Flood Mapping: Hydrology and Communities

2013 Boulder Floods

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During the period of September 11-17, 2013, eighteen Colorado communities experienced record rainfall resulting in sustained flooding [3][26]. In the community of Boulder, Colorado, over the course of seven days, 16.9 inches of rain fell, an area record [13]. According to studies of the flood, the professionals in the hydrologic sciences and meteorology were surprised by the geographic and temporal scale of the flooding [17]. Surprise was attributed to flood models created prior to the event that only considered large scale flood events as a result of rain over the front-range rather than a prolonged rain and inundation over a large area [17].

After the flood, the costs of damages to private residences, 485 miles of highways, and businesses exceeded $2 billion [13]. The damage of the flood extended beyond structural damage to large scale community impacts: 18,000 people had to evacuate their homes; 1,102 people were evacuated via airlift; and, 8 fatalities occurred - seven attributed to drowning and one to a mudslide [3][26].

From the reports generated about the flood and datasets relating to the event, there is a divide between hydrology and community generated information. The range of agencies and groups generating information about floods took many forms: weather warning information created by weather forecasters, public officials, media personal, and members of the public. Each of the groups generated content about the impacts on health and safety, loss of life, property damage, and impacts on infrastructure, all presented in different forms [17].

The objective of this combined hydrologic-community study is to connect diverse dataset formats and information to visualize the relationships of hydrology and human-centered information. In order to connect diverse information, I obtained and organized datasets and created maps to represent the spatial and event driven relationships of hydrology and communities during the 2013 Boulder floods.

Data & Data Processing

To understand the relationship of the Boulder flood and the community, I used two types of data sources: hydrology focused datasets and community focused datasets. Each dataset had elements that addressed the flood and the characteristics of the Boulder area, which when combined, showed the impact of the flood on the community. To obtain data, I used online services to search and download data.

After obtaining data, I had to consider the diversity of the data sources and range of spatial definitions imposed by data creators. The hydrology based datasets defined the area of interest in three ways: national, county, or watershed. In contrast, the community datasets defined the area by populated regions: city, county, state, or census block. Based on the spatial overlap, I defined the community of Boulder within the zip codes that United States Postal Service attributed to Boulder, Colorado (henceforth to be referred to as Boulder) [10]. Each of the datasets was processed to reflect both regions of interest: watershed and zip code.

Hydrology Datasets

USGS. From the USGS, I obtained streamflow locations for the St. Vrain watershed. After mapping all the gages and locating gages within Boulder, I downloaded the tabulated 5 minute measurements of streamflow for the three Boulder gages. I then aligned the data in excel sheet to show the different stream flows by time [27].

ArcMap Server Data. Using the services provided by ESRI, I downloaded and used the following service layers: USA_NHDPlusV2 for stream mapping and USA_NLCD_2006 for land cover. I clipped the land cover dataset for the St. Vrain watershed and the zip code area for Boulder.

FEMA. From the FEMA Flood Map Service Center 'Search All Products' page, I obtained the Boulder County FEMA flood layers [12]. From the collection of files, I used the S_FLD_HAZ_AR layer (special flood hazards).

National Oceanic Atmospheric Administration (NOAA). From the NOAA Climate Data Online Search I obtained hourly precipitation measurements for the rain gages located in Boulder County. This service took several days to deliver the data via an email link [18]. From the two datasets obtained, I used the rain gage located near the City of Boulder and aligned the hourly measurements with the stream gage measurements obtained from USGS.

Community Datasets

Census, 2010. From ERSI's website, I obtained the 2010 census layer files built by ESRI [8]. I first clipped the file to the St. Vrain watershed and then to the Boulder zip code area.

Centers for Medicaid and Medicare Services (CMS). Using the datasets available through CMS I found the names and geographic coordinates of nursing homes, hospitals, and dialysis centers in Boulder, Colorado [14][15][16].

ESRI Building Datasets. To find additional hospital locations and the coordinates for The University of Colorado at Boulder, I downloaded the USA Institutions dataset from the ESRI website[9]. After clipping the dataset to the zip code, I edited the data table. I kept the hospitals and CU Boulder and added an additional coding field to differentiate the University and medical locations.

Timeline Data

To build a timeline of events, I used newspaper articles covering the event and selected events that included a timestamp [3]. I obtained additional event information from scientific papers published by the following area: NOAA, CU Boulder, and NCAR [25][6][13].

National Weather Service (NWS). From the archives for weather alerts, I obtained the national storm warnings for September 2013 [20]. In an excel spreadsheet, I narrowed the alerts to Boulder County and then to those affecting Boulder.

Twitter. To gather tweets, I created a Twitter account and followed 60 accounts in the Boulder area related to municipal services, CU -Boulder, government facilities, local media outlets, and weather forecasting agencies. To search the content of the tweets related to the flood event, I used Twitter’s built-in search utility and input the following query:

> keywords: boulder, OR flood, OR flash OR flood, OR rain, OR precip, OR rainfall, OR emergency, since:2013-09-10 until:2013-09-18

To narrow the search, I filtered the tweets by the accounts I followed. Then, I selected the tweets that first reported information related to flood events and also public service announcement post-flood. The search resulted in a sample of 88 tweets over the course of the flood event.

Mapping: Hydrology versus Community

For spatial analysis, I used ArcGIS tools to create a series of maps from the collected data and shapefiles. During the process, I used two definitions of the area: the St. Vrain watershed and the area of Boulder delineated by US Postal zip codes.

I first delineated the St. Vrain watershed using the ArcGIS hydro watershed tool and created a buffer around the resulting area.[1] I then added the NED30m USGS digital elevation model from ArcGIS connected services and extracted the DEM area of the watershed with the extract by mask tool, as seen in Figure 1.

