CENTRAL TEXAS HILL COUNTRY FLOOD

Term project report

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CE394K: GIS in Water Resources Engineering
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Introduction

When rushing floodwaters in the Llano River completely wash away a bridge in Kingsland on October 16th, 2018, it was certain that a devastating flood in the region was on the way. The same day, the river reached the highest height in more than 80 years. A series of evacuations were set on for multiple cities in the Central Texas Hill Country, roads and property were inundated and damaged, and water boil notices issued due to overwhelmed water treatment plants in addition to several casualties along the way. (Kvue, 2018)

The purpose of this report is to provide a GIS analysis of the flood in order to assess the situation based on the hydrological models, tools and datasets at our disposal. The main software used in this work is ArcGIS Pro, and the tools include spatial and hydrological analysis to help provide better insight and understanding of the situation.

Context

The recent Central Texas Hill Country flood event is only one of a series of frequent floods in the region. In fact, due to its position largely affected by weather patterns between the Atlantic and the Pacific oceans, the state of Texas extreme weather conditions have almost become the norm. Additionally, the region that extends from the southwest to the central north of the state is known as the Flash Flood Alley which is considered one of the most flood-prone regions in the whole continent (Texas Water Resources Institute, 2016). The map in figure 1 below shows the number of flood events over the period from 1996 to 2016. (Federal Emergency Management Agency, 2017)

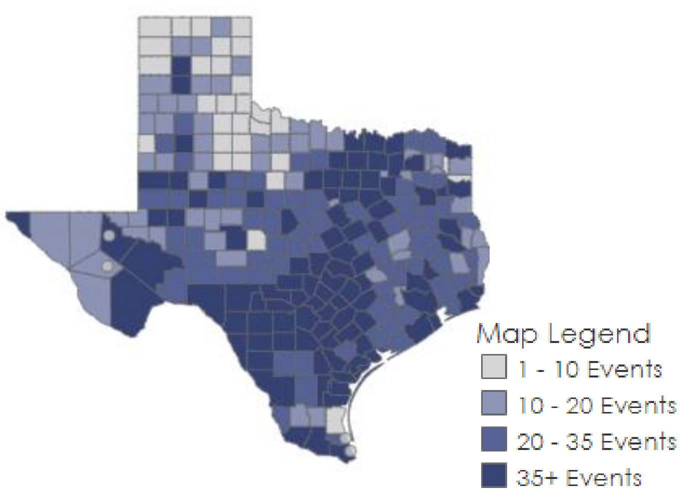

Figure 1. Flood events in Texas (NOAA's Storm Events Database 1996-2016)

It in fact illustrates the concentration in the Flash Flood Alley where the Highland lakes are located. Clearly, the region where the flood occurred is familiar to such events. However, as the news unfolded, the magnitude was obviously exceptionally high. As we look at what happened around mid-October 2018, the stream gage at the Llano river at Llano recorded 2 peaks with the highest one on October 16th at a staggering 40.17 feet, which is 30 feet above the flood stage. This is only around 1 ft lower than the highest crest ever recorded by the stream gage at 41.5ft in 1935. Figure 2 shows how the gage height evolved during the month of October. (United States Geological Survey, 2018)

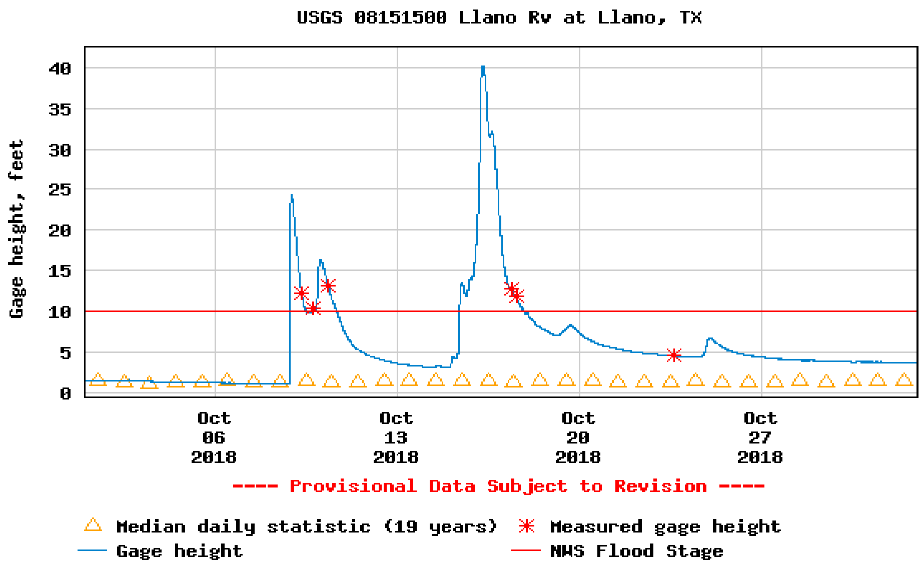

Figure 2. USGS Stream gage height, Llano River at Llano, TX

Basemap and focus area

Based on the national geospatial framework, NFIE-Geo, we can use the portion of the dataset for the Texas-Gulf Region that covers the USGS Water Resources Region 12. Along with the Colorado river, 2 other rivers and streams that drain to the Texas Gulf Coast are represented in this dataset. This allows to extract features for the watersheds and subwatersheds in the Highland lakes basin that consist of NHDPlus catchments and flowlines. The coordinate system chosen to project all feature datasets and rasters in the scope of this project is the North American Datum of 1983, Zone 14N.

