Is HAND an Effective Tool to Model Dam Failure?

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Introduction

Teton Dam is located to the northeast of Rexburg, Idaho. Construction of the dam was completed in October of 1975. The dam was approximately 305 feet tall, with a storage capacity of 251,700 acre-feet (Graham 2008). During the process of filling the reservoir, the dam began experiencing leakage, which resulted in the dam's eventual failure. This resulted in a flood event that drained 240,000 acre-feet of water within 6 hours of when the breach occurred. The peak discharge of the initial flood was 2.3 million cubic feet per second (cfs) that gradually declined as the water level dropped. In the process of the flood, 771 homes were destroyed, 3002 homes were damaged, and 11 people were killed. Research has been conducted to understand the reasons for the failure and how to prevent it in other dams. This project will focus on predicting flood inundation areas created by dam failures and evaluating if GIS is an effective modeling tool, specifically the HAND method.

Figure 1. The Teton dam during the failure.

The Teton Dam flood event inundated an area that stretches from the dam's location all the way down to American Falls Reservoir, approximately 100 miles to the southwest. An area of this size would be beyond the scope of a semester. For the purposes of this project, the area that will

be analyzed encompasses the area from the dam's location to where the Teton River empties into Henry's Fork River, west of Rexburg, Idaho.
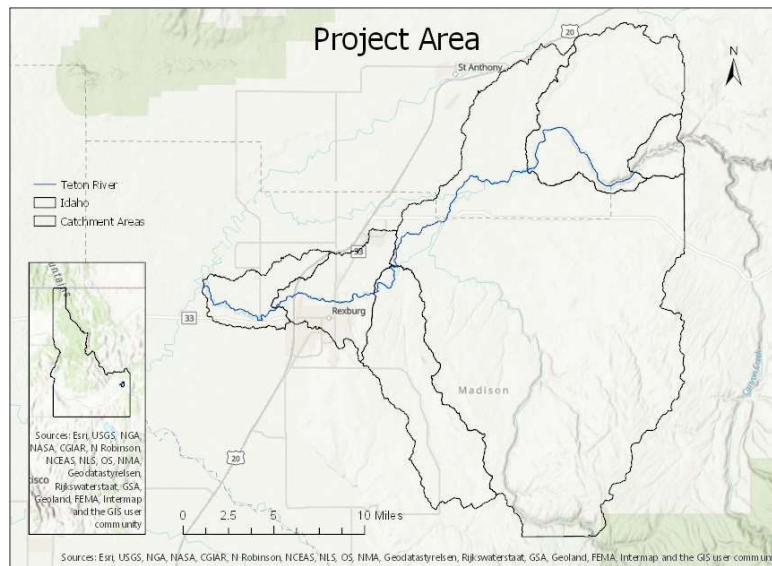
Figure 2. A map of the project area.

Methodology

The term HAND is an acronym that stands for Height Above Nearest Drainage. Through a series of steps, a raster is created that assigns a value of zero for the streambed within a catchment area. Using a Digital Elevation Model (DEM), a height is calculated for each grid cell based on the elevation of the nearest drainage point. Using this HAND map a flood inundation depth can be calculated that mimics a flood event.

For the analysis in this project, several different analyses were conducted to map the flood inundation area. All analyses utilized the HAND method with only slight differences. This section will discuss the general procedure for the HAND method and then comment on the differences in each of the analyses.

Hand Method

The first step in the process of creating the HAND map was acquiring the data sources. For the Hand Method, a DEM was required. Catchment and stream features were also used. The DEM, catchment, and stream data came from the National Map online tool, created by the USGS. A 10-meter DEM tile was selected that encompassed the area of interest.

These data were brought into ArcGIS Pro. Using the Feature Vertices to Points tool, points were created at the ends of the stream vertices. These points were used to create a raster that establishes a grid cell with the value of one at the start and zero at the end of the river using the Feature to Raster tool. These values were then reclassified such that nodata cells are also assigned a value of zero.

