope vegetation, the first step was to use available elevation data to determine the watershed boundaries in the project site. In this case, the HRC had 0.09m resolution data that was captured by an Unmanned Aerial Vehicle (drone) used by IOM partners, 90m resolution SRTM data, and 30m resolution ASTER data. Through multiple iterations and testing, investigators determined that the GRASS AT least-cost algorithm, that can be implemented in the free GIS software QGIS, is a more reliable algorithm for watershed delineation than those implemented in ESRI ArcMap. All three data sets were used to delineate watersheds, including elevation data sets derived from upscaling the 0.09m resolution data to 0.5m and to 1m resolutions. Additionally, several iterations were required to determine the appropriate watershed size to represent each tributary’s contribution to flows in Ravine Millet. It was found that the 30m ASTER elevation data with a watershed size of 1.0 sq. km generated watershed boundaries that best matched the tributary network and was validated by aerial imagery.

Hydrologic modeling was completed using the US Army Corps of Engineers Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS). Additionally, the HEC-GeoHMS, a plugin developed by the HEC was used in tandem with ESRI ArcMap software to derive model parameters and geometries. This system requires the definition of both a Loss Method representing the amount of precipitation that is converted to runoff and a Transform Method representing the travel of that runoff across the watershed to the outlet. In addition, a method to route flows between sub-catchment outlets to the overall watershed outlet must be defined and parameterized.

Figure 14. Hyetographs for the design storms for 1-, 2-, 5-, 10-, and 35-yr return periods based on the strategy outlined in Figure 2.4 numbers in parentheses refer to the storm totals.

Figure 15. Percent of each sub-basin area with very dense vegetation, represented as a curve number of 50. Non-uniformity is due to revegetation restrictions varying across the study region.
The Loss Method, or hydrologic response, was modeled using the Soil Conservation Service (SCS) Curve Number Method (Chow et al., 1988). The Curve Number Method uses a single number to represent the soils and land cover controlling the hydrologic response of a given area. The Natural Resource Conservation Service developed a series of reference tables that use both soil group and cover type to determine the appropriate “Curve Number” to be used in the model. Hi-resolution aerial imagery was recorded over the project area (0.09m) which IOM Haiti partners used to assign Curve Numbers to a 50m X 50m grid across the project area (Figure 5).

Hillslope revegetation, was represented through development of a series of buffers around existing high density vegetation areas (those with low curve numbers). Because much of the area cannot be revegetated due to existing land uses such as urban area and roads, alternative revegetation scenarios were restricted by these limitations. Figure 15 illustrates the proportion of the area of each sub-basin with dense vegetation for the existing land cover, as well as the four alternatives tested. Increases in dense vegetation are not distributed evenly across each sub-basin, due to the restrictions described.

In order to assess the time it takes for precipitation falling over the watershed to reach the outlet, the Modified Clark Unit Hydrograph was employed, which derives a watershed unit hydrograph by explicitly representing two critical processes in the rainfall-to-runoff transformation: (a) translation (i.e. time of concentration) representing the movement of excess water from its origin through the catchment to the watershed outlet, and (b) attenuation (i.e. storage coefficient) representing the reduction of the magnitude of discharge due to storage in the watershed.

Time of concentration calculations were completed in accordance with the US Department of Agriculture, Natural Resource Conservation Service, Urban Hydrology for Small Watersheds (1986) that includes (1) the Manning Kinematic equation representing overland sheet flow, (2) the Natural Resource Conservation Service Travel Time method used to represent shallow concentrated flow, and (3) the Manning Equation used to represent channel flow. The Modified Clark Unit Hydrograph represents translation using a grid-based travel-time model. The travel time of runoff excess is determined by multiplying the time of concentration by the ratio of the distance of the individual cell to the outlet divided by the maximum distance a water packet must travel in the catchment.