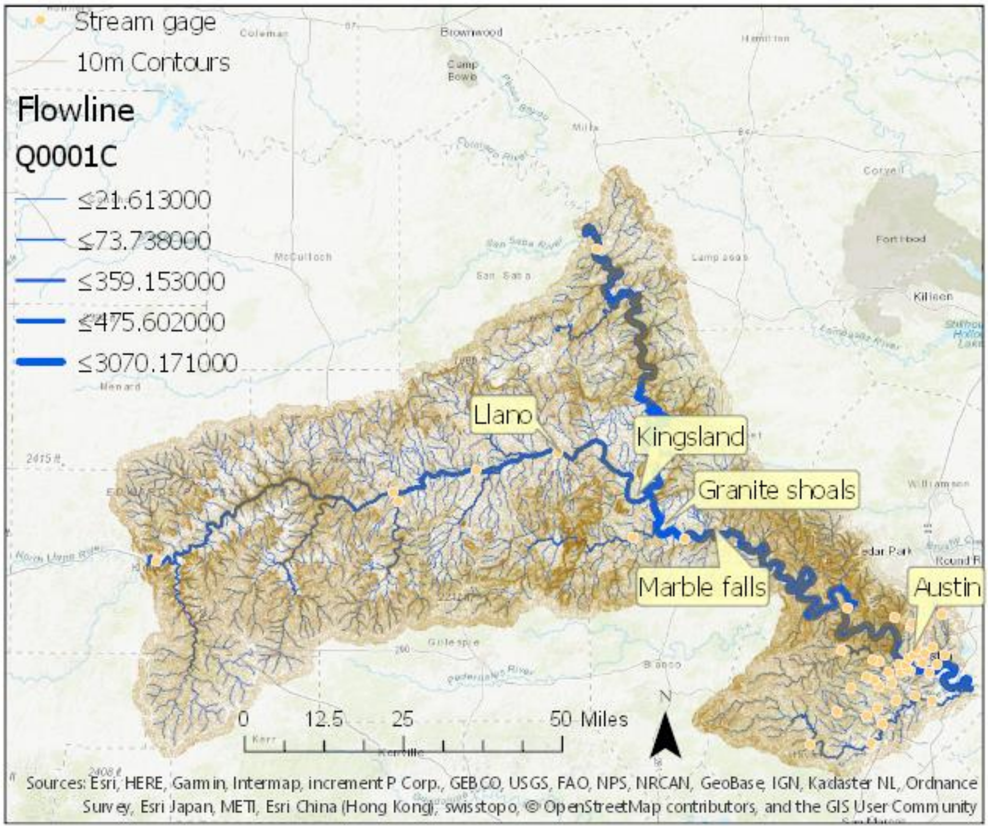

Figure 3. Map of the Highland lakes basin

The map in Figure 3 gives an initial idea about the hydrology of the basin based on the NHDPlus dataset and shows where stream measurements are taken. The symbology for flowlines reflects the the mean annual flow of each flowline in cubic feet per second (field Q0001C) which, added to the 10m contours, puts into perspective the basin's hydrology. Also indicated are the cities of Llano, Kingsland, Granite Shoals and Marble Falls that were most affected by the flood.

In fact, the raging floodwaters traveling downstream from the Llano river to the Highland lakes region took only hours to inundate parts of the cities of Llano, Kingsland, Granite Shoals and Marble falls around lake LBJ. For flood control, the Lower Colorado River Authority (LCRA) operates 6 dams in the area. However, almost all of them are designed mainly for water supply and hydroelectric energy, except Mansfield dam which has a flood pool able to store the water until the LCRA decides to safely release it downstream towards the Gulf of Mexico. Figure 4 illustrates the normal flow time in the Highland lakes, which is usually shorter during flood events, and shows where the dams are located in the area. (LCRA, 2018)

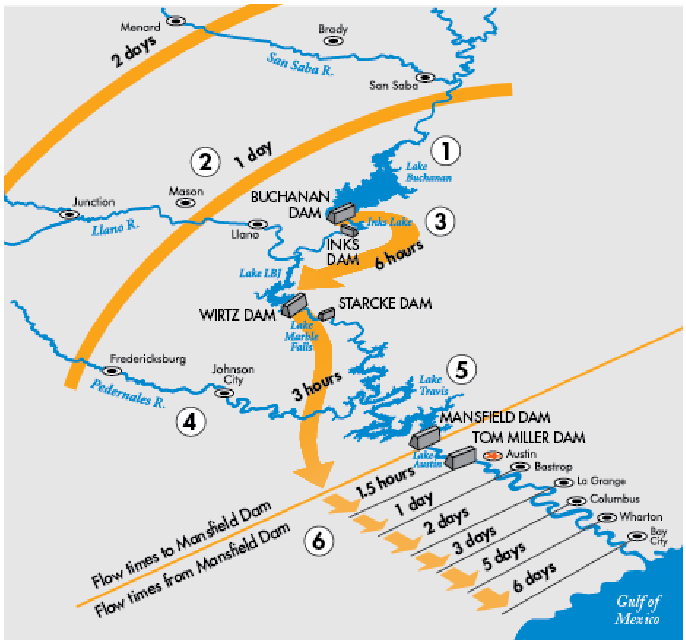

Figure 4. Flow times to and from Mansfield Dam

As a result, the inundated areas were mostly contained prior to Mansfield dam. In this project, the focus is on the city of Kingsland where the Llano river meets the Colorado river. It was one of the most affected areas by the flood and where the RM2900 Kingsland bridge collapsed.