The next step was to derive the stream network. The DEM is hydraulically conditioned using the Fill tool to remove sinks. Then the Flow Directions tool was used with the D8 method. The flow Accumulation Tool uses the stream start points raster for the weighted flows and creates a stream path based off the flow direction raster. Then using the CON tool a new stream raster was created to only show grid cells with a value greater than one. The Flow Direction tool was then used again with the Dinfinity method to be used in calculating distances to the drainage points. The final tool used was Flow Distance which calculates the height above the nearest drainage point or HAND.
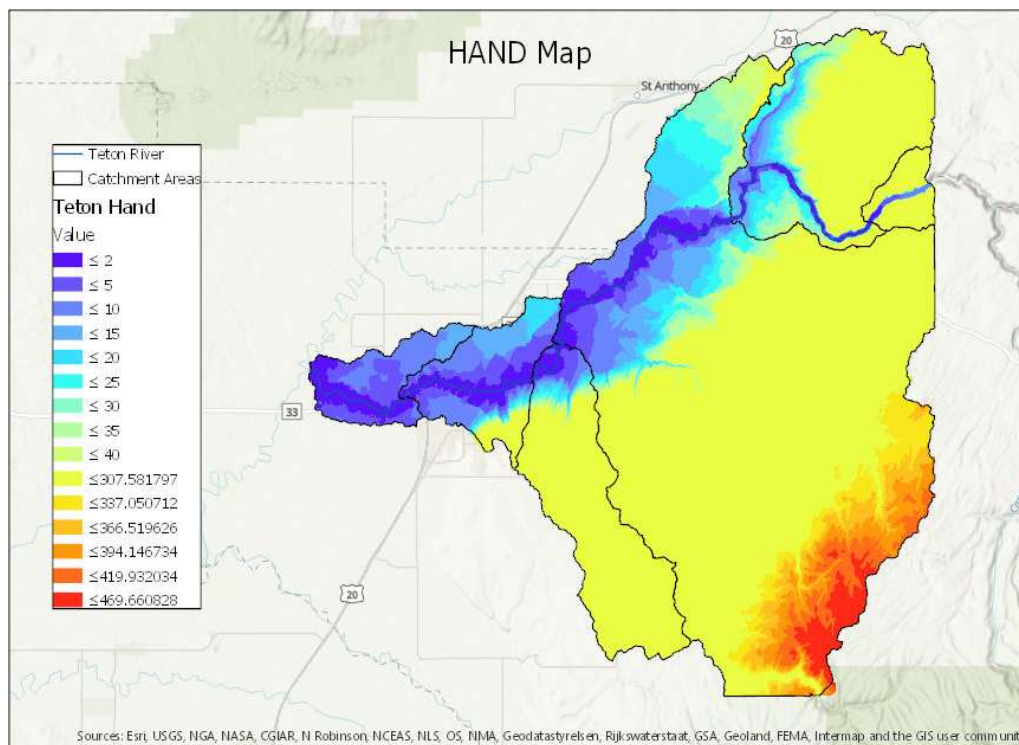

Figure 3. The HAND map created for the third analysis.

The HAND map was created for the whole area but the actual calculations were done on smaller catchment areas to be more accurate and better represent the flows. Using the extract by mask tool, the hand map is clipped at the boundaries of each of the catchment areas. After the Hand map was clipped, the raster calculator tool was used to create several hydraulic property rasters that represent the hydraulic properties of the flood area for a specific catchment. The first calculation uses the HAND raster created for the catchment area and evaluates it to show the area of the map that has a value less than one meter, or whatever depth is being evaluated. This raster is used to determine the flood area by multiplying the number of cells with a value less than one meter and multiplying by the area of each cell. The next raster that is calculated evaluates the inundation depth for the flooded area at a stage height of one meter. The final raster created calculates a bed area for the flood area. The average bed area is represented by a number just slightly greater that one that is multiplied by the flooded area that was calculated from the first raster.

Table 1. The data taken from the raster is used in the table to calculate the flow.

