Assessing Flood Inundation Mapping with the Use of a DEM and GIS along the Missouri River at Sioux City, Iowa

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Assessing Flood Inundation Mapping
With the Use of a DEM and GIS along the
Missouri River at Sioux City, Iowa

by

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Abstract

There are various methods that are used to predict flood inundation. The U.S. Army Corps of Engineers provided inundation maps for the 2011 Missouri River flood event that did not utilized aerial photo imagery. This study assesses the suitability of using a digital elevation model (DEM) in combination with aerial photo imagery within a geographic information system to predict flood inundation mapping along the Missouri River in Sioux City, Iowa. GPS data was collected during the height of this flood event in order to validate the positional accuracy of the DEM. Using the GPS receiver’s accuracy standards to determine the suitability of the DEM and GIS for inundation mapping, it was concluded that the DEM and GIS could be used for small scale site-specific management of flooding in Sioux City, Iowa more effectively than the basic USACE inundation map.

Table of Contents

Abstract and Table of Contents Page 2
Introduction Page 3-4
Figure 1: U.S. Army Corps of Engineers flood inundation map Page 3
Study Area Page 5
Figure 1: Missouri River at the heart of Sioux City, Iowa Page 6
Figure 2: Detailed study area along the Riverfront in Sioux City, Iowa Page 7
Materials and Methods Page 8
Definitions Pages 8-9
Research Design Pages 9-10
Figure 3: GPS data points with 10 m buffers and 3 m DEM Page 11
Data Collection Page 12
Figures 5 and 6: Areas of data collection Page 13
Figure 7: Area of data collection Page 14
Data Manipulation Pages 15-16
Results and Discussion Page 17
Summary and Conclusion Page 18
References List Pages 19-20
Introduction

In the spring and summer of 2011 the Missouri River Basin received record runoff from large snow packs in the Rocky Mountains and the Great Plains, in addition to record rainfalls. In early May it became apparent that the 16.3 million acre feet (MAF) of space in the river system’s 6 reservoirs would not be able to hold the 60.4 MAF of water that the system had received (Pearson 2011). The best option available to the Army Corps of Engineers (USACE) was releasing the water in progressive increments over a prolonged period of time. This led to expansive flooding that affected communities from North Dakota to Missouri. The result was damage amounting in the millions of dollars done to farmland, businesses, homes, and infrastructure (Hendee 2001).

In Sioux City, Iowa, flood preparation began in late May with the sandbagging of homes and businesses, the creation of levees at the river’s edge, and the construction of barriers for protecting infrastructure. For the most part, land owners compared inundation elevation predictions from the USACE with the elevation of their own properties, which is in accordance with methods used by the Federal Emergency Management Agency (FEMA 2011). The USACE provided them with basic inundation maps which included an overview of projected flood extent and predicted flood depth without the use of underlying aerial imagery as a basemap (Figure 1).

Figure 4: USACE flood inundation map of Sioux City, Iowa
The USACE uses one-dimensional hydraulic models to estimate the flooding along the river’s channel. A one-dimensional model is one that assumes the water moves only in one direction in relation to the model geometry. Within the model, cross-sections depicting the topography of the river channel and surrounding overbank area are digitized perpendicularly to the flow of the water. The model then interpolates the underlying ground surface between cross sections and estimates the water elevation at a specific time interval for each cross section in the model (Breitkreutz 2010).

Once the interpolation of the areas between the cross-sections has been completed, the resulting data are put into a standard geographic information system (GIS) which consolidates the model results. The flood inundation is generated within the GIS by plotting the modeled surface elevations against a digital elevation model (DEM). This is done by performing a 3D centerline process on the river, buffering the tributaries and then clipping these areas to the DEM. The accuracy of the predicted inundation is affected by the level of detail in the geometry that is put into the model. For example, the number and layout of the cross sections, the level of detail which defines the underlying topography of the cross sections, and the resolution and accuracy of the DEM (Breitkreutz 2010).

Other models have been used to predict flood inundation. At the University of Memphis, Chen, et al. (2009) tested their GIS-based Urban Flood Inundation Model (GUFIM) to predict flood inundation in areas which are prone to flooding. The model is a GIS-based, flat-water model that uses publicly accessible elevation data and non-detailed underground sewer system data. This type of model was suitable for use during urban flash flood events caused by large amounts of precipitation. The study’s results were used to prioritize evacuation zones within the study area (Chen, et al 2009).

