FEATURE-LEVEL FLOOD INUNDATION DETECTION AND ALERTING

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Abstract:

The impact of flooding can be severe often resulting in loss of life, destruction of property and damage to the environment. Understanding the impact of flood inundation on surface features such as roads, utilities, and buildings can improve mitigation efforts. When combined with the hydrological prediction of inundated areas, direct alerts can be sent directly to stakeholders, in advance, maximizing the time needed to carry out mitigation plans. Geospatial technology can play an important role in these efforts. Hydrological prediction tools can now generate results as geospatial data layers, and data layers are increasingly available for many important surface features. Analyzing the data together establishes which features might be inundated. However, many feature data layers are created with two-dimensional geometry, to determine if a feature is truly inundated requires a Digital Elevation Model (DEM). The purpose of this project is to develop a prototype system, using open-source software that analyzes how the relationship between surface features and flood inundated areas change over time. The system consists of server processes that monitor changes in inundated areas along a river. As changes occur, inundated areas are compared to surface features to determine overlap. Surface feature elevation is established by the DEM and determines if a feature is truly inundated. Significant changes in the status of a feature results in the generation of individual alerts. Mapping of feature layers is achieved with Open Geospatial Consortium (OGC) Web Feature Service (WFS), Web Mapping Service (WMS) and Keyhole Markup Language (KML) formats. The result is an automated mapping and alerting system that produces detailed data layers of inundated features that can be viewed in a broad range of geospatial clients. Layers are continually updated depicting the state of inundation over time and direct alerts go to those who can best carry out mitigation plans for their areas of responsibility.

1. INTRODUCTION

Flooding is one of the most common hazards seen in the United States. Major flooding events occur almost yearly. Flooded areas can be a local occurrence or span several states. The impact from flooding is often severe resulting in loss of life, destruction of property and damage to the environment. A primary example of severe flooding occurred in eastern North Carolina from August 29 to September 5, 1999 when Hurricane Dennis dropped 8-10 inches of rain. Less than two weeks later Hurricane Floyd contributed another 10-20 inches during a four day period. An example of Floyd's impact is shown in Figure 1. The result was 57 deaths and 6 billion dollars in damage (NOAA, 2009). A major flooding event like the aftermath of Hurricane Floyd has a significant impact on many things. Closed roads impact evacuation, supply and emergency response routes. Damaged residences require temporary housing. Closed businesses disrupt common services.

Flood compromised industrial sites can cause environmental damage. Mitigation efforts can improve through a greater awareness of the potential impact on surface features like roads, utilities and buildings. Often limited by time, mitigation activities need to be focused. Steps can be taken to protect property, assemble relief supplies, and formulate plans for a streamlined response. Awareness of potentially impacted features paves the way for feature specific preparations. Increased awareness can also be achieved by alerting those with a stake in the potentially impacted area. The sooner an alert is received, the quicker stakeholders can execute mitigation plans. Many existing alerting systems broadcast messages via radio or television. When away from these devices alerts are easy to miss. In 2009 mobile device usage

Figure 1. Edgecombe County, NC, September 19, 1999. Severe flooding impacting populated areas as a result of Hurricane Floyd. Photo by Dave Saville/ FEMA News Photo

surpassed 90% of the U.S. population (CTIA, 2010). Direct alerts sent to mobile devices can reach individual stakeholders quicker. Business owners, home owners, emergency responders, civic leaders can all receive direct notifications and can mobilize to protect their interests. This project explores the role of automated geoprocessing in predicting the impact of flooding at a feature-level scale, and alerting stakeholders in advance of an event. The primary goals are to increase response times and focus mitigation efforts. This is demonstrated through the design and development of a prototype software system. The project begins by geospatially modeling an area prone to flooding. Many applicable feature data layers can be acquired through public sources. This project limits analysis to roads, railroads, property parcels and building footprints. While the primary focus is on flooding, the system was designed to model additional effects. Flood