	1	5	9	10	15
Stage h (m)	1	5	9	10	15
stage (ft)	3.28	16.40	29.53	32.81	49.21
cell size (m^2)	100	100	100	100	100
flooding cell num	32479	160507	237089	252984	306909
sb	1.000083	1.000120976	1.000137301	1.00013737	1.000159267
As (m2)	3247900	16050700	23708900	25298400	30690900
Ab (m2)	3248169	16052641.75	23712155.26	25301875.24	30695788.06
Inundation depth (m)	0.676951	2.628010793	5.154139898	5.805209794	9.407500308
Depth (ft)	2.22	8.62	16.91	19.05	30.86
V (m3)	2198669	42181412.83	122198987.4	146862519.5	288724651.2
L (m)	8979.5	8979.5	8979.5	8979.5	8979.5
A = V/L (m2)	244.9	4697.5	13608.7	16355.3	32153.8
P=Ab/L (m)	361.73	1787.70	2640.70	2817.74	3418.43
R=A/P (m)	0.677	2.628	5.153	5.804	9.406
S	0.001346	0.001346	0.001346	0.001346	0.001346
n	0.05	0.05	0.05	0.05	0.05
$Q = 1/n*AR^{2/3}*So^{1/2}$ (m3 /s)	138.5	6563.5	29792.0	38760.0	105128.6
Q (ft3 /s) = Q (m3 /s) x 35.3	4889.3	231692.8	1051656.1	1368227.2	3711040.2
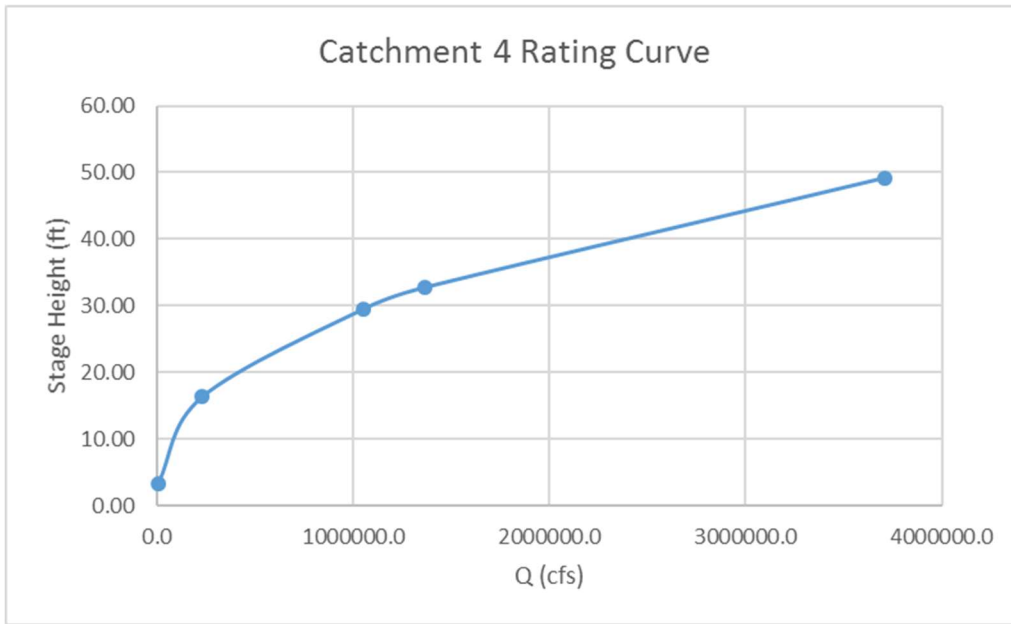
Figure 4. The rating curve created from the hydraulics spreadsheet.

Using the values from the hydraulic rasters, in addition to the cell size, reach length, slope, and the manning's coefficient, Volumes are calculated as well as the cross sectional area, wetted perimeter, hydraulic radius and finally the total flow. The process of creating the flood raster calculations was repeated several times at varying depths to create a rating curve that was used to pinpoint the precise inundation depth for the target flow as shown in Table 1 and Figure 4. For the purposes of this project, the initial peak discharge of 2.3 million cfs (Graham 2008) was used for the river reaches of the Teton River, and 1.07 million cfs for the South Teton fork. The 1.07 million cfs value was determined from data downloaded from the USGS stream stats tool. There is a gage located just downstream of the dam on the Teton River and another gage located on the South Teton River. The flow from the south Teton River gage is divided by the flow from the Teton River gage to determine percentage of discharge that flows down the South Teton River after the fork, see Table 2 for details.

Table 2. South Teton River flood Discharge.

|	Flow (cfs)
Teton River	394
South Teton River	184
% of total:	0.467005076
Flow for South Teton River:	1074111.675