Height Above Nearest Drainage approach to estimate inundation elevation

Based on the 10m Digital Elevation Model (DEM) from the National Elevation Dataset, a DEM raster is extracted with a 2km buffer around the basin. This raster will serve to delineate DEM-based feature dataset and rasters necessary to compute the Height Above Nearest Drainage. First, a stream raster is delineated from the pit filled DEM following the D8 flow direction method and based on dangling vertices extracted from the NHDFlowline feature dataset. The stream raster produces then a drainage line and catchment polygons features. Using the Dinf flow direction option, vertical distances between each grid cell of the DEM and the delineated drainage line are finally drawn and constitute the HAND raster.

Figure 5 shows the HAND raster over the whole extracted DEM with different elevation levels (2m, 5m and 10m), the delineated drainage line and catchment polygons.

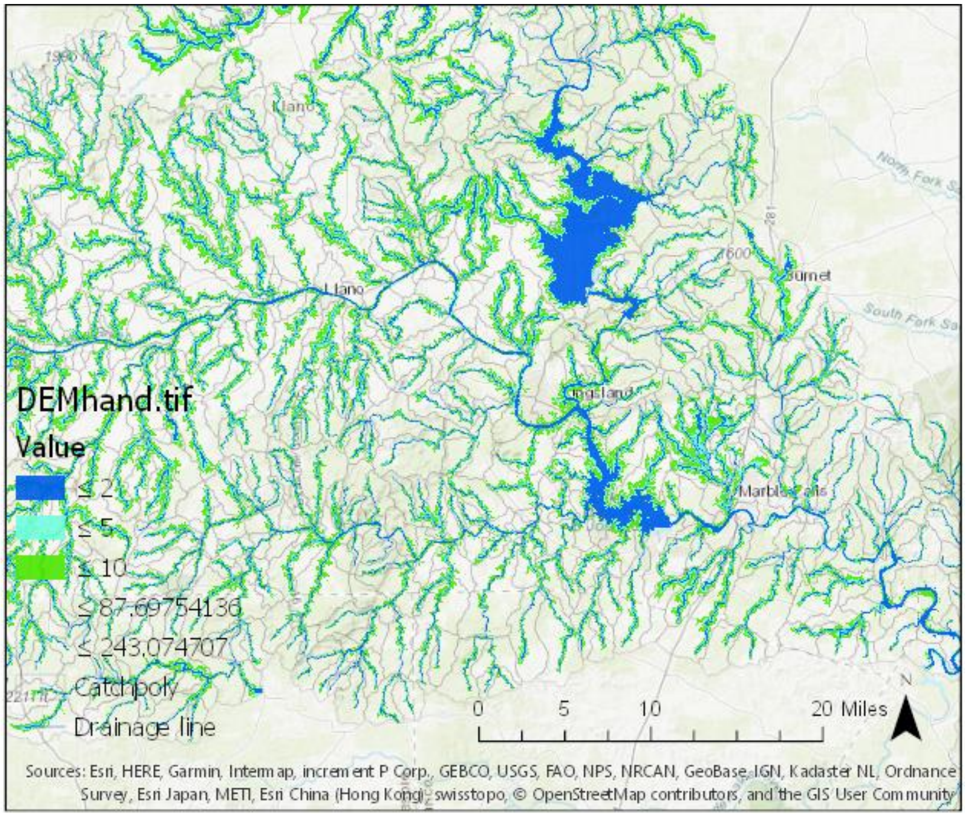

Figure 5. Map showing the HAND raster, drainage line and catchments

For the rest of the analysis, the catchment polygon -where the RM2900 bridge is located- is chosen as a focus area to investigate further some hydraulic aspects of the inundation. Figure 6 illustrates the HAND layer applied on the Kingsland catchment.