monitoring considers both current and forecasted conditions. When conditions change, the boundary of the impacted area is computed. Changes to the impacted area trigger a spatial comparison with all feature data layers. The first step isolates features that intersect an impacted area. A feature intersecting a flooded area is not definitively impacted. Its elevation compared to flood water levels determines its impacted state. Since the geometry of feature data layers is often limited to two dimensional points, elevation can be established from a high resolution Digital Elevation Model (DEM). Changes in a features impacted state triggers alerts. Separate alerts are sent for features that are newly and formerly impacted. Feature specific alerts help get the right people into the right places for flood mitigation efforts. Additional system goals include low cost, flexibility and a short development cycle. Low cost is achieved through the use of free open-source software tools. The desire for flexibility addresses the need to monitor larger areas, analyze multiple feature types and model effects other than flooding. System flexibility is achieved through an event driven design. Prototype development was constrained to a part-time effort over ten calendar weeks. Visual awareness is also important. Potential users are likely to visualize results with a variety of geospatial software applications. Data interoperability with these applications requires no additional end-user investment. Interoperability is achieved through the use of Open Geospatial Consortium (OGC) data formats. The interoperability of system results is demonstrated through several applications. The following sections provide an overview of the study area and system design, and implementation. Interoperability of results is demonstrated in a variety of applications such as ArcMap, Google Earth, and an example web-browser client application.
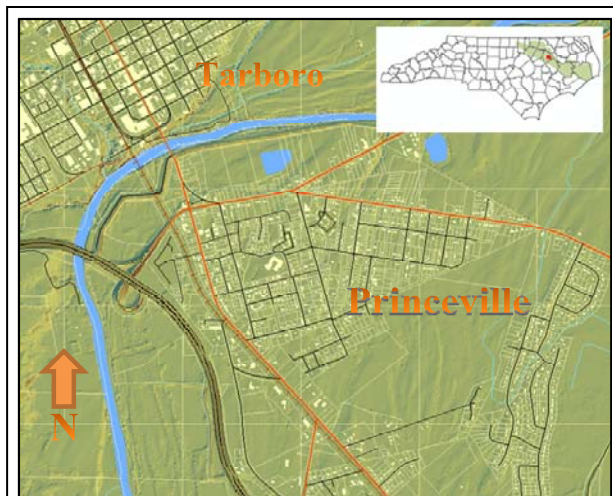
2. STUDY AREA

Figure 2. The study area along the Tar River as it splits the towns of Tarboro and Princeville, NC. The inset in the upper right corner shows a map of the 100 state counties and the Tar River basin colored in green. The study area is highlighted in red.

This project models a region on both sides of the Tar River as it splits the townships of Tarboro and Princeville, North Carolina. A map of the study area, with all the monitored features, is shown in Figure 2. Several factors make this area attractive. A USGS river gauge is situated between the two towns. Real-time values from the gauge can be used to establish current water levels and flood boundaries. The Princeville side of the Tar River has a history of being susceptible in major flood events. It was heavily damaged by flood waters from Hurricane Floyd in 1999. As a consequence, the State of North Carolina conducted a major project to update flood maps for the entire state. This led to the generation of a new high resolution statewide DEM (NCFMP, 2010). This DEM is also highly suitable for inundation analysis. Feature data for roads, railroads, building footprints and property parcels are available through a variety of county, state and federal sources. The combination of a USGS river gauge, data availability and the area's flooding history make an excellent study area.