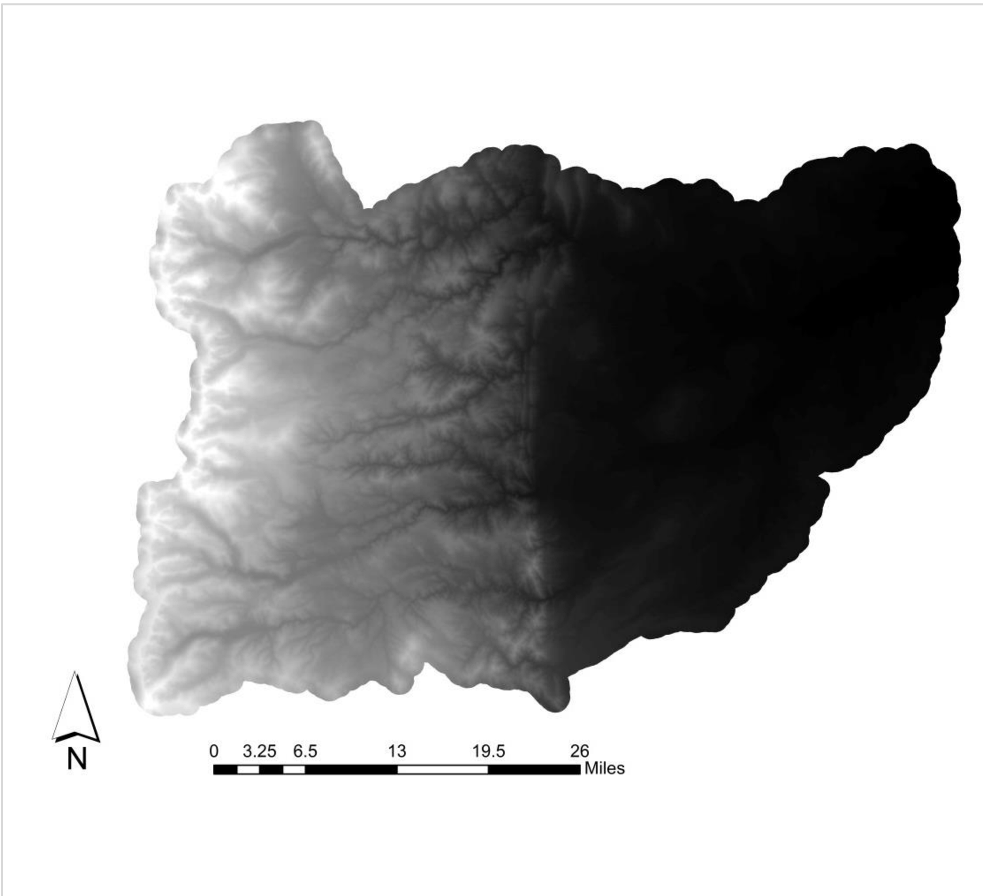

Figure 1. St. Vrain DEM.

To illustrate the Boulder area, I took zip code data from ESRI [10] and outlined the area containing the zip codes that the US Postal Service defined as Boulder, Colorado, as seen in Figure 2.

[1] To verify the delineated watershed, I used the watershed map in ARCGIS.

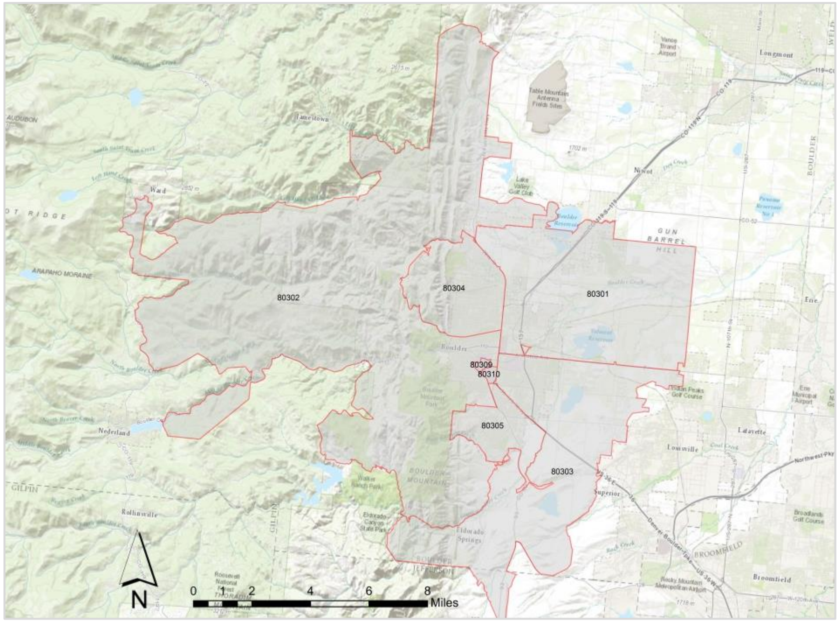

Figure 2. The Boulder area defined by US zip codes.

After defining the two areas, I then used code created by Dr. Tarboton to automate the process of creating a geodatabase (please see the appendix for the python code). I mapped the drainage lines and catchments for the St. Vrain watershed, see Figure 3.

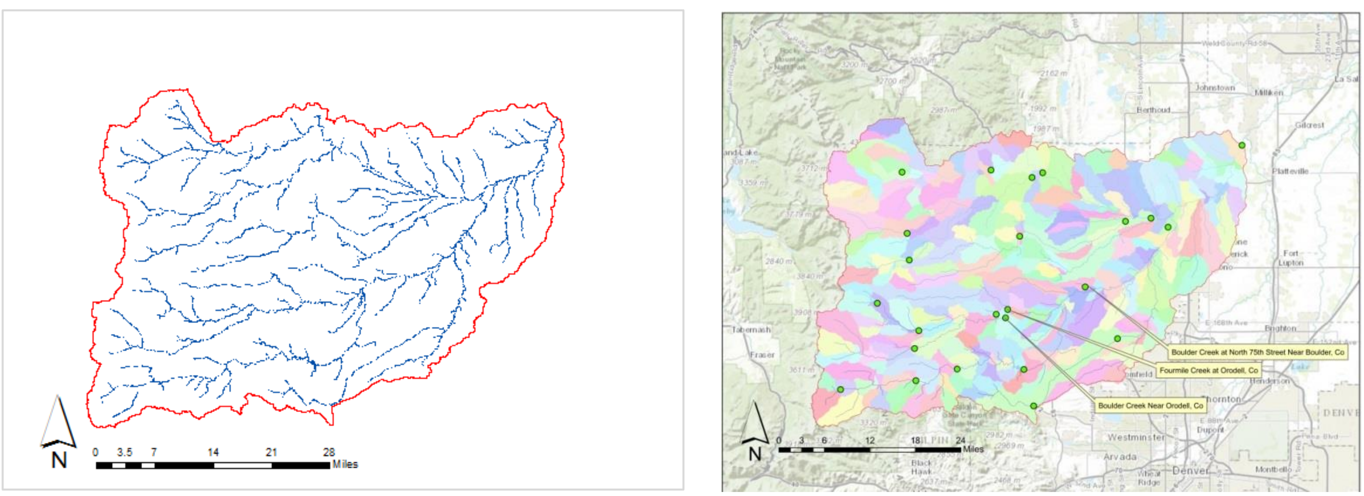

Figure 3. To the left, drainage lines delineated as part of the Python program and to the right, the St. Vrain watershed catchments with associated stream gages.