Changes to flow at the study area catchment outlet were translated to changes in inundation area through the development of a steady-state HEC-RAS model of the downstream area of concern for flooding around Bois Moquette (Figure 9). Simulated discharge values from each of the original land cover and alternatives for different return period design storms were used as the upstream inflow to the hydraulic model. Normal Depth boundary conditions were implemented using the slope derived from the hi-resolution DEM (S=0.07914). Manning’s n values used were nominal values representing natural streams (Main Channel
n=0.055, Floodplain n=0.035). The length of stream simulated to assess inundation area is approximately 2 km, which was determined by the available data and to minimize the likelihood that additional flows enter the domain that are unaccounted for.

The impact that revegetation of hillslopes has on inundation area of various return period storms is illustrated in Figure 15. The 35-yr return period results are omitted from the figures due to the finding that hillslope revegetation impact is negligible in that case. Figure 15 show that while hillslope vegetation has significant impacts on the 1-yr storm, this impact is reduced dramatically when storms of larger magnitudes fall on the area. Differences between the impacts of the higher return-period storms depend on the magnitude but also on the time distribution of the precipitation within the storm duration.

3.4 QUANTIFYING POTENTIAL IMPACT OF CHANNEL REVEGETATION

Ravine Millet and its tributaries are ephemeral channels that flow with water only when precipitation events occur of sufficient magnitude to generate runoff, leaving them dry for most of the year. In addition, there are many years when bankfull flow does not occur at all. The absence of regular flow represents an opportunity to establish vegetation in stream channels, riparian buffer strips, and dense floodplain vegetation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Length [m]</th>
<th>Slope [m]</th>
<th>Bottom Width [m]</th>
<th>XS Side Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millet Head</td>
<td>1671</td>
<td>0.140155</td>
<td>16.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Millet Mid 2</td>
<td>1610</td>
<td>0.183413</td>
<td>25.4</td>
<td>0.86</td>
</tr>
<tr>
<td>Millet Mid 3</td>
<td>100</td>
<td>0.08343</td>
<td>11.8</td>
<td>0.73</td>
</tr>
<tr>
<td>Millet Mid 4</td>
<td>1075</td>
<td>0.125651</td>
<td>12.0</td>
<td>1.36</td>
</tr>
<tr>
<td>Millet Mouth 1</td>
<td>955</td>
<td>0.1062</td>
<td>15.0</td>
<td>2.95</td>
</tr>
<tr>
<td>Millet Mouth 2</td>
<td>990</td>
<td>0.09266</td>
<td>30.5</td>
<td>2.95</td>
</tr>
<tr>
<td>Trouchat</td>
<td>800</td>
<td>0.284034</td>
<td>14.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Balanyen</td>
<td>1491</td>
<td>0.268923</td>
<td>6.9</td>
<td>0.79</td>
</tr>
<tr>
<td>Fortain</td>
<td>1570</td>
<td>0.231762</td>
<td>2.0</td>
<td>0.79</td>
</tr>
<tr>
<td>Fermat</td>
<td>773</td>
<td>0.159455</td>
<td>8.0</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The set of inputs to the KRM was derived using design storms from different return period storms. Input design storms were of hourly resolution and were disaggregated to minute inputs, whereby uniform hourly values were used as 60 individual 1-minute forcings. This disaggregation was required to ensure that sub-hourly impacts were not missed during the simulation.

These storms were used as forcing for the hydrologic model described above. In order to best represent flood wave propagation from the tops of the tributaries to each sub-catchment outlet, the Time of Concentration of each sub-catchment was reduced to one minute, thereby representing a nearly instantaneous response from each sub-catchment. The hydrograph derived from each sub-catchment with minute resolution was used to obtain the upstream-most and lateral inflow hydrographs to the Kinematic Routing Model. Domain geometry was derived using ESRI ArcMap and the 0.09m resolution aerial imagery and DEM to define stream channel thalwegs, average cross-sections for

Figure 17. System geometry for Kinematic Routing Model. Geometric values found in Table 4.
individual reaches, and downstream slopes for each stream reach (Table 4; Figure 17).

The impact that revegetation of channels has on inundation area for various return period storms is illustrated in Figure 18. Despite having a greater total volume and marginally higher input hydrograph, the 2-yr design storm results in significantly higher maximum instantaneous discharge at the outlet than both the 5- and 10-yr storms.