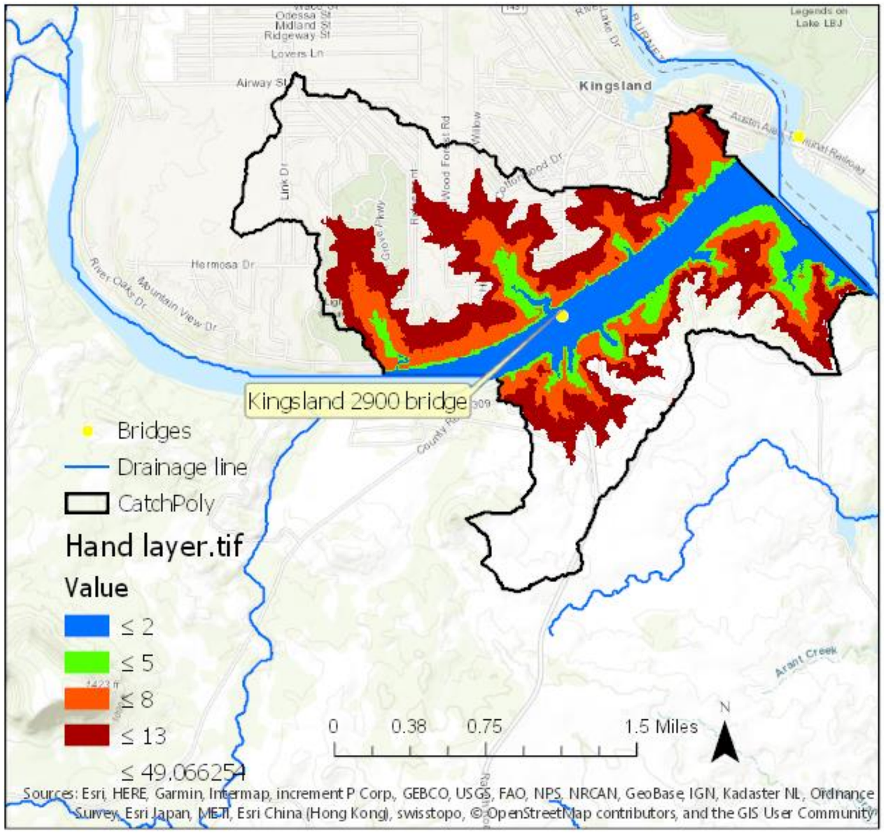

Figure 6. HAND map of the Kingsland catchment

The hydraulic properties of the flow in the catchment are therefore obtained based on the HAND raster and drainage line. In the absence of a stream gage in the catchment, and under the assumption of uniform flow conditions, we can use the Manning's equation for open channel flow to estimate the flow rate in the catchment. Table 1 shows the calculated parameters to obtain flow rates for different stage heights.

Table 1. Hydraulic properties and flow rates for select stage heights

Stage height (m)	**1.00**	**3.00**	**6.00**	**9.00**	**12.00**	**15.00**
Stage height (ft)	3.28	9.84	19.68	29.52	39.36	49.20
Grid cell size(m2)	100.00	100.00	100.00	100.00	100.00	100.00
Flooding cell number	9,851.00	12,246.00	20,361.00	32,600.00	44,627.00	55,622.00
$S_b = \sqrt{1 + slope^2}$	1.00	1.00	1.00	1.00	1.00	1.00
Stage surface area As (m2)	985,100.00	1,224,600.00	2,036,100.00	3,260,000.00	4,462,700.00	5,562,200.00
$Bed\ area\ A_b(m^2) = A_c\sqrt{1 + slope^2}$	985,196.34	1,225,962.93	2,040,885.13	3,267,091.44	4,472,437.12	5,574,662.85
Inundation depth (m)	0.94	2.53	3.82	4.84	6.13	7.62
Flow volume V (m3)	924,811.88	3,098,218.72	7,786,485.33	15,762,530.06	27,365,205.31	42,407,639.10
Stream length L (m)	3,910.56	3,910.56	3,910.56	3,910.56	3,910.56	3,910.56
Stream start elevation z1 (m)	252.05	252.05	252.05	252.05	252.05	252.05
Stream end elevation z2 (m)	251.54	251.54	251.54	251.54	251.54	251.54
Cross section flow area A = V/L (m2)	236.49	792.27	1,991.14	4,030.76	6,997.77	10,844.39
Wetted perimeter P=A_b/L (m)	251.93	313.50	521.89	835.45	1,143.68	1,425.54
Hydraulic radius R=A/P (m)	0.94	2.53	3.82	4.82	6.12	7.61
$Bed\ slope\ S = \frac{z_2 - z_1}{L}$	0.00	0.00	0.00	0.00	0.00	0.00
Mannings number	0.05	0.05	0.05	0.05	0.05	0.05
Flow rate Q= $\frac{1}{n}AR^{2/3}S^{1/2}\ (m^3/s)$	51.61	334.58	1,106.59	2,619.57	5,328.40	9,547.49
Q (ft^3/s)= Q(m3/s)*35.3	1,821.70	11,810.58	39,062.46	92,470.92	188,092.37	337,026.40

The obtained flow rate values for each stage height are then used to plot the rating curve for the stream as shown on Figure 7.