Luino, et al. (2009) also utilized a model to evaluate flood damage along the Boesio Stream in Lombardy, in northern Italy. In this case, the projected flood extent and base flood elevation were acquired through the use of a hydraulic model that utilized real-time stream gauge measurements and event simulations. The simulation of the real-time event used discharge measurements taken during a flood in May 2002, riverbed cross sections, and a DEM. The May 2002 flood event was reconstructed with the use of aerial photographs and surveys, and the model and its projections corresponded closely to it.

Instead of modeling, Dobosiewicz (2001) used a GIS and DEMs of different resolution to predict flood inundation in Raritan Bay, New Jersey. He normalized the data sets from various agencies and was able to determine the best resolution for determining a flood’s extent. Despite scale, accuracy, projection and errors within his tested DEMs, he determined that realistic flood zones can be attained if post-storm [or post-flood event] water level observations are available.

The focus of this study is to assess the potential use of a GIS for flood inundation mapping and site-specific management along the Missouri River in Sioux City, Iowa, in comparison to the inundation map provided by the USACE. The GIS will use a 3 m DEM from the Iowa Department of Natural Resources to project the base flood elevation calculated from stream gauge height data provided by the U.S. Geological Survey. The effectiveness of the DEM and GIS will be assessed by Global Positioning System data collected along the river’s edge during the height of the 2011 flood event.
Study Area

Sioux City, Iowa, resides along the eastern side of the Missouri River in the western part of Woodbury County (Figure 1). Sioux City encompasses the relatively flat Missouri Alluvial Plain and extends into the rugged Loess Hills region. The floodplain’s topography is characterized by low relief ridges and swales, denoting the previous river channel. Within the study area the elevation of the river valley ranges in from 1,090 to 1,100 feet above mean sea level (MSL). In the Loess Hills region, elevation extends above 1,200 feet above MSL (Christiansen 2003).

Since the 1900s the Missouri River has been dammed, channelized, and stabilized by numerous wing dikes and other structures (Christiansen 2003). Upstream from Sioux City, there are six major dams which are controlled by the USACE. Gavins Point Dam in Yankton, South Dakota, and Oahe Dam in Pierre, South Dakota are the two dams that affect the discharge of the river at Sioux City. At Sioux City the Missouri River also receives input from two of its tributaries, the Big Sioux River and the Floyd River.

The study area encompasses what is referred to as “The Riverfront” by the townspeople (Figure 2). The Riverfront is where the majority of the flood inundation occurred and includes: a park, walkway, casino/riverboat, a dance pavilion, two museums, a boat marina and ramp, two restaurants, and the Sioux City Municipal Well Field. To the north of The Riverfront are the Downtown Sioux City and the Historic 4th Street areas; to the east of the Riverfront resides the old Sioux City Stockyards. In the past 10-15 years the City of Sioux City has done significant restoration and revitalization to these three areas. These areas are the most vulnerable to flooding in Sioux City because of their low local relief and proximity to the Missouri River, Floyd River, and Perry Creek. It is also important to note that during past floods of similar severity these three locations have received considerable damage.
Figure 5: Missouri River at the heart of Sioux City, Iowa
Figure 6: Detailed study area along the Riverfront in Sioux City, Iowa
Materials and Methods

The focus of this study is to assess the possibility of using a GIS for flood inundation mapping in Sioux City, Iowa, along the Missouri River similar to the method used by John Dobosiewicz (2001). The GIS will be compared to the flood inundation map provided to the public by the USACE. A DEM available from the Iowa Department of Natural Resources (IDNR) was used to project flood inundation based on U.S. Geological Survey (USGS) stream gauge height. The USGS stream gauge height was used to calculate the base flood elevation (BFE). Once the BFE was projected by the DEM, Global Positioning System (GPS) technology was used to validate the capabilities of the GIS and the positional accuracy of the DEM. This was done by conducting an overlay analysis of the DEM and the GPS data. Idealistically, the BFE projected by the DEM would coincide with the GPS data that was gathered at the extent of the flood during the peak of the 2011 event. Once this is generated, the output information will be overlayed onto an aerial image which will provide users with a better reference point than that of the USACE’s map.

The following definitions will be useful while reading this paper.

Definitions

1: **Basemap**: a map used to orient map users and provide a geographic context and the background information for that map. The basemap used in the USACE inundation map is basic in that it shows a few major roads, a couple different land uses, and the political boundaries of Sioux City, Iowa. An imagery based basemap provides users with a detailed view of the map region (Esri 2011).

