Flood Risk Assessment and Mitigation Using Small Unmanned Aircraft Data

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Abstract

Globally, floods are the most expensive and frequently occurring natural hazard. Geospatial technologies such as remote sensing play a crucial role in better understanding the hazard as well as in estimating the associated risk. Several detailed, in-depth research has been conducted in flood related analysis, especially in flood zone delineation and in flood risk assessment. The crucial part of any flood related research is in identifying flow direction and flow accumulation and Digital Elevation Models or DEMs form the core of the data needed. The objective of this study is to better understand the least resistant path and in determining flood zones using very high resolution remotely sensed elevation data. The increased availability of Unmanned Aircraft Systems (UAS) and the ease of data processing have resulted in the possibility of readily available solutions for flood risk assessment. Combining factors such as slope, land use and the ortho-mosaic raster, a very high-resolution flood risk assessment was conducted. The results of this project were compared with the Federal Emergency Management Agency (FEMA) flood map data for accuracy and compared to manually digitized water drain locations to assess flood mitigation efforts and approach disaster risk reduction.
Keywords: UAS, Drone Imagery, Flood Risk Assessment, Least Cost, Random Forest,

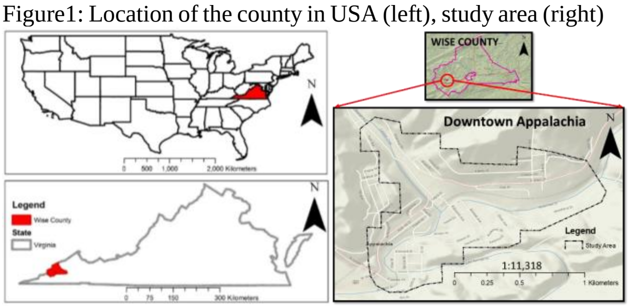
1 Introduction

In the past few decades, extreme weather events have been increasing world-wide. It has been estimated that global floods and extreme rainfall events have surged by more than fifty percent in this decade alone (Vitousek *et al.*, 2017). According to the UK National Oceanographic Center, flooding could cost 14 trillion USD worldwide by 2100. Given the damage to lives and livelihood, demand for high resolution, reliable flood risk assessment at community level has been increasing. In recent years, the use of Unmanned Aircraft Systems (UAS) are growing in popularity and there is a notable rise in case studies for flood modelling (Giordan *et al.*, 2018; Restas, 2018). A recent common practice is to intersect a horizontal plane with a Digital Elevation Model (DEM) in a 3D environment and raise the plane's Z axis until it is visible in the lower elevations, highlighting those areas where water will most likely build up displaying flood potential. However, there may be other variables such as surface texture and slope that should be considered that will impact the flow of water during a flood event and their use may increase the accuracy of the hydrological model. For instance, a steeper slope with heavy vegetation will have a much different impact on the flow of water as compared to a level area consisting of concrete. Methods and tools within ArcGIS were explored in order to reveal if there are current ways to accurately create a flood risk map using multiple variables derived from high resolution UAS data.

2 Study Area

The study area is the town of Appalachia which is located on the western side of the Commonwealth of Virginia, USA. This town is flooded annually making it a suitable location for flood risk mapping. Recent notable floods have occurred in October 2018, February 2018, June 2017, August 2016, and February 2015. Numerous buildings are impacted by these floods according to the FEMA flood risk data. According to the Virginia Department of Emergency Management the average annualized flood loss is $391,061 for Wise County and $44.104,298 for the whole state (Anon, 2012). A study area this size, approximately 5 sq. km, is hard to be inspected using traditional, freely available remote sensing data from satellites. With the best publicly available DEM at a spatial resolution of 30m, the hydrological environment of this downtown area cannot be properly analyzed.