Using summary tools provided in ArcGIS, the report listed 289 catchments delineated over the 7 counties in the St. Vrain watershed. On the combined stream and catchment area, I added the 24 USGS stream gage locations to the map.

To illustrate the wide range of topography in the watershed, I used the delineated DEM and the drainage lines to create a 3D representation of the area. The resulting maps show the start of the Rocky Mountains and the identified area of interest delineated by zip codes. I drew a circle around the Boulder zip codes to see the extent of the area on a 3-dimensional representation. As seen in Figure 4, the 3D image shows the abrupt change from the plains to the Front range. The map to the right shows the Boulder area is at the base of the mountain range and at the outlet of several canyons.

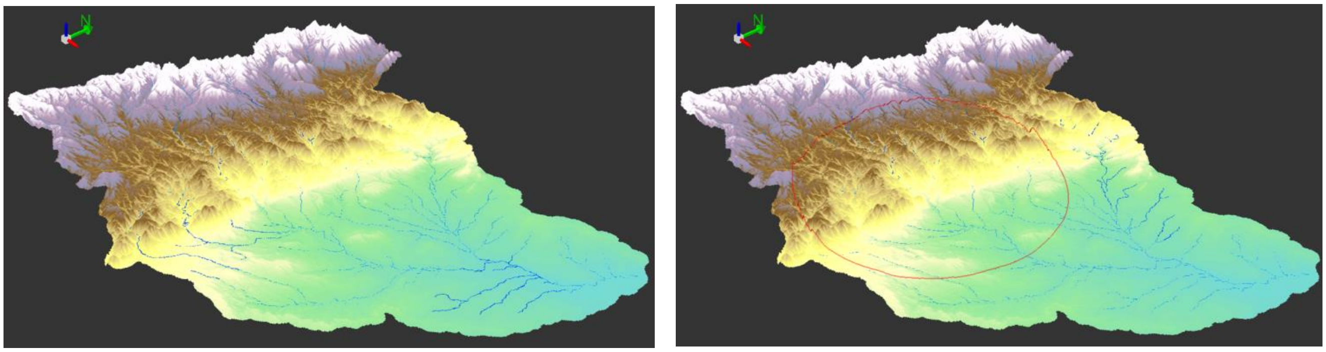

Figure 4. Three-dimensional representation of the St. Vrain watershed. The red circle in the image on the right shows the Boulder area delineated by zip code.

To illustrate the flood plains, I added the FEMA 'Special Floods Hazard' layer. I then used the FEMA Flood Insurance Rate Map (FIRM) technical manual to determine what the individual flood zones represented, see Figure 5. From the technical documentation, I assigned shades of blue to the potential flood zones as defined be FEMA:

A – 1% annual chance of flood
AE – 1% annual chance flood
AO - designated floodway
X – 0.2% annual chance of flood. No color-fill was assigned on map because it covers the entire map.

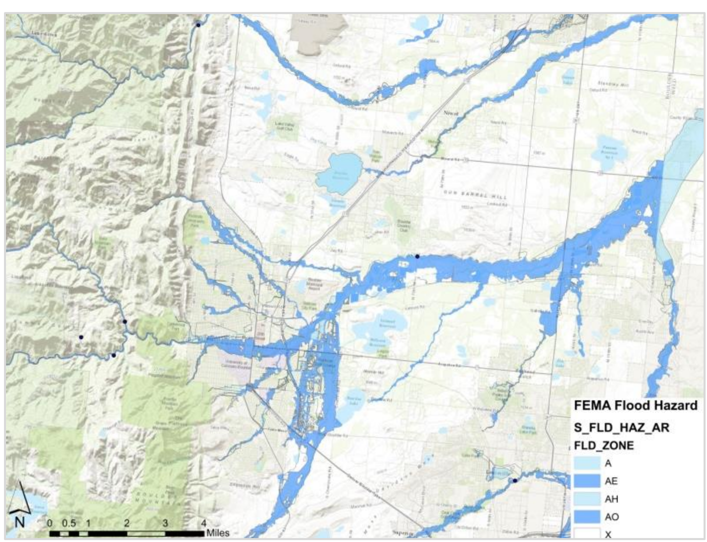

Figure 5. FEMA flood hazard layer.

After creating maps representing the hydrologic character of Boulder, I used the land cover dataset to see areas of development over the St. Vrain watershed and the Boulder area, as seen in Figure 6. According to the data displayed in the maps, the St. Vrain watershed land cover distribution was 38% Forest, 20% agriculture, 18% scrub, and 10% development as of 2006. In the Boulder area the distribution was 40% forest, 28% scrub, 15% developed, and 7% agriculture. The large percentage of forested area may be attributed to the Rocky Mountain National Forest. Observations of the two land cover maps also show concentrations of development around three areas: Boulder, Longmont, and suburbs of Denver. Continued examination of the Boulder land cover map also shows development at the mouth of a canyon and on top of a stream area. On the right map of Figure 7, the red line of development heading west is a road going through the canyon and up into the Rocky Mountains. As part of the damage reported during the floods, roads such as this one experienced damage due to flooding in the canyons.