2: **LiDAR**: the IDNR DEM was derived from *Light Detection and Ranging* (LiDAR) data. LiDAR is a remote-sensing technique that uses laser light similar in fashion to the use of radar (Sorenson and Seibert 2007). LiDAR acquires high spatial resolution data that captures discreet changes in the earth’s surface. It is easily used for temporal studies as the data is gathered by airborne platforms. With a resolution between 1-10 meters, in general, LiDAR data provide the best quality and most accurate data derivations for the creation of data sets, such as the IDNR 3 m DEM (Li and Wong 2010).

The IDNR 3 m DEM is a data set that was derived from detailed 2 m LiDAR data. Li and Wong (2010) established accuracy standards ranging from 17 cm to 26 cm for LiDAR that was flown in Richland County, South Carolina. Doug Hallum of the Nebraska Department of Natural Resources (2011) has found that LiDAR in Nebraska can have a vertical accuracy range of 9.5 cm to 18.2 cm. Using the vertical accuracy standards for LiDAR in these two places, one can conclude that 18 cm of error will be near negligible when taking local relief, elevation, and inundation into account.

3: **BFE**: *base flood elevation*, or BFE, refers to the computed elevation to which floodwater is anticipated to rise during a flood event. This term is commonly used in flood plain mapping among various agencies (FEMA 2011).

4: **DEM**: a *digital elevation model*, or DEM, is elevation data in raster, or grid cell, format. Each grid cell is assigned a value, dependent upon what kind of data is in use. In this instance, each grid cell of the
DEM has a value of elevation above mean sea level (MSL); however a DEM can be used for other kinds of data, such as precipitation data. Raster data have spatial resolution equivalent to the area of the cell size (Merchant 2011, 1). For this particular DEM, the cell size and spatial resolution is 3 m. As mentioned above in the LiDAR definition, vertical accuracy of this DEM is negligible for this study.

5: **Overlay Analysis**: this refers to the process of overlaying two or more spatial layers. Typically, an overlay analysis involves a spatial join of the data linked to the two layers (Change 2009). For this project’s purpose, a simple visual overlay analysis will suffice; and the terms visual analysis and overlay analysis are synonymous and interchangeable.

6: **Buffer Analysis**: the process of forming two distinct areas around a vector feature: one within the specified distance, and the other outside of that distance (Figure 4 Pagex). The area within the specified distance is the buffer. Often, buffers of more than one distance are created. Buffer zones are zones of a specified distance from the feature of interest. For this study, a buffer analysis is used to measure the positional accuracy between the GPS data collected in the field and the DEM (Chang 2009).

7: **Accuracy**: in GIS refers to the closeness of an estimate to true values (e.g. location) (Merchant 2011, 2).

8: **Precision**: in GIS refers to the degree of specificity to which measurement is described (e.g. decimal places) (Merchant 2011, 2).

9: **Positional Accuracy**: in GIS refers to the closeness of spatial coordinates to true position. Positional accuracy testing involves using independent sources of higher accuracy, such as a more detailed map, GPS, or raw survey data (Merchant 2011, 2).

10: **Site-specific management**: refers to the application of data sets (e.g. DEM) for managing study areas that are detailed and on a smaller scale, such as the Riverfront, versus the tri-state area on the USACE inundation map

**Research Design**

A Garmin eTrex Venture HC GPS Receiver (accurate within 10 m 95% of the time), GPS software, Microsoft Office Excel, and ArcGIS 10 were needed for this study. ArcGIS 10 was used for this study because of its user friendly GIS that is capable of displaying and manipulating spatial data, while also providing advanced geo-processing tools (Dobosiewicz 2001).

County-wide GIS layers were downloaded from the Iowa Department of Natural Resources (IDNR) and include: a 3 m DEM derived from 1 meter LiDAR and a color aerial image, that was flown 20,000 above ground level in the spring 2009 (IDNR 2011). The former was used as a base map layer. In addition to GPS points and GIS data, the stream gauge height for the day of GPS point collection was obtained from the United States Geological Survey (USGS) website.