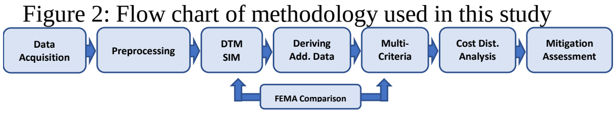
Figure1: Location of the county in USA (left), study area (right)



3 Methodology

An overview of the methodology that was used and that will be discussed in this study can be found in Figure 2. The data acquisition was done mostly through operation of UAS and additional data was obtained from the local GIS department. Then the UAS data had to be processed using photogrammetry software. The Digital Terrain Model (DTM) derived from the UAS data is initially used to show flood extents using only elevation and is compared to FEMA flood risk data to assess the accuracy. Additional data, such as slope and terrain, was then derived to increase the number of variables considered in the flood risk mapping. These variable dynamics on the hydrological environment were analyzed using multi-criteria evaluation to depict the likeliness of an area to flood. These variables were then used in a least cost-path calculation to analyze the most likely paths of water from the river to the borders of the flood extent. These least resistant areas for water flow were then compared with water drain locations to create the final results and assess flood mitigation possibilities.

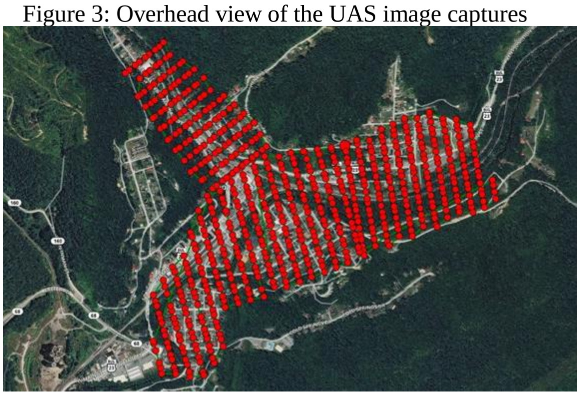
Figure 2: Flow chart of methodology used in this study



3.1 Data Acquisition

The data acquisition took place on December of 2017. This is the best time to acquire data using UAS for DTMs especially for those involving rivers. During winter there is less foliage covering the terrain so that it can be more accurately captured and calculated. The UAS was flown at 122m in altitude covering approximately 1.14 Sq. Km. and taking a total of 4 hours to complete with 4 separate flights. Overlapping images were used to process an orthomosaic and other derived products. A total of 686 photos were taken. A forward overlap of 70% and side overlap of 65% was used among the images and was calculated based on the onboard GPS of the UAS.

Figure 3: Overhead view of the UAS image captures



Additional data was gathered from the Wise County GIS Department. The data shared was the Federal Emergency Management Agency (FEMA) flood risk areas shapefile for the county and is used in comparison with the flood mapping done in this study. FEMA flood risk maps are created and maintained using data through Flood Insurance Rate maps (FIRMs) and risk assessment FIRMs include statistical information such as data for river flow, storm tides, hydrologic analyses, and rainfall and topographical surveys. In addition, infrastructure vector files were shared such as roads, railroads and building footprints to use throughout the study to make them more pronounced in certain data structures.

3.2 Preprocessing

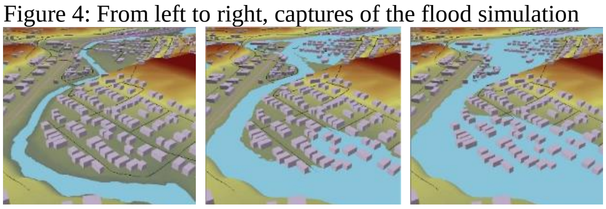
Pix4D was used to pre-process and prepare the drone imagery before use in ArcGIS. This software uses photogrammetry and computer vision algorithms to transform RGB images into 3D maps and models. Photogrammetry is the science of making measurements in photographs and to derive products such as DTMs. It uses the overlapping images to calculate the parallaxes or movements of objects in relation to the sensor position using the assistance of texture topology. The Ground Sampling Distance (GSD) or resolution calculated by the software for the 2D orthomosaic image was 2.72cm. Because of the smoothing nature of the DTM generation algorithm, Pix4D's default resolution for DTM is 5x greater than that of the project making the DTM's GSD 13.6cm. Ground Control Points (GCP) were used in the project from known locations and coordinates on the map and the final accuracies were an absolute geolocation variance RMS Error (ft) X = 8.023, Y= 17.21, Z= 11.32 and a mean geolocation accuracy (ft) of X = 5, Y = 5, Z = 10.