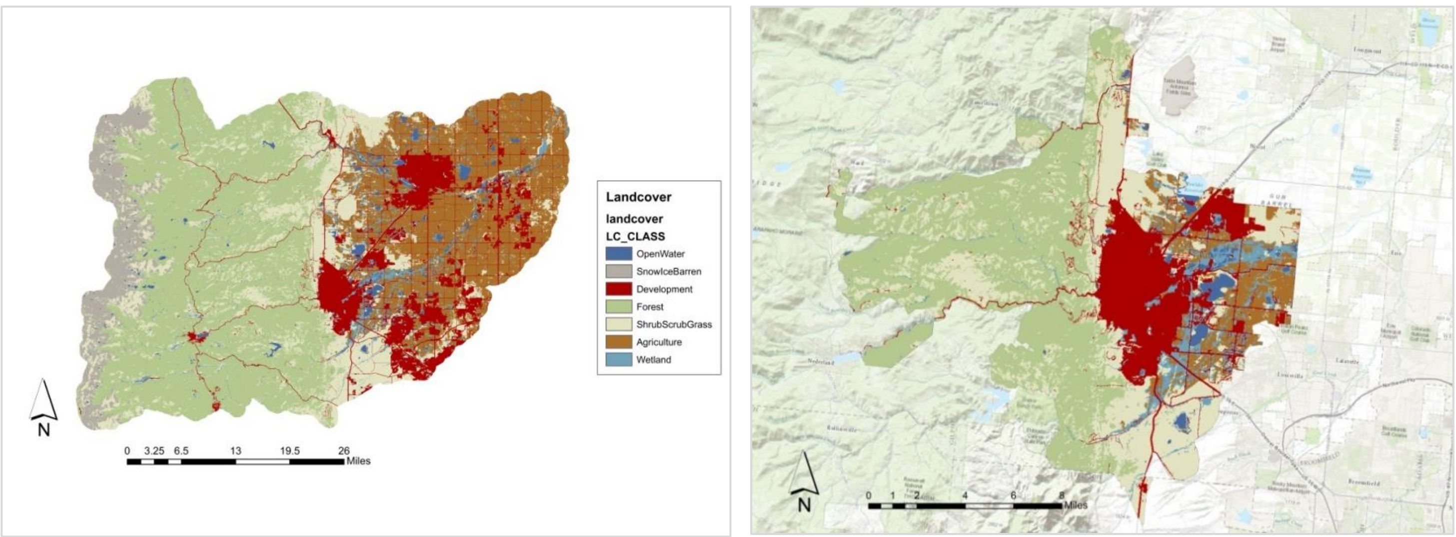

Figure 6. Land cover distribution for the St. Vrain watershed and the Boulder area.

After mapping the area, I mapped the distribution of people with ArcMap's dot density function. Dot density along with census data, allows mapping of census groups to illustrate the density of populations.[2] Each polygon is filled with dots based on the field value and associated settings. For the St Vrain and Boulder maps, the dot value was equal to one, representing one person per dot. Dot density does not identify the exact location of people, rather it shows the concentration of the chosen characteristic by census tract. By using dot density, I could identify areas of high density in my chosen demographic groups.

To select demographic groups for mapping, I used the ages of the people who died in the Boulder area and additional key demographic factors to determine which groups of the census data to use. I first looked at vulnerable age groups based on mobility and increased need for assistance during evacuations. Based on the ages of the fatalities in the area, the majority were over the age of 70, which matches the census data for people 75 and older.

[2]Instructions from: http://desktop.arcgis.com/en/desktop/latest/map/working-with-layers/using-dot-density-layers.htm

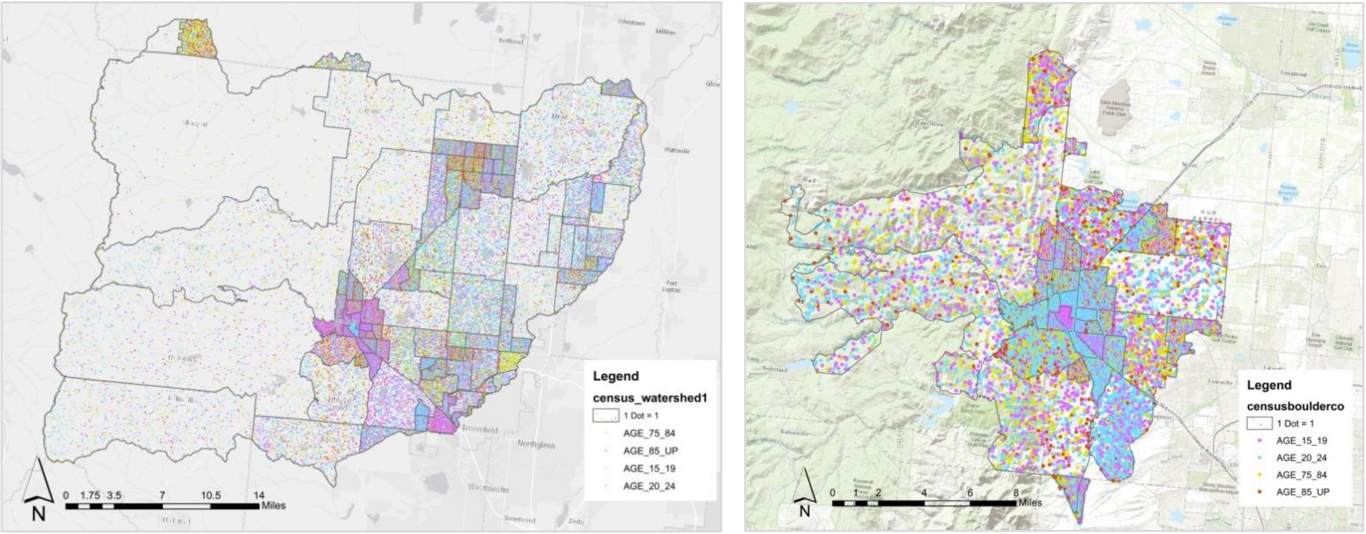

Figure 7. The population distribution by dot density. The map to the left shows the St. Vrain watershed and the figure to the right shows the Boulder area.

Also, Boulder is home to the University of Colorado at Boulder, and according to CU Boulder records, 29,000 students were enrolled in 2013. In addition to a large, young demographic, two flood fatalities were 19 year olds. Based on the combination of loss of life and a young, transient population, I used the census data for people in the 15-24 age groups.

After creating layers for the two groups, I created maps of St. Vrain and Boulder for the two age groups, seen in Figure 7. Then, I added the location data for the health related buildings to the 75+ map and the University location for the 15-24 age group, as seen in Figure 8.