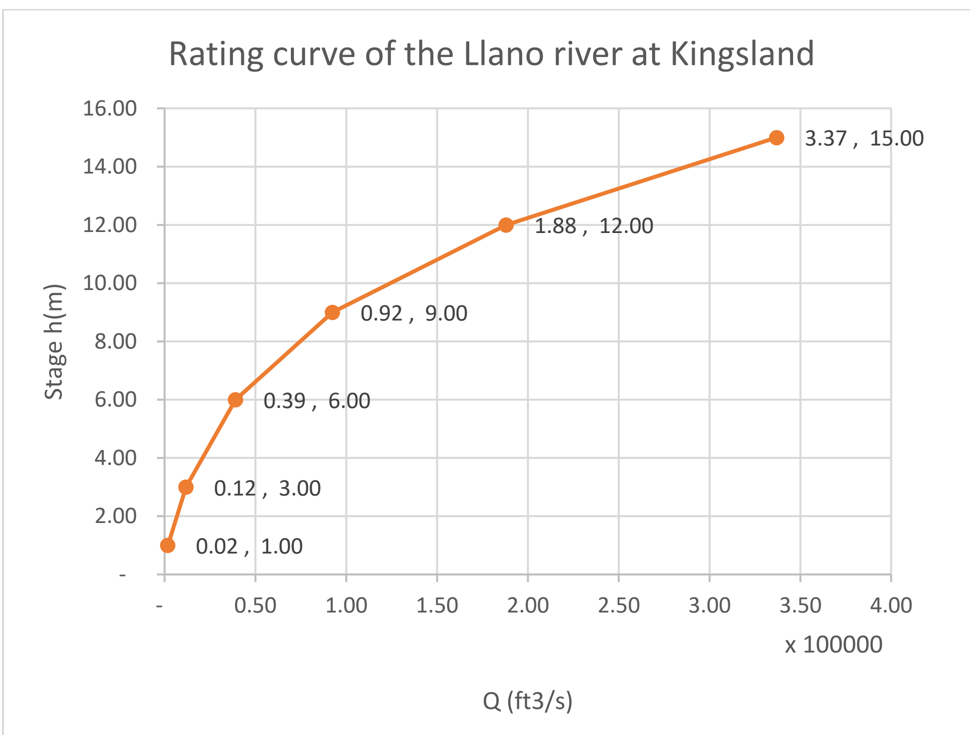

Figure 7. Rating curve of the Llano river at Kingsland

In order to estimate the inundation elevation, the mean daily flow rate at the llano river at llano stream gage is obtained with a value of 169,000 ft^3/s on October 16th. The flow from runoff (Q0001A field) from the NHDPlus flowline dataset is used to scale and estimate the flood flow rate for the catchment in Kingsland at a value of 180,318.6 ft^3/s. According to the rating curve, this flow rate reflects a stage height of 11.75m. This provides an estimate of the inundation level that is illustrated on the HAND map on Figure 8.

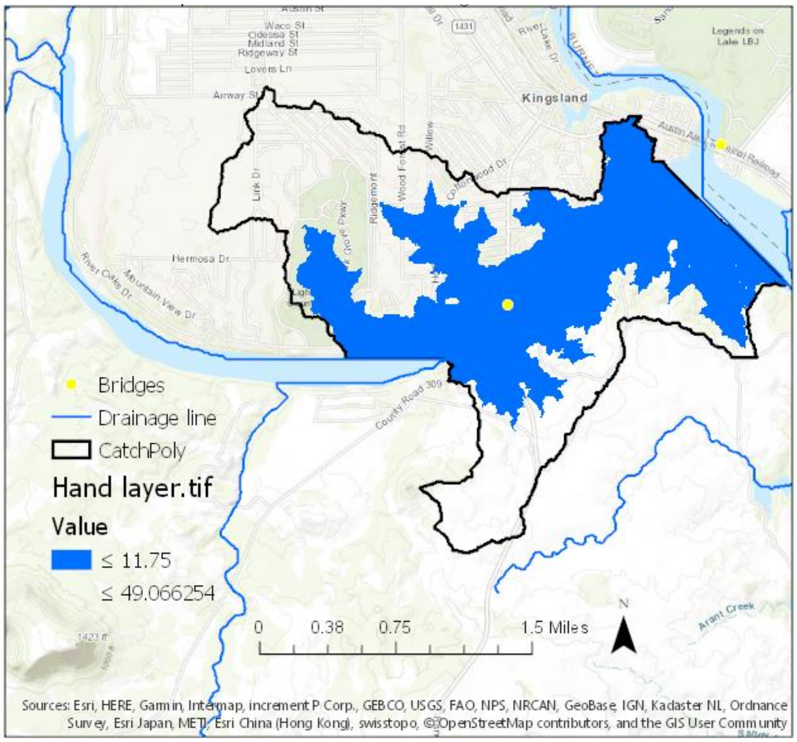

Figure 8. Expected inundation depth in the Kingsland catchment

Analysis and results

At this point, the estimated inundation level relies on the 10m DEM delineated features dataset and rasters, HAND approximations in terms of flow direction, estimated hydraulic properties of the stream and related flow rate. It is important to confront the expectation to available data on field and flood models to verify its relevance.

The Federal Emergency Management Agency (FEMA) openly provides flood hazard data in the form of the National Flood Hazard Layer to publicly share the level of flood risk for covered areas. By clipping the layer to the Kingsland catchment, we're able to look at the different levels of risks and compare it to the HAND processed inundation level. Figure 9 conflates this information and shows that the estimated flood level of 11.75m is beyond the 0.2% annual chance flood hazard, which is the lowest likelihood available in the layer. This in fact confirms the severity of the flood, but also suggests that the estimated flood level surprisingly exceeds the 500-year flood. However, the fact that this flood event was recorded with the second highest crest at the Llano river stream gage informs on its historic magnitude. Additionally, the very low bed slope in the catchment doesn't help evacuate the floodwaters which accentuates the impact.