1st Analysis

The first analysis of the flood model was completed using NHDPlus catchments. This was not an effective way to model the flood area as the catchments were very large. Only the streams of interested were given the seed points which start far upstream of the dam location. In the process of creating the river vertices, a mistake was made and the raster of the river only included the section of Henry's Fork River in between where the Teton and South Teton rivers drain. This created an inundation depth map of the flooded area from the Snake River shown in Figure 5, which is not included in the scope of this project.
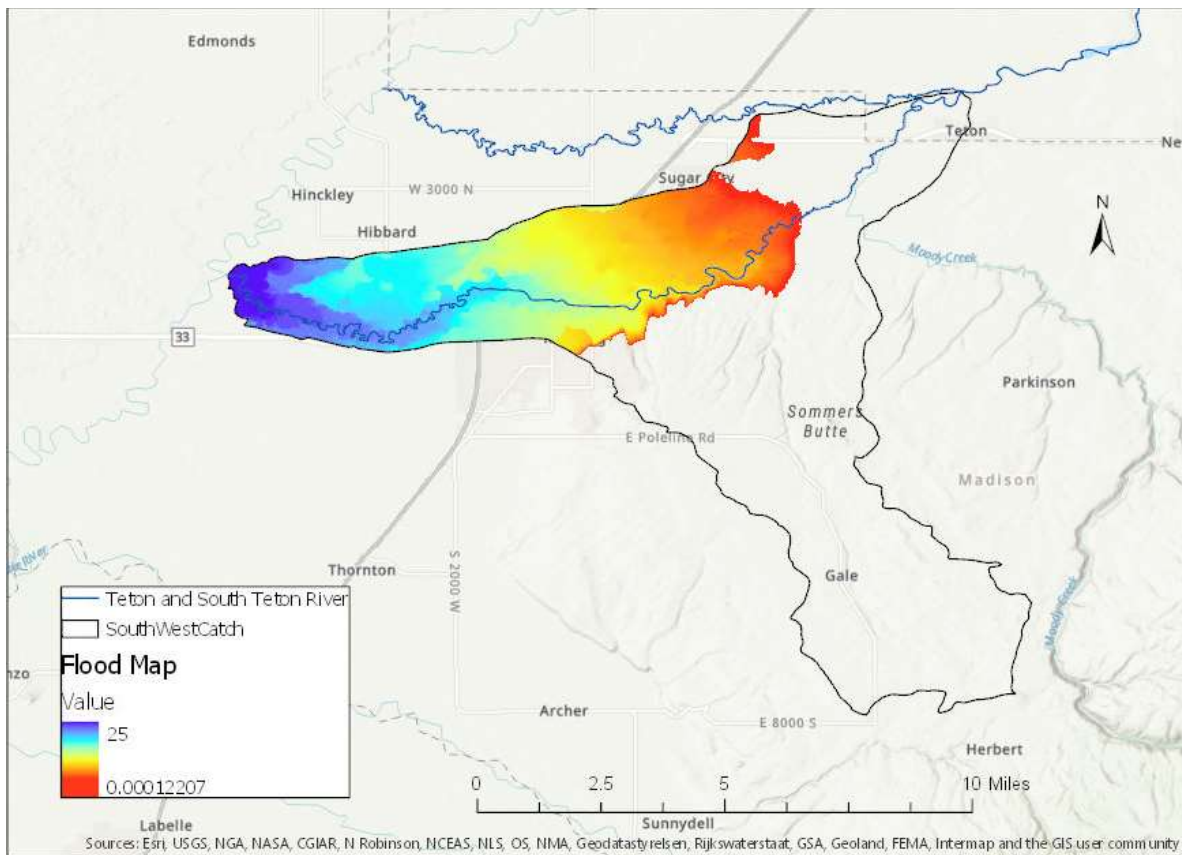
Figure 5. Results from the first analysis.

2nd Analysis

After the first analysis didn't work, the process was repeated using DEM derived catchments and streams. A seed point was placed at the location of the dam breach. This analysis was much more successful than the first as shown in Figure 6. One of the limitations of this analysis was that several of the catchment areas were smaller than the extent of the flood area and were not useful when comparing with the actual flood area.
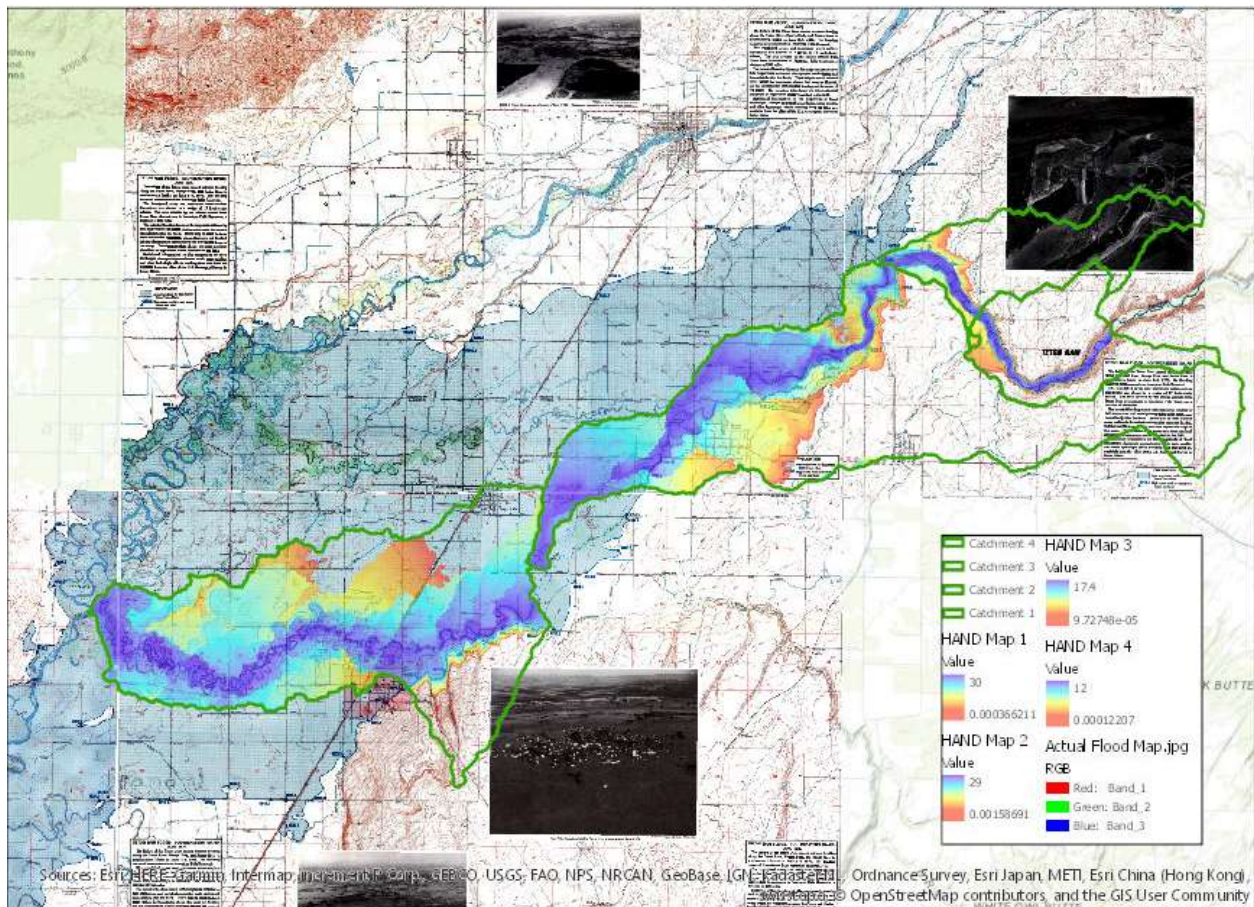