3. SYSTEM DESIGN

The overall system is divided into three subsystems. The flowchart in Figure 3 illustrates the flow of information between them. Processing begins in the 'Effect Generation' subsystem. Its purpose is to analyze an effect and generate updated impacted area boundaries when conditions change. A river monitoring component updates inundated area boundaries as water levels change. Updated boundaries are sent to the 'Monitoring' subsystem where the impacted area boundaries are compared to the geometry of surface features. This analysis is performed by the 'Effect Impact Analysis' component (Figure 3) which is responsible for producing a collection of impacted features and generating alerts. It is a higher level abstraction of a group of components described in more detail below (Figure 4).
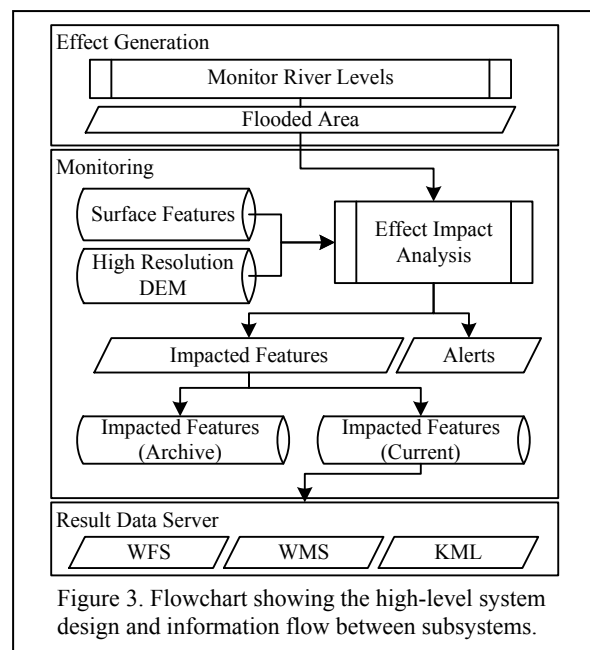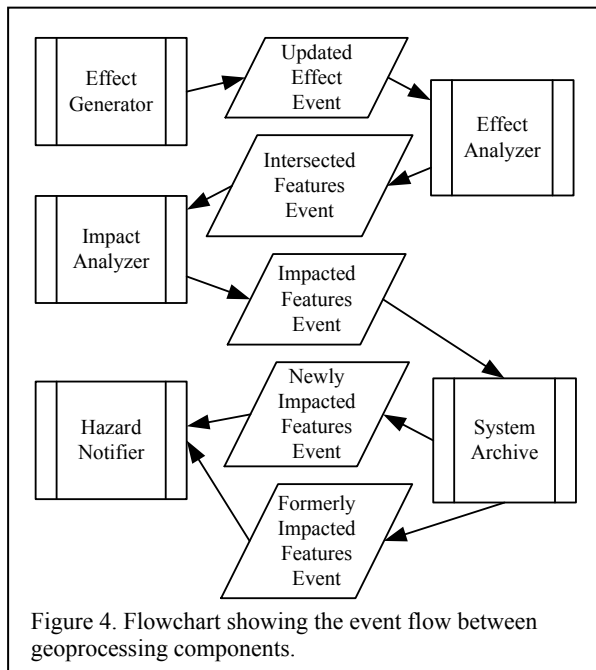

Figure 3. Flowchart showing the high-level system design and information flow between subsystems.
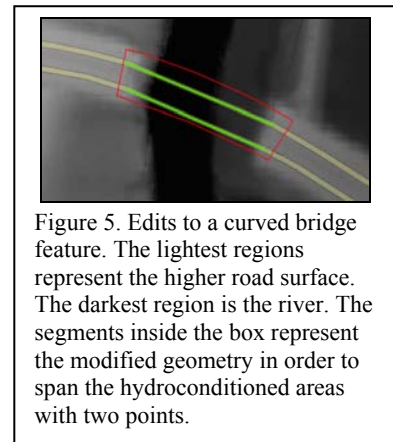
Every updated collection of impacted features is time stamped and archived. The most recent collection of impacted features is stored in a dedicated database table. Previous collections are removed as new data is computed. Each updated collection is compared with the previous one and changes trigger alerts. The 'Result Data Server' subsystem accesses the most recent impacted features upon request from client applications, and returns data in open formats. Information flows through the system components via five events (Figure 4). The 'Updated Effect' event captures changes in impacted area boundaries. The 'Intersected Features' event captures the collection of features influenced by an effect. Additional processing refines this collection and results in an "Impacted Features" event. Flood analysis generates this event after the comparison of surface features with the DEM. Change detection performed on the updated collection of impacted features yield 'Newly' or 'Formerly Impacted Features' events. These events result in stakeholder alerts. System components plug into this information flow by sending and receiving events.

Figure 4. Flowchart showing the event flow between geoprocessing components.