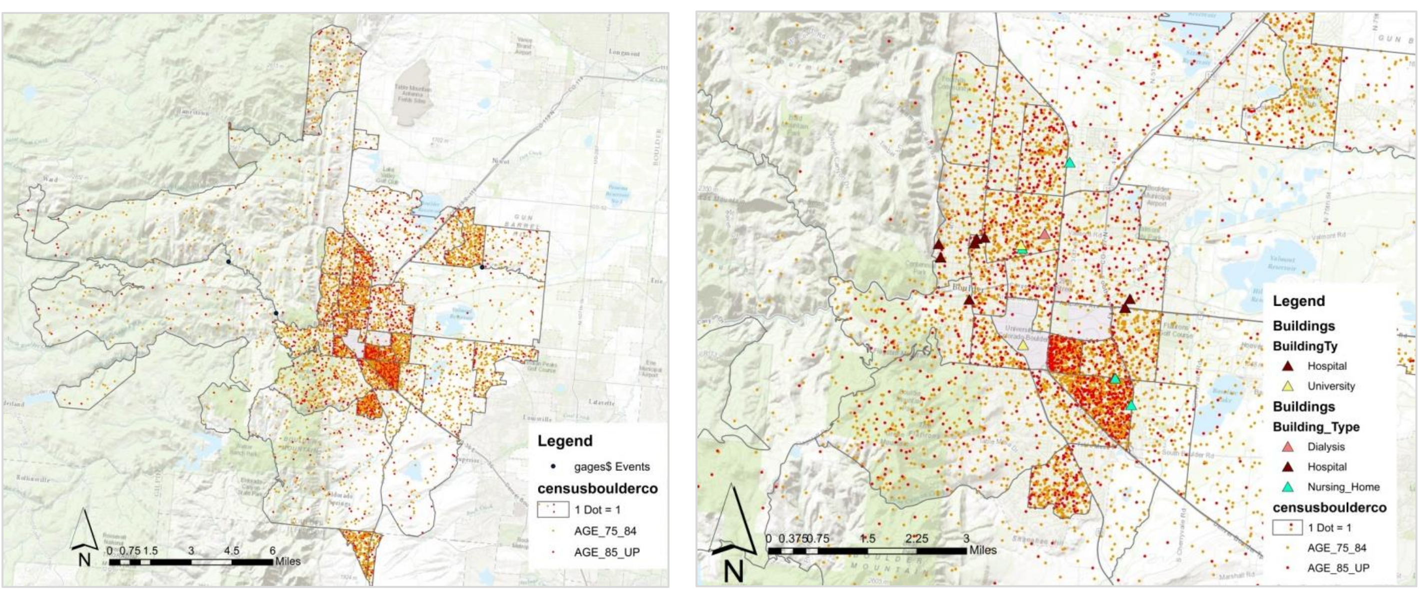

Figure 8. The population density of persons 75 and older by census tract in the Boulder area. Where red dots are those over 85 years of age. The map to the right illustrates the Boulder area and buildings.

As seen in Figure 8, the buildings displayed in the map to the right show the locations of the 9 hospitals, 2 universities, 4 nursing homes, and a dialysis center. In the southeast quadrant of the building's map the greater density of people shows a higher population of people 75 and older in the region. An overlay of the FEMA flood hazard layer shows the dense area of people over the age of 75 appears to be close to the flood plain, as seen in Figure 9.

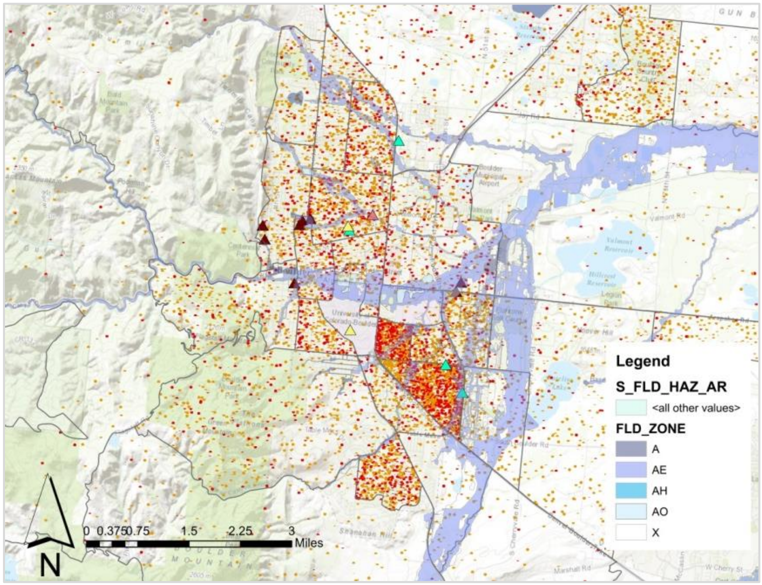

Figure 9. The population density of persons 75 and older with the FEMA flood hazard layer.

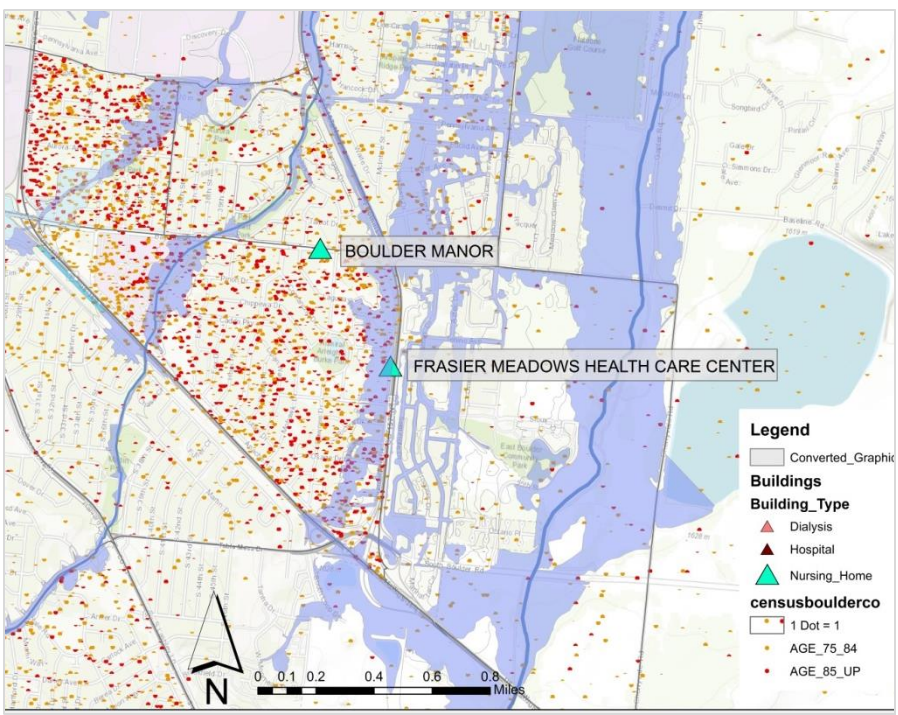

Figure 10. Area with the highest density of people age 75 and older and high risk buildings.

A closer examination of the area shows the reason for the increased density in people over 75: two assisted living centers. Figure 10 shows Frasier Meadows, as assisted living facility, in the middle of a flood plain area. During the 2013 floods, the facility flooded and residents were safely moved to other buildings on the facility's campus.[3]

A similar examination of the 15-24 age group shows a concentration around the UC Boulder campus, at the center of the map in Figure 11. A closer look, seen in Figure 12, shows the flood plain of Boulder creek goes directly through the CU Boulder Campus. At this location the flood plain crosses student housing and recreation areas.