The DTM, which was produced by Pix4D, is an elevation model of the terrain that removes surface structures such as buildings and trees. This data structure was then imported into ArcGIS where the rest of the processing took place.

3.3 DTM SIM

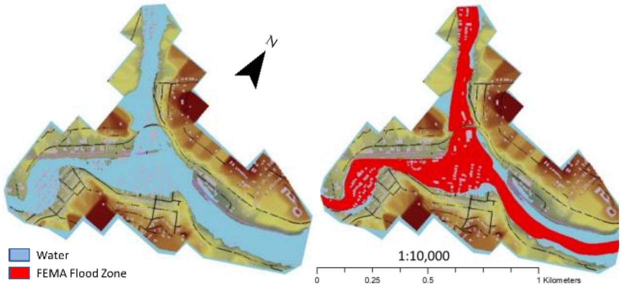
The initial step in this project was to create a flood simulation of just the DTM elevation data that intersects with an increasing plane (Z axis) representing water. This was done to assess how these current methods match up with the FEMA flood maps and then how this study can then improve on these methods. This type of model helps identify those areas that will most likely flood first because of the lower elevations. The places that are most likely to flood in the study area around the river crest can clearly be seen in Figure 4 as the water level increases.

Figure 4: From left to right, captures of the flood simulation



This simulation was created using the 3D ArcScene environment. The water level was increased until there was lack of expansion in the flood area to which this was considered the peak extent of the flood. The study area can be seen from an aerial view in Figure 5 showing how this flood extent compares with the FEMA flood map. The simulation does a fairly good job of matching the FEMA data except for some areas in the east of the study area.

Figure 5: Flood extent at peak (left), FEMA flood zone (right)



3.4 Deriving Additional Products

The concept of this project was to introduce additional variables to consider the likeliness of flooding when analyzing the flow and accumulation of water. The appropriate additional variables to include, common in hydrological projects, are slope and surface texture. Depending on the degree of slope of the surrounding area and differences between smooth (non-absorbent) textures such as asphalt and rough (absorbent) textures such as vegetation can impact the behaviour of water flow. These additional products were derived in ArcGIS using the RGB orthomosaic and DTM produced by Pix4D. The slope was calculated using the geoprocessing tool in ArcGIS. The surface textures were created using supervised classification techniques. Two different algorithms were tested, Random Forest (RF) and maximum likelihood. The RF algorithm was implemented using a R script in RStudio and is a powerful machine learning technique that uses a large number of decision trees created from random sampled selections. The maximum likelihood classifier algorithm that was used was the default one found in ArcGIS and is considered more of a statistical method based on probability of distribution models. As can be seen in Figure 6, the maximum likelihood method produced more generalized and consistent textures that would be easier to interpret further in the analysis. The generalization did not appear to sacrifice much on accuracy and was the method chosen. Five classes were created from this classification to create a map representing asphalt, gravel, dirt, grass and brush throughout the study area.