Figure 6. The flood map created for the second analysis.

3rd Analysis

Based on a suggestion from Dr. Tarboton, and with his assistance, the third analysis also used DEM derived catchments and streams, but these were created using the TauDem program tools, which simplified the process. Also, only the South Teton River was modeled and for the analysis the river was separated into five reaches the largest being 16000 meters, which is approximately 10 miles. The catchments were derived for each reach making the catchment areas better for the

analysis by allowing more of the inundated area to be mapped. Since there were five catchment areas needing to be evaluated at varying depths, the model builder was used to speed up the process. Each of the five clipped HAND maps were input into the model builder and used to create the hydraulic properties rasters at depths ranging from 1m to 30m. After the rating curve was created the flow was pinpointed to most accurately depict the inundated area for each stream reach. The resulting map can be seen in Figure 7.
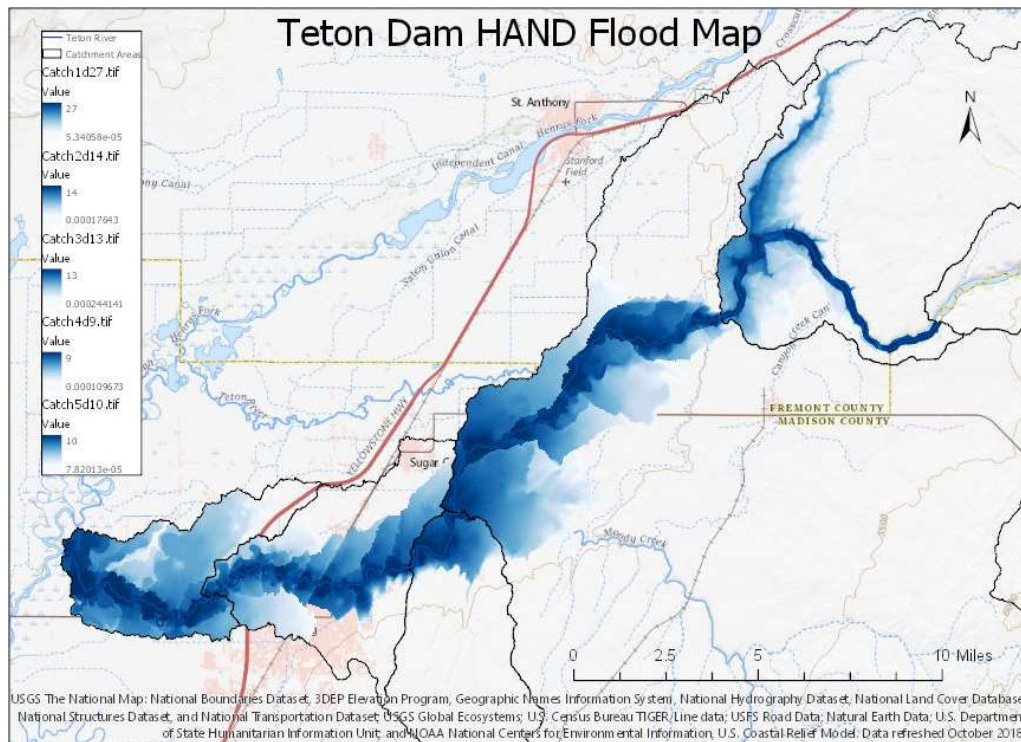
Figure 7. The flood map from the 3rd analysis.