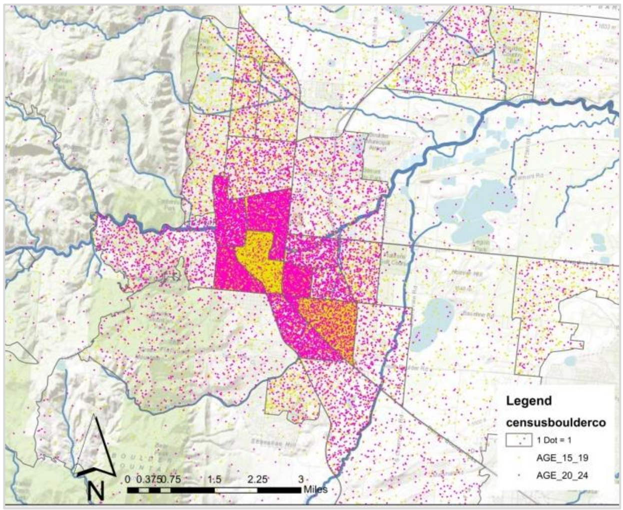

Figure 11. Distribution of people 15-24 in the Boulder area.

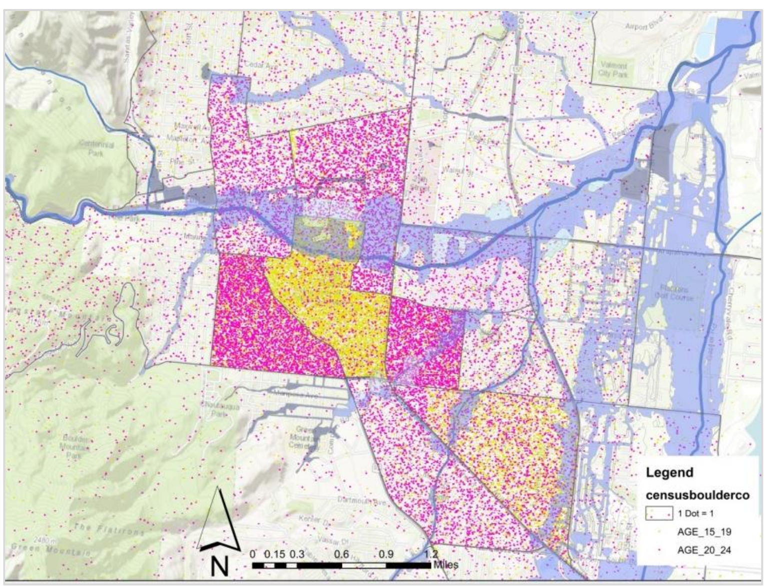

Figure 12. Distribution of people age 15-24 around the University of Boulder campus and intersection with the FEMA flood plain.

[3] Daily Camera: http://www.dailycamera.com/news/boulder-flood/ci_24117699/boulders-frasier-meadows-staff-members-called-heroes-after

Timeline of Events

After illustrating the spatial components of the flood, I combined streamflow data and rainfall data. The resulting graphs illustrate rainfall versus flow in cubic feet per second, see Figure 13. I selected the three gages that were upstream and directly downstream of the city of Boulder and the rain gage closest to the city of Boulder, see Figure 14.

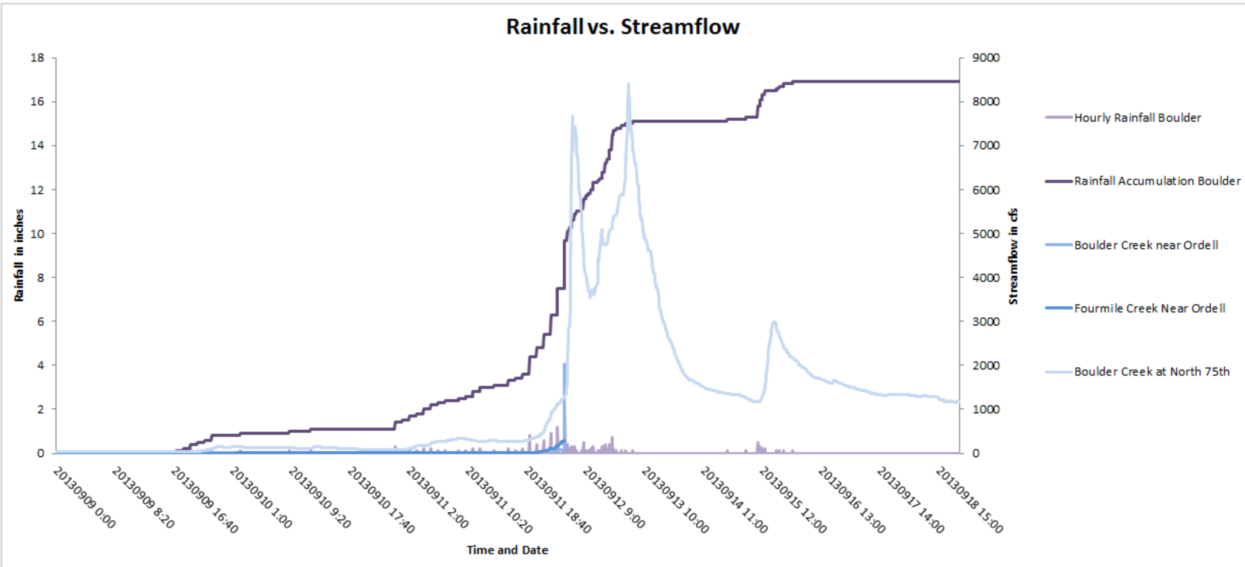

Figure 13. Graph of rainfall versus streamflow for Boulder County, with rainfall on the left axis and streamflow on the right axis.

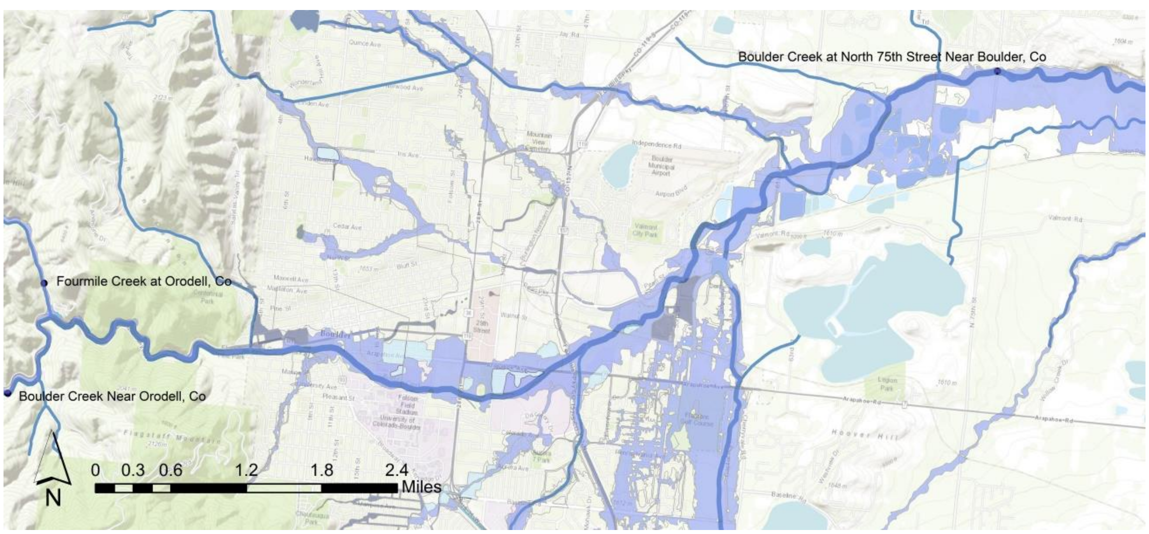

Figure 14. Map of FEMA flood hazard and stream flow gages.