With the exception of the 2-yr storm, additional vegetation in the channels results in additional reductions in inundation area. In addition, during a 1-yr return period storm, according to this investigation, there is no additional benefit from going from a 109% to a 145% increase in the amount of vegetation in the channel. Finally, the impact of channel revegetation is reduced during larger storm events associated with the 35-yr return period storm.

The other assessment was an analysis of the time of arrival of the peak discharge at the catchment outlet. Figure 19 illustrates the change in arrival time for different return period storms as a function of increases in channel roughness (due to increased in-stream vegetation). These results show that while in most cases additional in-stream vegetation slows the arrival of the peak discharge (positive values in y axis), there are some cases where additional vegetation actually decreases the time to peak. In addition, while the 2- and 5-yr return-period storms have a relatively normal and predictable response to increases in channel vegetation, other return-period storms have responses that vary widely.

Lastly, the changes in time to peak due to channel vegetation can be significant, e.g., on the order of one to two hours change.
3.5 QUANTIFYING POTENTIAL IMPACT OF GABION DAM CONSTRUCTION

The subsequent step in this strategy allows the user to input gabion dams between segments to simulate their impact on flows through the domain. Assessment of gabion dam impacts to flow were determined by first estimating outlet discharges with no gabion dams, then tests were run with the existing 19 gabion dams already constructed by IOM Haiti. Lastly, an additional 38 gabion dams were added to the domain representing the construction of gabion dams throughout all of the tributaries and the main stem of Ravine Millet.

Gabion dams act to impound a volume of water based on the height of the dam, the width of the stream channel at the dam site and immediately upstream, and the slope of the stream bed behind the dam. Flows continue downstream only after the total storage of the dam is filled. The sequence of filling and overtopping continues downstream as flows reach subsequent gabion dam structures. Figure 20 illustrates the impact of gabion dams on the discharge at the outlet of the catchment. The analysis shows that the gabion dams:

1) Reduce the severity of the initial flood wall,
2) Increase the time to peak flow,
3) Reduce discharge of peak flow,
4) Have minor impacts on the duration of flow.

![Figure 20](image)

Figure 20. Catchment outlet hydrographs for the 1-yr return period storm with the nominal roughness value (Manning's n=0.055) and with no gabions and gabions.

![Figure 21](image)

Figure 21. Percent change in peak discharge at outlet for both existing (19) and many (57) gabion dams as related to conditions without any gabions for various return periods (1-, 2-, 5-, 10-, 35-yr) and roughness conditions (a) n=0.055, (b) n=0.095 (increase of 73% from nominal), and (c) n=0.135 (increase of 145% from nominal).
For the nominal roughness values \((n=0.055)\), Figure 21a illustrates that for the majority of cases construction of gabion dams will decrease the flood peak discharge by less than seven percent. However, Figures 21b and 21c illustrate that the combined impact of roughness and gabion dams has the potential to increase the peak discharge of many different return-period storms.

Figure 22. Changes in Time to Peak in minutes at outlet of catchment for both existing (19) and many (57) gabion dams as related to conditions without any gabions for various return periods (1-, 2-, 5-, 10-, 35-yr) and roughness conditions (a) \(n=0.055\), (b) \(n=0.09\)

The larger and more notable impact of gabion dam construction is in regards to the time delay of peak arrival at the outlet of the catchment. Figure 22a through c illustrates the change in Time to Peak given gabion dam construction relative to the conditions with no dams. These figures illustrate that the combined effect of gabion dams and channel roughness can act to delay the onset of peak discharge by up to 100 minutes. Figure 22 also illustrates that this relationship is not monotonic, and in some cases peak discharges are both increased (see Figure 21) and speed up.