Results

In order to most effectively compare the inundated areas with the actual areas that were flood by the Teton Dam failure (Thomas 1976), maps of the actual flood were converted into .jpg format and imported into ArcGIS. Once imported the images were georeferenced to be placed at the appropriate locations on the map. Figure 8 shows the comparison between the actual flooded area and the HAND calculated flood area. For the most part the HAND calculated flood area is fairly similar to the actual flooded area. The analysis focused on the south region of the flood event as the Teton River downstream of the was not included in the analysis.
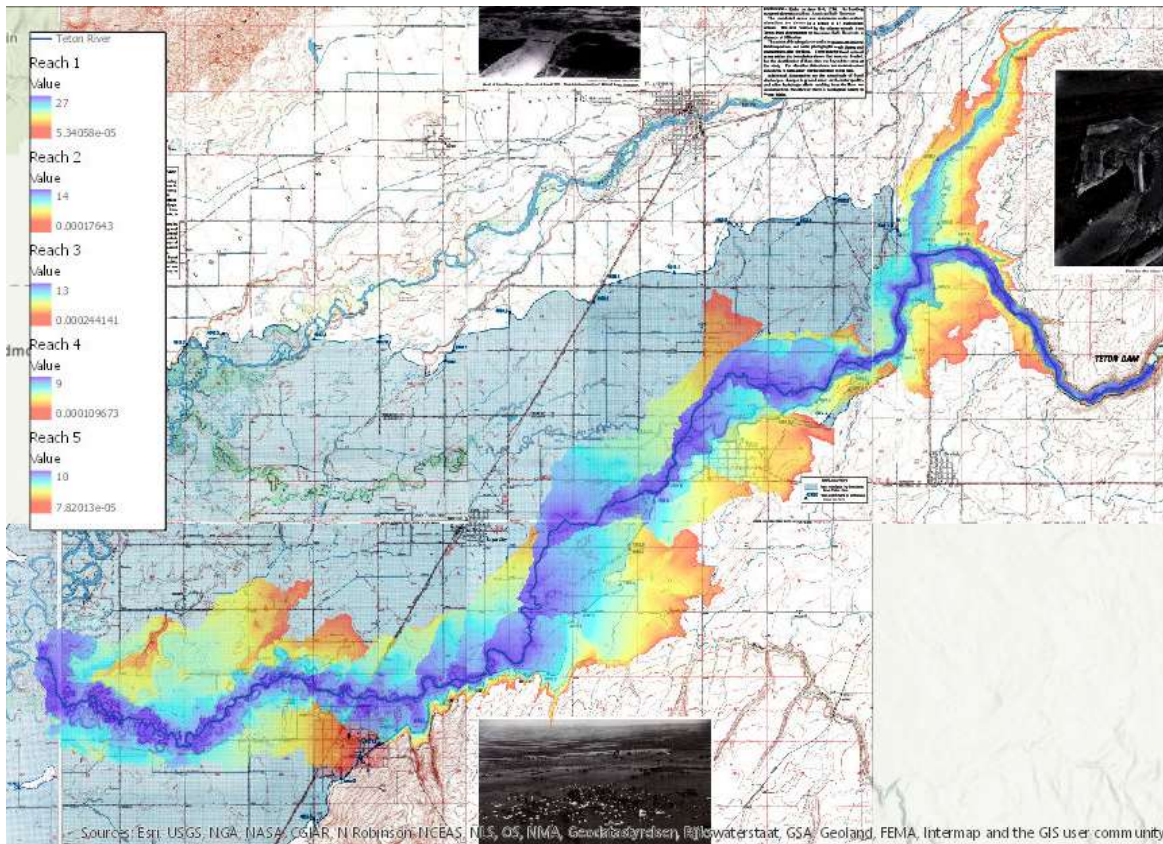
Figure 8. A map comparing the HAND calculated flood map with the actual flood area.