Within the study area, GPS data points were taken at the edge of the flood waters. Once the GPS data were entered into the GIS, the data and the DEM were overlayed onto the base map aerial image. In
order to do this, USGS stream gauge height data was used to determine the BFE. Next, a buffer analysis was performed on the GPS data points. A buffer zone of 10 m was created in order to determine the positional accuracy of the DEM and the GPS receiver (Figure 4).
Figure 7: GPS data points with 10 m buffers and 3 m DEM
Data Collection

The GPS data were collected on the 19th day of July, 2011, along the extent of the flooding. The Garmin eTrex Venture HC GPS Receiver was used to mark the waypoints (formerly called GPS data points) along the river’s edge. Each waypoint recorded the latitude and longitude coordinates, elevation above mean sea level, the time of day and the date. To get data of a higher quality, information from each waypoint was collected for one minute. This was to ensure that the GPS satellites and the GPS receiver were able to acquire a secure and accurate signal. The waypoints were collected along the Missouri River’s edge in the temporal and spatial format listed below.

The first waypoint was marked east of the Argosy Casino (Figure 5). Here the water had reached a retaining wall. Waypoints were marked standing on this retaining wall, just east of where the wall ends, and to the west of this wall on the bank that slopes from the parking lot down toward the walkway (Figure 5). The second set of waypoints was marked standing along the water’s edge near the western side of the Argosy Casino (Figure 6). After this, the third set of waypoints was marked where the water had inundated the grasslands of the walking trail and Chris Larson Road (Figure 6). The final area of data collection was on Hamilton Boulevard along the I29 entrance ramp (Figure 7), and west entrance to the Riverfront, where a single waypoint was marked.

In total, 19 waypoints were marked. The sample size was strongly influenced by the accessibility to the inundation along the Riverfront. It must be noted that data were not collected further into the Riverfront area because government authorities had barricaded and closed the vast majority of the area, thereby limiting access. Data gathering was not an option in residential areas.

The accuracy of the waypoints’ positions is reflective of the Garmin GPS receiver. The receiver’s accuracy is within 10 m, or 33 feet, 95% of the time. The data that the receiver acquired was precise to 3 decimal places. The accuracy was validated by visual analysis of overlaying the waypoints onto the aerial image of Woodbury County.
Figure 5: Screen shot looking northwest onto the parking lot of Argosy Casino, taken from Google Earth Pro. The bottom red quadrangle accentuates the retaining wall where GPS Point 1 was collected. The top red quadrangle accentuates where GPS Points 2, 3, and 4, were collected.

Figure 6: Screen shot looking northwest along the west side of the Argosy Casino, taken from Google Earth Pro. The left red quadrangle accentuate the general vicinity of GPS Points 5-9. The left red quadrangle accentuate the general vicinity of GPS Points 10-18.
Data Manipulation

All waypoints were moved from the GPS device into the Garmin software. Once transferred, the software created a spreadsheet that contained the latitude, longitude, and elevation of the waypoints. These data were then transferred into an Excel file. The latitude and longitude coordinates were transformed from degrees, minutes, and seconds to decimal degrees, which is a more compatible format when working with ArcGIS software. To do this, the Excel Text to Columns tool was used to separate the degrees from the decimal minutes. Next, a simple equation was developed to format the points’ latitude and longitude correctly. This method of conversion worked best to minimize user error that can occur when transforming data by hand with a calculator.

Once these data were formatted, the Add XY Data tool in ArcGIS was utilized. It was imperative that the data in the Excel file were entered as shown in Figure 8, i.e. with the latitude first and the longitude second. It was also important to note that the study area is west of the Prime Meridian, thus the longitude values are negative, and should be entered this way into the Excel file.

Within the Add XY Data tool, the North American Datum 1983 was defined as the shapefile’s datum. Subsequently, a new waypoints layer was created and was projected into UTM Coordinate Zone 15 so that they could be overlaid on top of the aerial base map and the DEM. This is the same projection as the DEM and aerial image acquired from the IDNR.
The USGS’s mean stream gauge height for July 19, 2011, was 34.96 ft. (vertical datum NGVD 29) above the elevation of the river bed. The river bed elevation above MSL at that particular gauge is 1056.98 ft. (NGVD 29). The stream gauge height and the river bed elevation at that gauge were then summed to calculate the flood stage’s elevation above MSL: 1091.94 ft. (USGS 2011). To correct for the elevation differences between the two vertical datums (stream gauge height is in NGVD 29, DEM in NAVD 88), an additional 0.542 ft. was added to the river’s calculated height. The final calculated BFE of the inundated areas was 1,092.52 ft.

The IDNR converted the DEM units to centimeters (cm) to compress the file size. Because of this, it was necessary to convert the BFE from feet to centimeters. The BFE of 1,092.52 ft. is equivalent to 33,300.07 cm.