Figure 13 shows the peaks in streamflow coincide with spikes in rainfall and an increase in accumulated rainfall on the 12th of September. To illustrate the occurrence of events and social media frequency, I added the twitter and timeline data to the chart, see Figure 15.

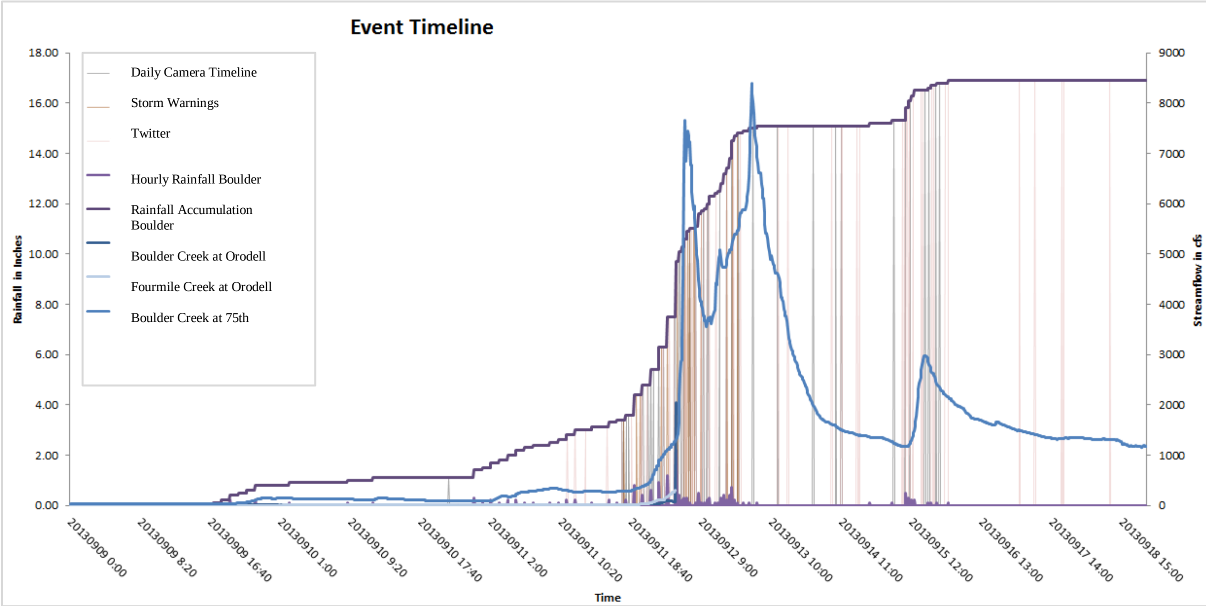

Figure 15. The timeline of hydrologic and timeline events.

As seen in the integrated chart, the number of events increases during spikes in streamflow. A closer look, as seen in Figure 16, at the peak of the event, illustrates the increased number of tweets and events surrounding the peaks in rainfall and streamflow.

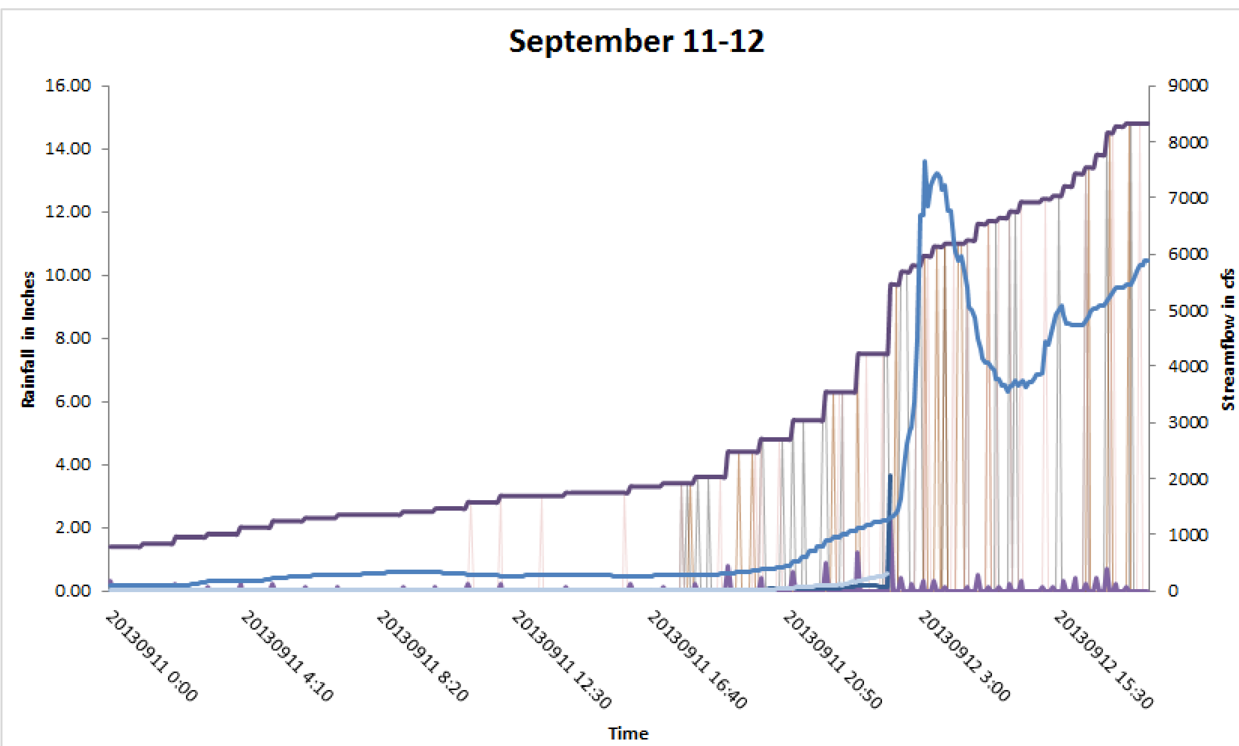

Figure 16. Timeline of events for September 11 and 12.