3.6 INTERPRETING INVESTIGATION RESULTS

Scientific investigations require great care in both their design, implementation, and interpretation of the results. This is especially true in data poor regions that are often the focus of these types of investigations. Many of the parameters used to control the relationships between variables are unknown and cannot be properly calibrated; therefore, all results should be considered as relative to a nominal or baseline state, which is also unverifiable with the given data. That said, there is a significant amount of information that is gained through this quantitative analysis. The ability to compare quantitatively the potential impact of various mitigation strategies can be combined with the costs of each strategy to determine the most effective and efficient use of scarce resources. Each location will have unique climatological regimes and hydrologic characteristics, and while many of the relationships found in the Ravine Millet investigation will likely be similar elsewhere, these results cannot be transferred directly to other locations. Nevertheless, the following interpretations, discussion, and conclusions should be thought of as a guide to interpretation of results generated from the strategies outlined herein.
3.6.1 Discussion of Ravine Millet Investigation Results

The investigation yielded some predictable and some surprising results. An important decision was to search the satellite rainfall record to identify storm patterns and durations observed by the satellite. This resulted in design storms with more realistic depictions of temporal storm dynamics, yielding much more interesting results underlying the complexity of real-world situations.

Hillslope vegetation is the most predictable of all outcomes, having a monotonic response to alternatives representing increases in hillslope vegetation. The generation of runoff from hillslopes occurs after the storage in the catchment is saturated. Water storage in a watershed is primarily a function of soil properties and depth, but also the vegetation or land cover. There is a relatively small impact that planting and contour terracing can have on the size of this storage component. This is especially true in catchments with very steep slopes, as water moves quickly downslope. This simple hydrologic concept explains why Figure 16 illustrates that larger storms are less impacted by hillslope revegetation. Available water storage in the catchment is filled relatively quickly, even in smaller events, and the remainder of the precipitation falling over the watershed will runoff to the catchment drainage system.

While not being perfectly monotonic, Figure 18 suggests that increases in channel roughness are proportional to their commensurate decreases in inundation area, at least for return period storms 1-yr through 10-yrs. In fact the same monotonic relationship is seen in the 35-yr storm albeit a much smaller impact. In addition, Figure 16 suggests a threshold relationship with respect the impact of channel roughness on peak discharge, whereby increasing roughness will reduce discharge at the outlet for increasing the size of storms until a threshold is reached and the size of the storm and the discharge generated surpass the ability of the channel roughness to have much impact.

Hydraulic theory says that flow velocities are close to zero near the streambed and increase parabolically with height away from the bed (Figure 24). Any increases in channel bed roughness will impact flows nearest to the bed surface. The further flows are from the bed (i.e. near the water surface) the less impact channel bed roughness has on those flows. This relationship may explain the threshold relationship seen in Figure 18, as larger flows exceed the potential impact of channel bed roughness due to their increased depth. This is especially true in this project site due to the narrow channels and very steep banks that result in dramatic increases in depth with increases in discharge. Channels that are wider with more gentle side-slopes will not have as dramatic depth increases with
increasing discharge, suggesting that the threshold where increases in channel roughness can impact discharge will be greater.

Figure 24. Flow velocity vectors in open channels.

The impact of increased channel roughness on the time to peak arrival at the catchment outlet is more complex and, according to Figure 19, non-linear. Figure 19 illustrates that the impact of channel bed roughness on the 1-, 2-, and 5-yr return period storms is generally monotonic, where the impact increases with increased roughness. These first three return period storms can be distinguished from the 10- and 35-yr storms in that they do not possess multiple peaks of nearly equal magnitude (Figure 14). The 5-yr storm is somewhat unique compared to other design storms in that the storm is quite long (29 hours) and does not have any significant peaks, the 1- and 2-yr storms have a single peak.

The results from the 10- and 35-yr storms are highly non-linear. For example, in the case of the 10-yr storm with an increase of channel roughness of 109%, according to this analysis, the peak discharge will arrive over 100 minutes earlier than with the nominal roughness values. The 35-yr storm also shows a non-linear response to increases in channel bed roughness, where a small increase in roughness speeds the arrival of the peak and increasing roughness then slows the peak arrival. These non-linear results can only be accounted for due to the characteristic multiple peaks of those storms, giving the opportunity for peaks that occur later in the time-series to catch up to earlier peaks resulting in an increase in flow velocities.