To ease the assessment of the overlay analysis, the DEM was reclassified into two categories: elevations of 31,716-33,300.07 cm and 33,300.07001-46,139 cm. The former category denotes the river’s inundation up to the BFE, and was made blue. The second category was made hollow (i.e. transparent) to eliminate noise from areas where the elevation was higher than that of the BFE (Figure 4).

Next, a buffer analysis was performed on the waypoints with the Buffer Analysis tool in ArcGIS. The buffer distance was 10 m, which was chosen because is it the accuracy standards for the Garmin GPS receiver. Overlay analysis was used to see if the BFE projected by the DEM coincided with the waypoints and the 10 m buffers.

Assumptions:

1: It is assumed that the land and elevations within the study area have not significantly changed from the time of the GPS data collection and the LIDAR data collection that was used to create the DEM. Thus, the temporal integrity of the DEM is intact.
Results and Discussion

Results

Per the Research Design of this paper, it is logical to expect that the BFE of 33,300.07 cm, projected by the DEM, should lie within the 10m buffer zones of the waypoints. As seen in Figure 4, the DEM projection of the BFE was within this zone for all 19 waypoints. From these results it is determined that this DEM could be used for site-specific management along the Missouri River.

Discussion

The goal of this study was to determine the effectiveness of using the DEM and aerial imagery within a GIS for flood inundation mapping and site-specific management of flooding along the Missouri River, and to then compare it with the inundation map provided by the USACE. The effectiveness of the DEM and the GIS was then validated by the GPS data that was collected along the river’s edge during the height of the 2011 flood event.

In theory, the DEM should have been accurate enough to project a BFE that coincides with the waypoints taken at the flood extent. From the overlay analysis of the GIS layers, one can see that the DEM projection of flood waters corresponds closely with where the flooding occurred (Figure 4). This study supports the work of Li and Wong (2010) that indicated that areas of inundation derived from DEMs derived from LiDAR data are accurate.

In comparison to the flood maps created by USACE for Sioux City, Iowa, which did not utilize basemap aerial imagery, an inundation map generated by a GIS of this nature can be more beneficial in determining areas that are vulnerable to flooding. The USACE inundation map provided a good overview of the inundation that would occur within the tri-state area, however, its visible level of detail is mediocre in comparison to the inundation map generated in this study. Using a GIS to produce inundation maps similar to that of this study aids in visualizing exact locations of buildings and homes that could potentially be affected by flooding.

When determining the accuracy of the DEM and GIS, one must take into consideration the accuracy of the stream gauge data. Riverbeds are constantly changing due to the nature of water’s movement. As a result, it is highly likely that the elevation for the riverbed, according to USGS, is not exactly what was reported. This would have some effect on the BFE calculation, and therefore the projection of the BFE.

Addressing the accuracy of the GPS device, 10 m seems like a large margin of error. However, it is important to realize that if water is going to inundate within 10 meters of a location, there is the potential for significant logistical consequences and damage to buildings and infrastructure. Damage will be caused by standing flood waters outside and inside of the buildings, and also by rising ground water levels, or water table. A higher water table can cause soils to swell, and then shrink when it goes down, resulting in damage to buildings and infrastructure than standing flood waters.
Summary and Conclusions

Although events like the Missouri River flood of 2011 are detrimental to many aspects of society, the use of geospatial technology can help to reduce the damage that could potentially occur and mitigate that damage. The use of GIS is becoming ever more important for the management of natural resources. In the future, the need for accurate data sets, like those used in this study, and the applications of those data sets will increase significantly.

In general, spatial data sets should not be considered accurate until they have been validated by GPS field data, or some other means. The DEM acquired from the Iowa Department of Natural Resources was validated by the GPS field data acquired in this study, even though the positional accuracy of the DEM itself was not tested in the field by IDNR themselves. The validity and accuracy of the DEM is largely due to the acquisition of the elevation data through LiDAR, which was used to create the DEM.

Comparing the inundation map provided by the USACE and the map generated by the GIS in this study, one can determine that more detailed maps, aided by aerial imagery, are more beneficial to individuals attempting to manage and prepare for a flood. Overall, this study affirms the notion that a GIS which uses aerial imagery to produce inundation maps can be a more powerful tool than a basic inundation map which does not use aerial imagery, such as the one provided by the USACE in Sioux City, Iowa.
Reference List


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