Discussion

While the flood was contained within the canyon just downstream of the dam, the flood area is fairly accurate as shown in Figure 9. The section of the river that extends towards the top of figure 9 however is visibly less accurate. The HAND calculated flood extends well beyond the actual flooded area. And as the flood event propagated downstream out of the canyon area the discrepancies increase and the difference is much more apparent.
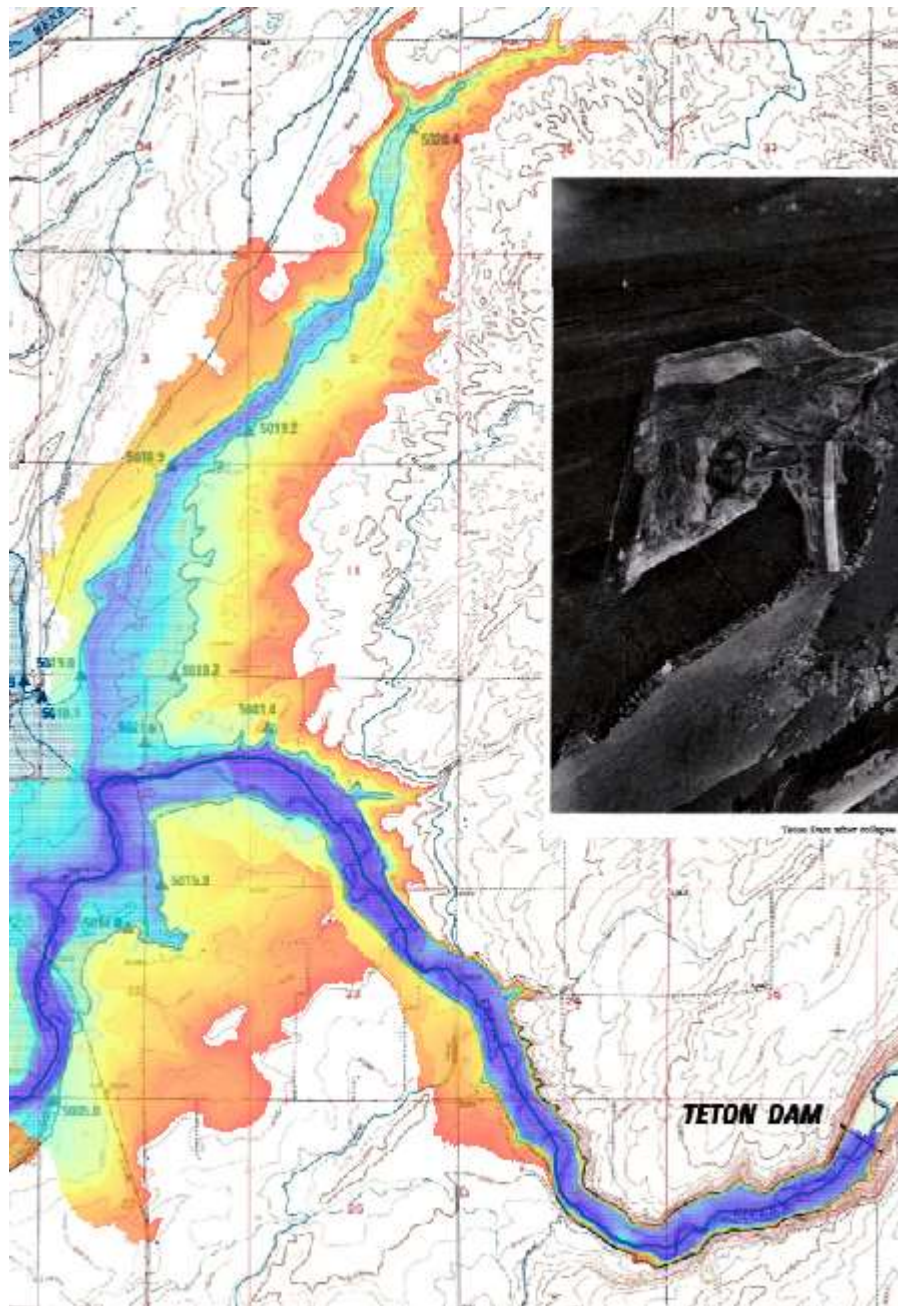
Figure 9. A close up of the canyon area.

It is interesting to note however, that in some areas the blue section of the HAND map matched up fairly closely with the line representing the actual flood map. It appears that the HAND map still follows the actual topography and the limitations are more as a result of the hydraulic calculations. Since the hydraulic calculations don't take into account the actual hydraulics of the river, the HAND map is only able to approximate the flood area based only on the depth. Upon