Flood wave propagation has a complex response to gabion dam construction. Figure 21a shows that the 19 existing gabions have virtually no impact on peak discharge values at the catchment outlet, with the exception of the 5-yr storm where the dams serve to decrease peak discharge. The fact that the 5-yr storm has relatively low peaks compared to other return period storms could account for this decrease. A decrease of 5% in the peak value of the 5-yr return period storm represents 20 cubic meters per second of discharge. The results become even more interesting when looking at Figures 21b and 21c that represent the impact of gabions dams with higher roughness values. These figures show that the combined impact of roughness and the gabion dams act to reduce and increase flood peaks or have a marginal impact, with the largest change occurring during the 10-yr storm.

Figure 25. Example of inundation area figures to be used in disaster risk reduction and preparedness
The non-linearity associated with the Kinematic Routing Model and the impact of the storm shape are also evident in the changes to the arrival of peak flows at the catchment outlet. Given the nominal roughness value, the impact to peak arrival of the gabions is quite small, Figure 22a shows that for the 2-yr storm any gabions will act to reduce the time of arrival or speed up the flood wave peak. The exception being that the 35-yr storm actually diverges, where existing gabions speed up peak arrival and many gabions slow it down by approximately 40 minutes. Figures 22b and 22c corresponding to higher channel roughness values tell a different story, illustrating that with only one exception (the 10-yr storm with Many Gabions) both the existing and many gabion dam scenarios serve to significantly slow the arrival of the peak discharge at the catchment outlet.

3.6.2 Conclusions from Ravine Millet Investigation

The opportunity to investigate multiple small-scale flood mitigation strategies represents numerous challenges. These challenges are magnified in locations with sparse data sets needed to properly parameterize, calibrate, and validate numerical models. Haiti is such a location, as there were no discharge data with which to implement standard modeling procedures. For this reason results are presented and should be considered as relative impacts to some nominal state.

Figure 26. A large sediment trap was required to protect a new bridge over Ravine Millet, due to the large amounts of sediment being transported from upstream. Gabion dam projects can negate the need for these much more expensive ones (HRC).

The conclusion that the potential impact of hillslope revegetation campaigns is limited to smaller return period storm events is consistent with other investigations. However, the investigation presented herein quantifies those impacts under these specific site conditions, illustrates the utility of the methodology of section 2.6, and puts the relative impacts in the context of other potential flood mitigation strategies.

Another important conclusion derived from the methodology implemented is the importance of how storms are represented. The often used strategy of using a single pulse storm event scaled to the maximum intensity at some time interval (e.g. mm/hr; based on available data and project goals) will miss the complexity and will not properly represent the dynamics of flooding. It cannot be understated that the existence of storm events with multiple peaks interact with geo-physical properties of the landscape that can lead to a resonance of those peaks, forming larger and faster moving flood waves. This finding leads to the important conclusion that there is no solution to mitigation of flooding done at a small scale that will impact all potential storm events. Large-scale flood control dams and a sophisticated system of levees is the only solution that will impact a very
broad range of storms, and even those sometimes fail. However, these findings also support the conclusion that small scale works do have the potential to impact many, if not all, of the most common flooding events.

These results highlight that small scale flood mitigation strategies have the most potential impact on the delay of the flood peak to downstream areas. An additional 30 to 60 minutes before the arrival of the flood peak could mean life or death for many residents in low-lying areas. In order to maximize the benefit of this delay caused by those mitigation works, construction and revegetation strategies should be paired with Warning Systems that alert residents in high risk areas of oncoming flood waters.

The development of the HEC-RAS hydraulic model used to translate changes in peak discharge into changes in inundation area can also be used to identify those high risk areas. Disaster managers in Haiti, with whom we are working, were provided polygons representing the high water mark of various return period events (Figures 10 and 25). These polygons can be opened in various map based applications and used to identify particular houses, blocks, and neighborhoods that are most at risk. In addition, HEC-RAS models can be used to assist in the design of levees by identifying the elevation required for protection under different discharges and/or other flood control structures, in the flooded regions.