During the increase in events and twitter messages on the 11th and 12th, the content[4] of the messages focused on the current flood hazards:

> WARNING UPGRADED TO FLASH FLOOD EMERGENCY; STAY AWAY FROM BOULDER CREEK - The storm is intensifying and Boulder Creek is rising.
> CU-Boulder 9-11-2013, 12:02. 48 retweets (RT)[5]
>
> SEEK HIGHER GROUND IMMEDIATELY: Wall of water coming down Boulder Canyon. Move away from Boulder Creek! #BoulderFlood
> CU-Boulder 9-12-2013 10:38, 310 RT
>
> Retaining wall @4000 Boulder Canyon Dr has failed, mountainside is unstable. Boulder Canyon closure has been requested. #cowx #coloradoflood
> NWS Boulder 9-12-2013 11:58, 64 RT

One of the storm warning summaries produced during the time period sums up the character of the storm and the impact on the people in the area:

> Continuous heavy rainfall produced flash flooding. Rainfall amounts up to this point ranged from 4 to 7 inches over central Boulder County. People were trapped as several major creeks flooded including: Coal Creek, Left Hand Canyon, Fourmile Creek and St. Vrain Creek. People were reportedly trapped on their roofs.
> NOAA Storm Warnings 9-12-2013 3:10

The focus during the peak streamflow and sudden increase in rainfall aligned with an increase in public service messages and content sharing. In the tweet sent by CU-Boulder at 10:38, 310 people reposted the message. A look at the map in Figure 12 shows the high density area of students in close proximity to Boulder Creek. Timely warnings from the University on social media platforms used by students could have been a factor in reducing injury and loss of life.

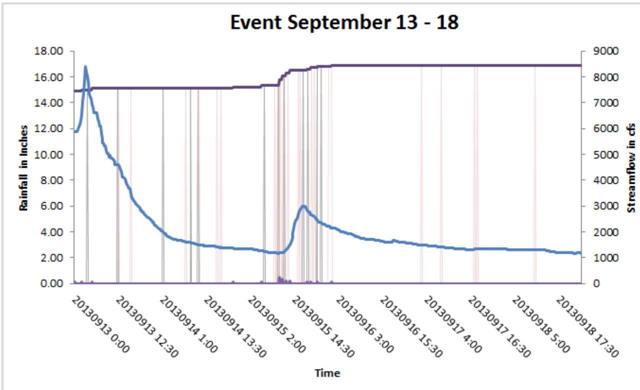

Figure 17. Timeline of events for September 13 through 17.

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[4] I choose not use geolocation because the accounts I targeted were associated with groups rather than individuals and location data would not represent proximity to events.

[5] A retweet is when another person re-posts the content of a tweet. One could suggest, the higher the number of retweets, the more potential viewers of the content.

A second increase in activity occurred on the 15th with an increase in rainfall and another surge in streamflow. As the storm subsided twitter message content shifted and contained information about impending recovery and assistance:

> RT @femaregion8: Individuals in #Boulder County #CO can apply for @fema assistance at DisasterAssistance.gov or call 800-621-3362
> FEMA 9-15-2013 8:46, 21 RT
>
> City of #Boulder sanitary sewer system has ~355 miles of pipes & ~9,200 manholes; crews are focused on sewer backups in low-lying areas
> City of Boulder 9-17-2013 2:40, 1 RT
>
> Involved in clean-up efforts? Be sure you are up-to-date on tetanus shots
> Boulder County 9-18-2013 10:42, 2 RT

As the threat of the flood subsided, the frequency of weather service agency messages reduced and municipal and recovery information became more prevalent. Public service announcements covered information about FEMA assistance and the status of utilities, such as busses, trash disposal sites, sewage, and clean-up efforts.

Conclusions

Based on the reports and information generated as part of the Boulder 2013 floods, hydrologic events and communication occurred in tandem. The potential correlation of geospatial datasets, census, and social media showed the effects of flooding on communities and information generation and proliferation. The ability to map vulnerable populations and projected flooding could be used to plan evacuation efforts. Connecting hydrology and social media shows potential for developing content for flood warnings to reach target audiences, which can be used when designing messages and creating social networks for dissemination of public service information. The importance of understanding the connection of media, distribution of people, and hydrologic modelling becomes increasingly important as the number of communication methods increases and the continued need to create effective warning systems to reduce injury and loss of life during flood events.

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Appendix: Watershed Database Delineation Python Code

```
#-------------------------------------------------------------------------------
# Name         Dem2Watershed
# Description:  Scripted Watershed Delineation using ArcGIS Hydrology Tools
# Author:      David Tarboton
# Created:     10/21/2015
#-------------------------------------------------------------------------------

import arcpy
from arcpy.sa import *

# Set inputs
outDir=r"E:/Fall2016/GIS/Project_Map/boulder.gdb"
DEM="dem"
gage = "BoulderOutlet"
threshold = 5000

# Set workspace environment and get license
arcpy.env.workspace = arcpy.env.scratchWorkspace = outDir
arcpy.env.overwriteOutput = True
arcpy.CheckOutExtension("Spatial")
print "spatial"

outFlowDirection = FlowDirection("fil")
outFlowDirection.save("fdr")
print "fdr"

outFlowAccumulation = FlowAccumulation("fdr")
outFlowAccumulation.save("fac")
print "fac"
```

```
outSnapPour = SnapPourPoint(gage, "fac", 50,"Id")
outSnapPour.save("Outlet")
print "outlet"

outWatershed = Watershed("fdr", "Outlet")
outWatershed.save("demw")
print "demw"

StreamRaster = (Raster("fac") >= threshold) & (Raster("demw") >= 0)
StreamRaster.save("str")
print "str"

outStreamLink = StreamLink("str","fdr")
outStreamLink.save("strlnk")
print "strlnk"

Catchment = Watershed("fdr", "strlnk")
Catchment.save("catchment")
print "catchment"

StreamToFeature("strlnk", "fdr", "Streamnet", "NO_SIMPLIFY")
arcpy.RasterToPolygon_conversion("catchment", "CatchTemp", "NO_SIMPLIFY")
print "one more"

arcpy.Dissolve_management("CatchTemp", "CatchPoly", "gridcode")
print "done"
```