closer examination of the map, the darker blue section of the HAND flood map more closely follows the actual flood boundaries shown in Figure 10.
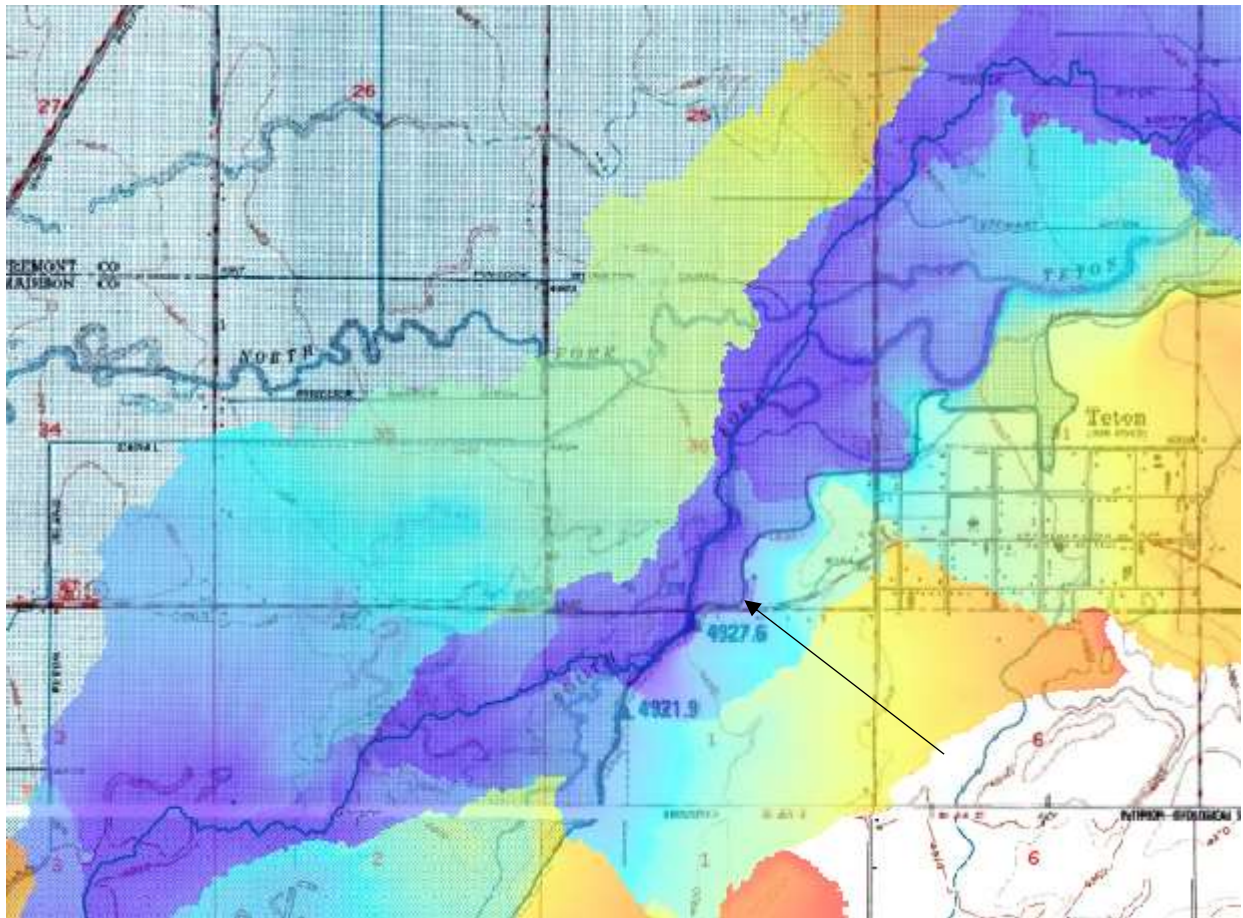
Figure 10. A map showing the similarities between certain depths.

Another limitation of the analysis was the use of a 10-meter DEM. This was the most precise DEM data available for this area. For more accurate results a 1-meter DEM should be used.

Conclusion

GIS was used to evaluate the effectiveness of using HAND in modeling a flood event created by dam failure. The Teton Dam was used as the case study for the analysis. The HAND maps were used to calculate the hydraulics of the flood event. A depth was selected for each river reach that corresponded with the actual flows of the Teton Dam failure. The HAND maps were compared against maps of the actual flood area to determine the accuracy of the HAND method in modeling a dam failure. Based on the analysis, HAND is a very quick method for determining the general behavior of a flood. The accuracy is limited by the availability of DEM data, the

hydraulics of the river, and the slope of the terrain. Overall, HAND is an effective tool when the analysis needs to be quick to give a basic idea of the flood area. When a more accurate analysis needs to be done, other programs such as HEC-RAS or CFD modeling would be more effective.

Sources

Graham, Wayne J. (July 30, 2008). "The Teton Dam Failure-An Effective Warning and Evavuation." < http://damfailures.org/wp-content/uploads/2015/07/075_The-Teton-Dam-Failure.pdf> (November 20, 2018).

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