Figure 6: RF classification (left), true color RGB (middle), maximum likelihood classification (right)

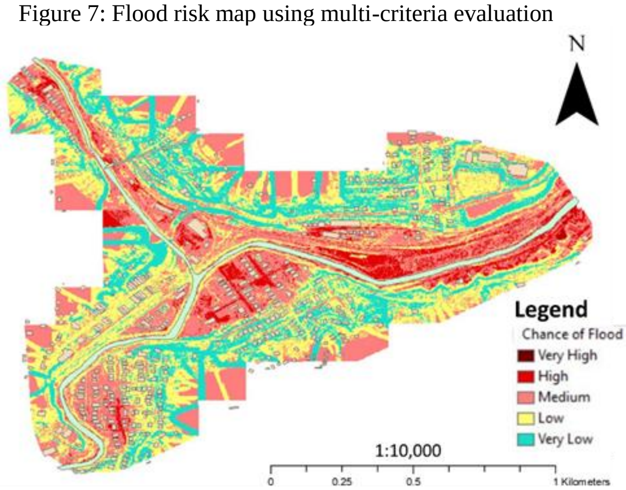
3.5 Multi-Criteria Evaluation and Selection

As the different datasets contained separate types of measurements and ranges, data transformation was done on the data values to rank them on the same scale. Rescale by Function and Reclassify was used to transform the DTM, slope and landcover surfaces to assign high and low water flow preferences to locations. Each data set was reclassified into 5 classes. For example, class 1 represented ranges of less resistance to water flow and class 5 represented ranges of high resistance to water flow. These parameters were obtained from a combination of typical water runoff values such as those slopes under 20 degrees having the largest amounts of change in impact and terrain analysis concerning water area increase in height increments after river crest is surpassed. The classes for each data set was structured as follows:

- DTM elevations (ft)_ - Class 1: 1335.16 – 1350, Class 2: 1350 – 1384, Class3: 1384 – 1400, Class 4: 1400 – 1405, Class 5: 1405 – 1556.16
- Slope (degrees) – Class 1: 0.0 - 0.5, Class 2: 0.5 – 5.0, Class3: 5.0 – 10.0, Class 4: 10.0 – 20.0 Class 5: 20.0 – 88.4
- Surfaces - Class 1: Asphalt, Class 2: Dirt, Class3: Gravel, Class 4: Grass, Class 5: Brush

As the data was now transformed under the same scale, the next step was to combine the layers. Using geoprocessing tools or raster functions, the transformed layers were combined onto a surface that would show the least resistance to the flow of water. When combining layers in a weighted suitability model, weights were applied to each layer based on their relative importance. The following weights were applied out of a 100: 50 for elevation, 40 for slope, and 10 for surface. The resulting surface, Figure 7, can be used to locate areas based on their likeness to flood from the combined attributes discussed. This result was compared with the FEMA flood map to investigate the accuracy, which can be referenced from figure 5. The similarity is high, but it is also dissimilar in certain sections of the study area. This is because FEMA is a national level flood estimate whereas this is a local level estimate. Since there is a conflict in scale and methodology some dissimilarities are bound to rise.

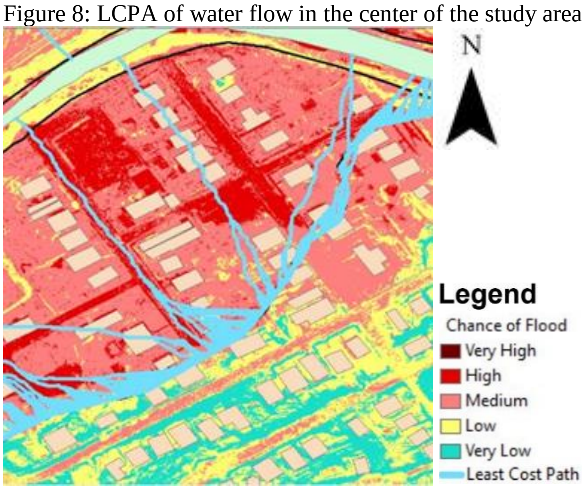
Figure 7: Flood risk map using multi-criteria evaluation