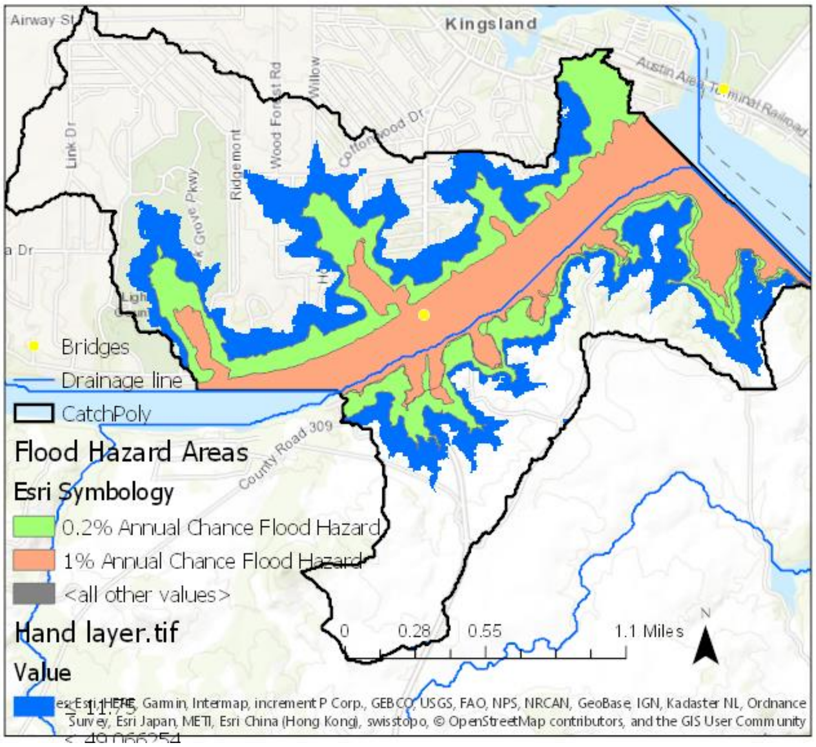

Figure 9. National Flood Hazard Layer and HAND flood depth

US Census data and flooded population

The 2010 US population census data provides various information about the population and is available both per tracts and per blocks. Applying the census per block layer on the catchment gives an initial look at the distribution of the population and shows how the population is more concentrated north of the stream with higher densities in the central part of the catchment. The southern part consists mostly of population living by the riverside and on the bank of the lake LBJ.

In order to analyze how the population is affected by the HAND-processed inundation level, an estimate of the population within the catchment is needed. To obtain the in-catchment portion of the population living in blocks crossed by the CatchPoly boundary, an area weighted population is calculated for each intersected block following the expression: $P_i = \frac{P_t * A_i}{A_t}$, where P_t is the population of the whole block, A_i is the area of the intersected block taken from the resulting Shape_Area field, and A_t is the area of the whole block joined to the intersected table from the initial layer. Summing up the resulting PopCatch field -where the values P_i are stored- gives an estimate of the population within the catchment while assuming a uniform population density across each block. The rounded up calculated catchment population is **1425**.

The map on Figure 10 illustrates the US census data intersected to the Kingsland catchment polygon with a symbology reflecting the population for the resulting blocks and sub-blocks.

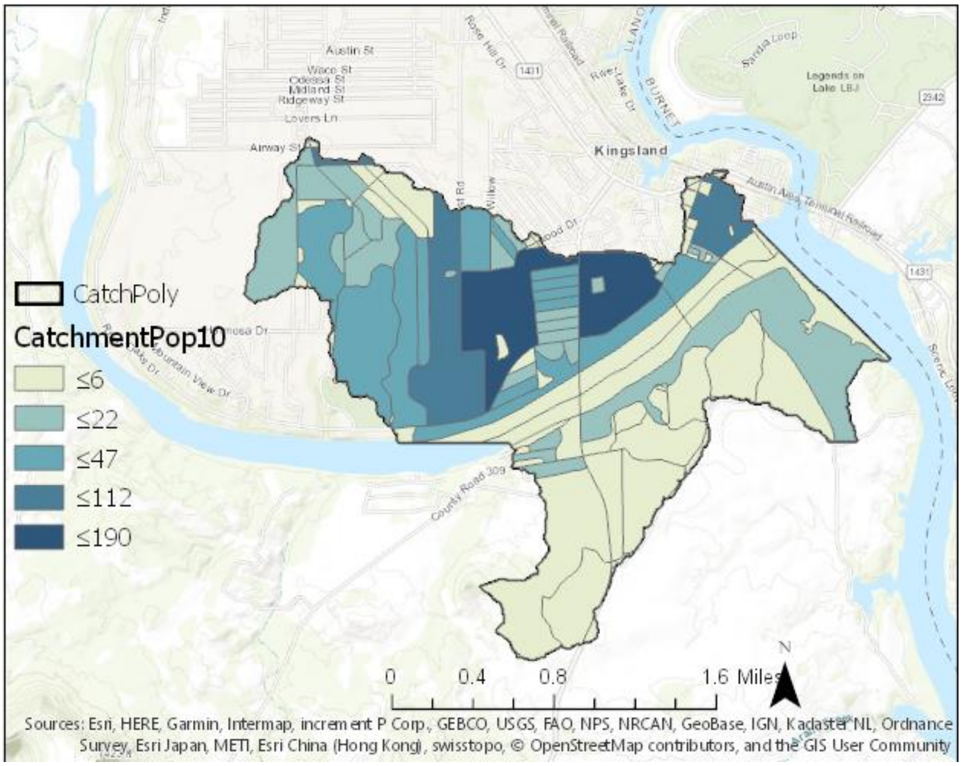

Figure 10. Population in the Kingsland catchment

Once the distribution of the population is known for the catchment, it is interesting to apply the HAND layer and see what portion of the population is affected by the inundation level. To do so, the population should be intersected to the inundation area determined within the HAND layer, and then proceed similarly to the previous method for the catchment population to estimate the flooded population. However, the inundation level is provided via the HAND raster, so it is first converted to a polygon and then intersected to the census data. The map on Figure 11 shows the inundated population of the catchment.