Based on the fact that there is no discharge data with which to calibrate the models used, it cannot be concluded that the nominal roughness value used in this investigation represents the conditions on the ground. Conditions on the ground may be more representative of larger Manning’s n values than were used as the nominal value in this investigation. Based on appropriate guidance tables, it is unlikely that the Manning’s n value is less than the nominal value used. Therefore, the result that increasing channel roughness by 36% can add from a half hour to an hour to the time of peak arrival for a large number of storms has a relatively high degree of confidence. Although there is conflicting evidence in the literature, a significant difference between submerged or non-submerged vegetation, and a threshold where additional vegetation does not impact overall channel roughness, there is evidence that a 36% increase in channel roughness can be interpreted to mean that for every three shrubs in the channel, one is planted. This kind of information helps planners to determine the scale of revegetation campaigns and their potential impact. The results of the analysis of channel vegetation relative to hillslope revegetation impacts shows that not only will channel revegetation impact a larger number of storm events, but will also create a larger impact during smaller events.

The impact of gabion dams on the propagation of a flood wave is entirely derived from the impoundment of water behind the dam. This serves to both reduce and delay the oncoming flood peak, with the exception mentioned regarding storms with multiple peaks. Therefore, it can be

Figure 27. Example of a gabion dam that has been filled with debris and sediment and no longer has any storage capability (HRC).
concluded that more dams create more storage in the stream channels, yielding the largest impacts. This conclusion is very important to project designers. The ravines in this location are highly variable, where bottom slopes, channel widths, and side slopes vary widely from one sub-reach to the next. With the obvious caveat that gabion dams should be built in locations where they can be properly anchored into channel banks and where flows are dominantly one directional (to minimize likelihood of scour around the sides), gabion dams should also be placed in locations to maximize storage behind them, where the local downstream slopes are least and the channel is widest. This conclusion also highlights the importance of maintaining the storage potential behind each dam. Flood waters can carry a significant amount of debris and sediment. The pooling of water behind dams allows suspended and rolling particles to settle and collect behind these structures. In order for them to have maximum impact, debris and sediment should be removed regularly.

The ability to quantify relative impacts of small-scale mitigation works is important for the development of the most efficient and effective flood mitigation strategies. There are many locations around the world with similar condition to those simulated in this investigation. The conclusions derived herein represent an important step toward those efforts and are already helping partners in Haiti make decisions for future projects. While each site is unique, this investigation represents a detailed, quantifiable, and robust set of results that will apply in many similar locations and can be used by project managers to build better plans with more confidence in their outcomes.

4 REQUIRED TECHNOLOGY AND APPLICATION

The strategies, methods, and procedures outlined in this reference guide use numerical models to simulate the relationships between geo-physical variables. In the development and construction of numerical models, the accuracy and precision of the data used is paramount. In general, the precision of numerical models is directly related to the resolution of the models, and the resolution of the models should be directly tied to the resolution of the available data. The accuracy of numerical models is related to the resolution of the model, but more importantly to the robustness of the data available to calibrate and validate them. This section will describe the technology required to implement the strategies outlined in this reference guide.
4.1 DIGITAL ELEVATION DATA

A Digital Elevation Model (DEM) is a digital gridded representation of elevation, generally taken from Mean Sea Level, distributed across the landscape. The DEM is a critical data source in implementing these strategies. The DEM is used to derive all of the geometric parameters defining the hydrologic and hydraulic models; therefore, it is imperative that the best available data be used. Note that the best data does not necessarily mean the highest resolution. DEMs are used at several different stages in the development of the models used in this strategy.

4.1.1 Watershed Delineation

Watersheds are contiguous land areas where all water is drained to the same point. Therefore, watersheds can be as small or large as is necessary to investigate the area and test the hypotheses put forth. In the case of small-scale flash flood mitigation, watersheds should be of a size to define the flows output from each individual tributary where projects may be occurring and include all possible sources of flow arriving at the area of interest where flooding is occurring. Hydrologic variables such as areal extent, slopes, and lengths are all derived from DEMs.