3.6 Least Cost Path Analysis (LCPA)

It should be noted that more research is needed regarding this type of study with water flow and flood analysis. Most Least Cost Path Analysis (LCPA) studies focus with the analysis of transport operations for various problems. LCPA was tested on downtown Appalachia using the spatial analyst function in ArcGIS. For finding the best "cheapest" route for the flood water to take, the least-cost path based on the spatial analysis functions of ArcGIS were utilized. Here, there were three important datasets that were required. They are the source, cost weighted distance and destination. Source is the origin of the water, which in this case is the river. The cost weighted distance is the cost distance raster produced by the spatial analyst functions which use the resulting surface from the multi-criteria evaluation discussed in the earlier section. It produces the cost raster and a backlink raster or direction raster that helps in calculating the least cost path for the flood water. The direction raster provides the route to take from any cell, along with the cheapest path, to the nearest source. The cost datasets or cost raster determines the cost of travelling through each cell. Although the cost raster is a single dataset, it is often used to represent several criteria. The destination was the outer border of what was evaluated as the probable extent of a severe flood in this location. The output is an output raster where each cell is assigned a value that is the least accumulative cost of travelling from each cell back to the source for instance the lower the value, the lower the cost. The routes produced will be in areas that we may want to inspect for the reasoning of these results, possible flood sources, and flood water paths.

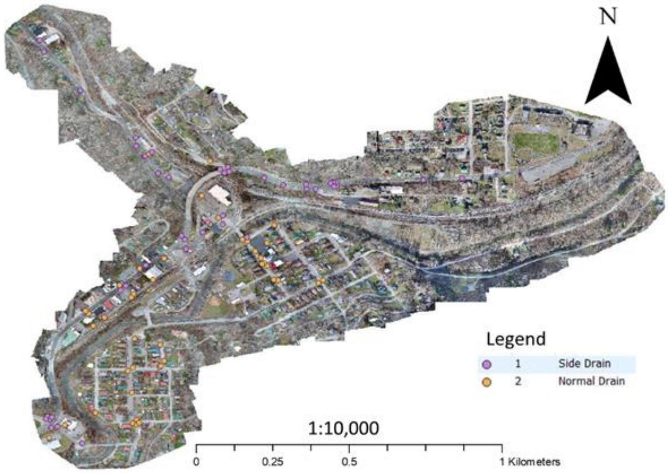
Figure 8: LCPA of water flow in the center of the study area



4 Results

In order to assess what flood mitigation efforts are already in place and those that might need to be added, the water drains were digitized within the study area. Those drains that are located on the side of the roads underneath sidewalks have been labelled as side drains and those drains found in parking lots and roads that are upward facing have been labelled as normal drains as can be seen in Figure 9. These two types of drains have been differentiated in order to understand the infrastructure layout.

Figure 9: Digitization of the water drains in the study area



With a closer look from figure 10, the right image shows how the drains can be easily labelled from the high-resolution imagery captured with the UAS. With the map overlaid with the LCPA data, as seen in the left image, it can be seen how the placement of water drains can be analyzed. The road in the middle of the image appears to have conditions suitable for increased water flow from flooding and which is why there may already be a high density of drains existing along that road. However, it seems there may be other areas from the river crest to the flood extent that need to be examined for possible placement of water drains or barriers.

Figure 10: Zoomed center view of the drains and LCPA (left) and a closer view of the drains and waterflow (right), demonstrating the data resolution from the UAS

5 Conclusion

This study clearly shows the advantage of using UAS for conducting very high-resolution flood risk assessment. Although coverage area is limited with UAS, the added value of community level flood mapping is high. This study also provides evidence that there are tools that can be used within a GIS software such as ArcGIS that supports flood risk mapping with UAS data. This study is an early adaption of these methodologies used for this purpose and improvements in parameters should be expected.

Acknowledgements

The Master program in Geospatial Technologies is funded by the European Commission within the Erasmus+/Erasmus Mundus program, grant agreement 2016-2054. http://mastergeotech.info/

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