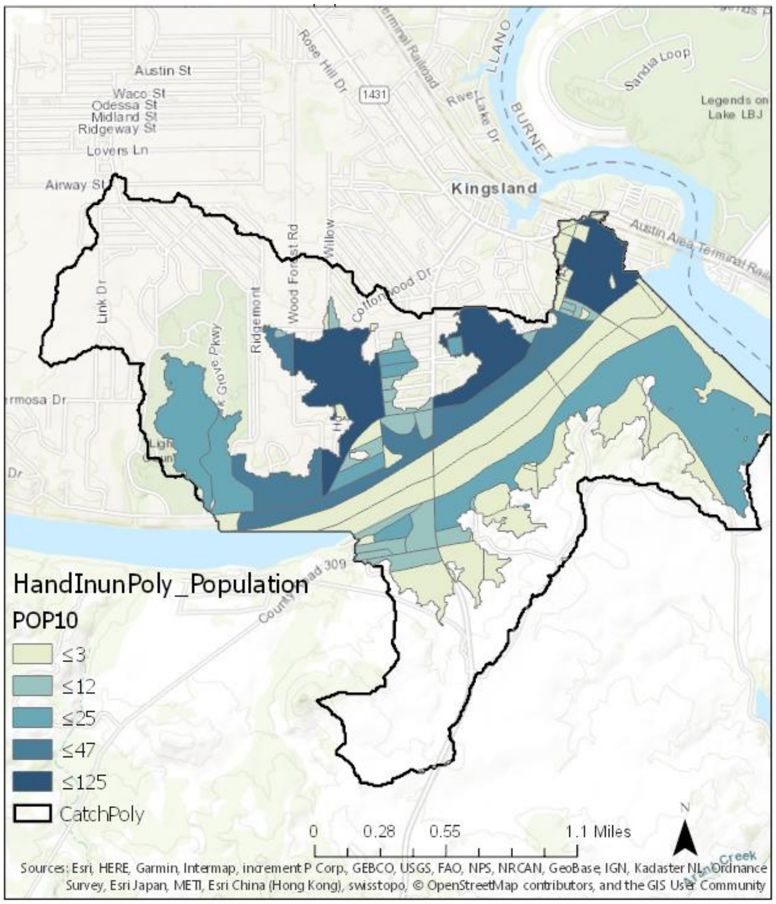

Figure 11. Inundated population in the Kingsland catchment

Based on this information, we can determine the portion of the catchment population affected by the flood:

Inundated catchment population= 766 or 53% of the total catchment population (1425)

Using the "Shape_Area" field, we can also determine the portion of the catchment area that is inundated by a 11.75m water elevation:

Inundated catchment area= 4.36 km2, which is 50% of the total catchment area (8.74 km2)

These results obviously rely on the assumption of uniform population density within each block, but they still provide a good estimate of the population living within the flooded area considering the reasonable size of the blocks. Proceeding likewise on tracts census data would clearly result in a much less accurate estimate. Also, the inundated area, as it is previously calculated, includes the area covered by the river during normal flow. So, it is more of an indication of how much surface water is covering the catchment than a flooded area per se.

Consequently, it is fair to say that around half of the population and area of the catchment is flooded by the expected 11.75m inundation level, which is based on the October 16th mean discharge. The USGS stream gage recorded, for the same day, a maximum discharge that is 65%

higher than the mean at Llano, which suggests that on certain times of that day, more population and areas could have been affected by the flood.

During flood events, resilience across populations can be very different depending on many socio-economic factors. So, having an estimate of the number of the flooded population doesn't necessarily inform on the extent of the damage. The Social Vulnerability Index (SVI) provides a measure of the vulnerability of communities by compiling 15 US census variables as shown in Figure 12. The SVI layer applied to the focus area is given in Figure 13. Also, the data is only available per census tracts, so it doesn't provide detailed information. However, it still shows that the southern part of the catchment with an SVI index of 0.16 is less vulnerable than the population in the northern part which has an 0.87 SVI index. The northern part is also where most of the population of the catchment is located. While it is certain that the index doesn't give a full picture of the situation, it can still help local officials identify parts of the community that need more support. In this case, the northern part would need more assistance since it is more populated and more vulnerable.