As eluded to in Section 3.3, there are a variety of sources of DEM data:

1. Unmanned Aerial Vehicle (e.g. drone)
   a. There are many makes and models with prices ranging from a few thousand dollars (US) to several tens of thousands.
   b. Many are sold as kits that include cameras, gps, and software needed to geo-locate aerial imagery and convert the imagery to elevation.
   c. Produces very hi-resolution data (<<1m).
   d. Elevations derived from aerial images reference the highest elevation of the image, meaning the tops of trees, structures, etc. NOT the ground surface.
   e. Watershed delineation algorithms may take a very long time with very hi-resolution DEMs and may crash many programs. It may be necessary to upscale these DEMs to lower resolutions.

2. Satellite-derived DEM
   a. Shuttle Radar Topography Mission (SRTM) - 80% global coverage, 30 and 90 meter resolution.
   b. Aster Global Digital Elevation Model (GDEM) - 99% global coverage, 30 meter resolution.
   c. The most convenient location to download this data, is the USGS Earth Explorer Portal (http://earthexplorer.usgs.gov/).

3. A thorough online investigation and inquiries to local researchers and governmental and nongovernmental agencies should be carried out, as there is a huge variety of potential data sources, too many to list.
4.1.2 River Hydraulic Model Parameters

Hydraulic modeling variables can also be derived from DEMs such as channel bottom slope and river cross sections. DEMs derived from UAVs are of very high resolution, on the order of 0.1m, making them ideal to use in GIS software to ‘cut’ river cross-sections. The HEC-GeoRAS plugin to ESRI ArcMap has this built-in capability and creates the required HEC-RAS geometry file automatically; however, any GIS software can also be used to create the necessary data. In order to derive the necessary geometric descriptions for the KRM, several cross sections should be ‘cut’ using GIS software to represent unique segments within each reach defined in the hydraulic model to best represent a nominal cross-section shape in that location. The length and number of reach segments may be determined based on the heterogeneity of channel cross-sections in the project vicinity.

In steep ravines that are heavily vegetated, or where water is present, UAV-derived elevation data may not be reliable due to the fact that elevations are derived from imagery in the visible spectrum. InSAR cameras can see through leaves, and LiDAR cameras see around vegetation where it is not too dense, to image the ground surface. These cameras are much more expensive.

Extensive validation of cross-sections derived from DEMs should be implemented using aerial imagery, other stream channel data, and site visits where and when possible.

The use of Global Positioning System (GPS) units are also effective and fairly inexpensive means of gathering river cross-section data (Figure 30).

4.2 Geographic Information System Software

A Geographic Information System (GIS) is a computer system for capturing, storing, analyzing, extracting, and displaying data and its position on the Earth’s surface. GIS software and the plethora of available data has become indispensable for a huge variety of analyses, including those outlined herein. GIS has also become a course of study in many universities where GIS Science degrees and certificates are now offered.

One example of available GIS platforms is the Environmental Systems Research Institute (ESRI) with their software now called ArcMap®. Due to the extensive validation that goes into its development, the US Army Corps of Engineers Hydrologic Engineering Center built ArcMap specific plugins HEC-GeoRAS and HEC-
GeoHMS, that can be used to create the necessary geometry files for the HEC-RAS and HEC-HMS modeling software, respectively.

There are numerous other GIS software packages available both commercially and open-source free software (e.g., QGIS [www.qgis.org]). QGIS is a free open-source GIS software package that, among several of its advantages, incorporates capabilities and functionality from several other GIS packages including GRASS GIS (https://grass.osgeo.org/) and SAGA GIS (http://www.saga-gis.org), as well as a Python Console where all software system functionalities can be automated and iterated over to facilitate processing and analysis. In addition, QGIS allows users to develop plugins that are incorporated into the QGIS interface. There are many of these plugins, including one called RiverGIS (http://rivergis.com) that can be used to create the geometry files input to a HEC-RAS model. QGIS has a large number of users and user forums where solutions to nearly any problem can be found.

5 FOOTNOTES