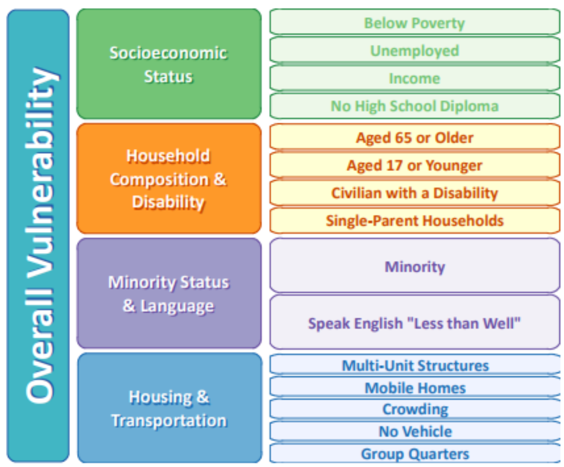

Figure 12. SVI key indicators

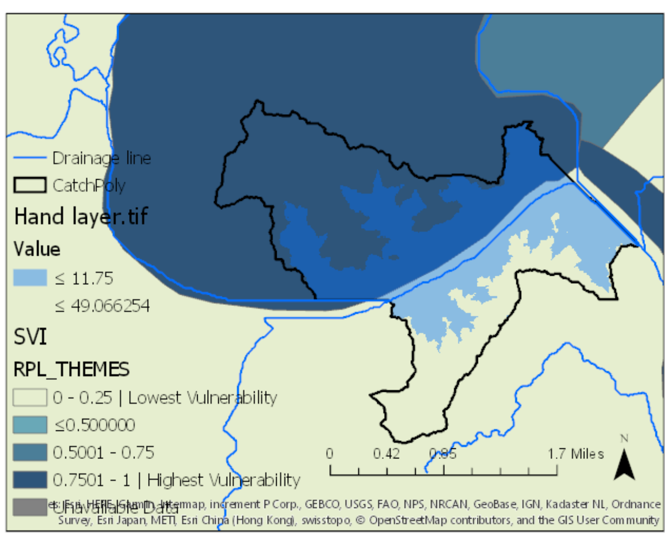

Figure 13. SVI in Kingsland

ESRI Story map and flood impact

The main source of data used so far to determine the impact of the flood is the USGS flood discharge. In order to have a better understanding of the situation, it is also important to confront these findings to what happened locally on the field. As of the date of this report, no detailed map or flood incident report has been released. However, a plethora of images has been shared by the press and on social media which represents a valuable source of information. To utilize it, several images that were shared with their locations were added to a story map as shown in Figure 14. These images were clearly taken at different times and days, but they can still give information about how elevated the surface water was. By associating the property shown in the images with their equivalent HAND values, an estimation of the surface water elevation can be drawn. The collected images show in fact a highest flood elevation of roughly 8m, which is almost 4m away from the HAND processed elevation. While more images from credible sources are certainly needed for closer estimations to the maximum inundation depth, crowdsourced data remains a valuable source of information for flood hazard and impact assessment.

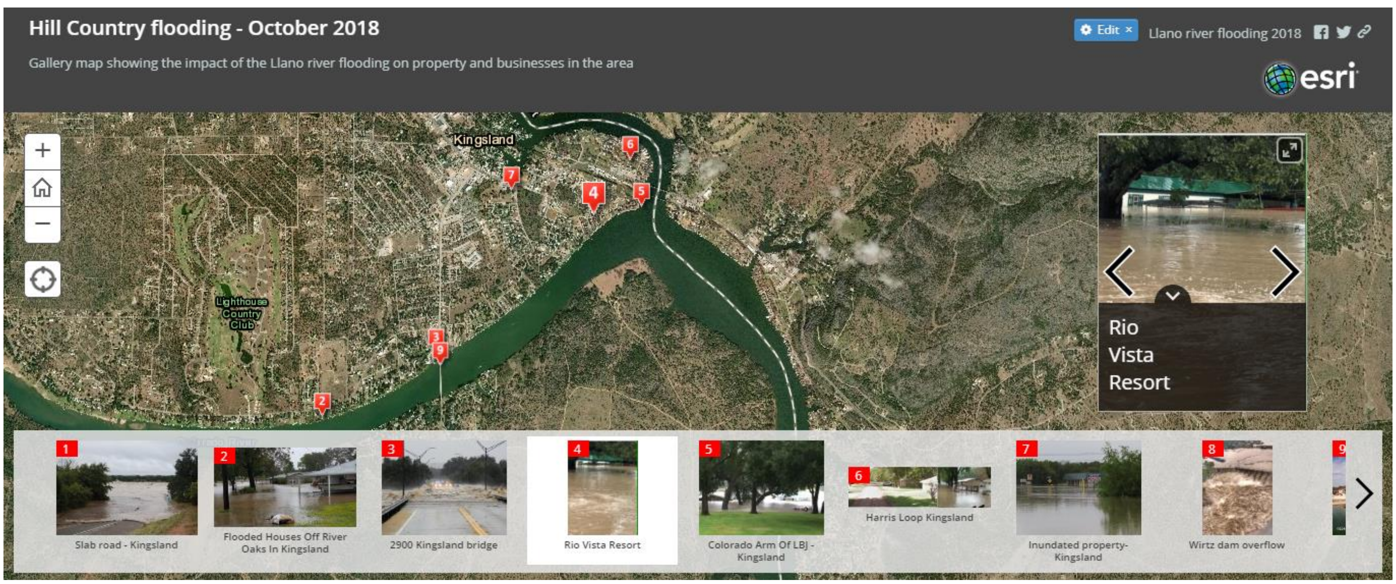

Figure 14. Screenshot of the Hill Country flood story map (https://arcg.is/1CD11X)

Conclusion

The Central Texas Hill Country flooding event that occurred on October 16th had clearly a devastating impact on the Highland lakes' area. The HAND analysis combined with the USGS stream gage data provide valuable information about the expected outcome and flood levels in a specific area. For the catchment where the RM2900 Kingsland bridge is located, half of the area and a mainly vulnerable population were expected to be inundated. Despite the few assumptions and uncertainties involved in the processed data, local officials can largely benefit from such information to help improve their flood emergency plans and operations. ArcGIS can in fact provide powerful tools for a crucial and a better insight of flood hazards. Also, in such extreme events, where organized and accurate field data is not always available, crowdsourced imagery can be a helpful tool to assess and determine the observed impact.

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