Event management is based on the 'Event Notifier' pattern (Gupta et al., 1998). The main appeal of this pattern is its ability to completely decouple components. Component knowledge of who sends or receives a particular event is unnecessary. This allows components to be added and removed without breaking the system. In the implemented prototype, components can be added and removed dynamically at runtime. The 'Event Notifier' pattern is much more full featured than what is required here. To meet cost and time constraints, a simplified version was implemented, by eliminating capabilities like event filtering and asynchronous event processing. With only a handful of system events neither capability is needed nor is system functionality adversely affected.

4. DATA PREPARATION

Study area data was collected from several sources. The USGS seamless data server supplied the high resolution (3m post spacing) DEM. Railroad data was downloaded from the "NC OneMap" GIS clearinghouse. Road and parcel data was downloaded from the Edgecombe County North Carolina GIS website. Building footprints were acquired directly from the state of North Carolina Emergency Management department. All data was referenced to the North Carolina State Plane coordinate system, North American Datum of 1983. Elevation values in the DEM, inundated areas and river gauges reference the NAVD88 vertical

Figure 5. Edits to a curved bridge feature. The lightest regions represent the higher road surface. The darkest region is the river. The segments inside the box represent the modified geometry in order to span the hydroconditioned areas with two points.

datum. The USGS DEM was derived from bare-earth LiDAR point mass data. The bare-earth production process removes features like vegetation and buildings, but road and bridge surfaces remain. This is ideal for establishing the feature elevation of roads and railroads. Because the DEM was originally created to update flood maps, a problem exists wherever a bridge spans a river or stream. The reflective nature of LiDAR makes bridges appear solid in the DEM. This creates a dam-like effect when used by hydrological models. The dam-like conditions were then cut away using a process called hydroconditioning (Bales et al., 2007). Unfortunately hydroconditioned surfaces can lead to the incorrect identification of inundated features in hydroconditioned areas. Modifying the DEM to undo the hydroconditioning areas would have been too labor intensive for the scope of this project. A quicker solution involved editing feature geometry so that no points fall in hydroconditioned areas. Edited features have the potential to deviate from the original geometry. This can be an issue on curved bridges. Figure 5 shows the single relevant occurrence of a curved bridge in the study area. The deviation from the original geometry is minor and a reasonable tradeoff for a quick solution and correct inundation detection.

5. FORECASTING FLOOD EFFECTS

This project does not address the hydrologic complexities of flood forecasting nor does it evaluate any particular forecasting approach. The feasibility of flood forecasting has been demonstrated by other efforts (Jones, 2004). Instead it is the impacted area boundaries of a forecasting system that are generically treated as system input. This project takes a simplified approach to generating flood area boundaries. Pre-generated flood inundation maps already exist for the study area. They represent impacted area boundaries as the Tar River exceeds flood levels. The USGS produced these maps using the same LiDAR derived bare-earth DEMs (Bales et al.,

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2007) used here. The flood inundation maps reflect impacted area boundaries at 1ft river stage height increments. Live instantaneous USGS river gauge values (NWIS, 2010) establish which inundation map will become the output of the "Effect Generation" subsystem (Figure 3). Instantaneous river gauge values are accessible programmatically through a web service. The combination of the pre-generated flood inundation maps and the live water level values establish current flood conditions. Forecasted conditions are needed for advanced warning alerts. Forecasted values for USGS river gauges are currently produced by the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS) in the form of hydrographs (AHPS 2010) but are not available programmatically. If this information were available via a web service like the USGS river gauge data, then the forecasted condition alerts could be fully demonstrated for the study area. Until then forecasted conditions are simulated.

Table 1. Open-source software

Description	Version
Java Development Kit	1.6.2
PostgreSQL	8.4.2
PostGIS	1.5
GeoTools	2.6.4
GeoServer	2.0.2
Apache-Tomcat	5.5.30

6. OPEN-SOURCE TOOLS

Several open-source tools were used to build this prototype system. An all open-source solution was chosen to control costs. Instability and lack of support is sometimes a concern when using open-source products, but no major problems surfaced with any of the open-source tools. The entire application is written in the Java programming language. Geodatabase functionality is provided by PostgreSQL and the PostGIS spatial extension. The GeoTools toolkit supplies geoprocessing functions and spatial data structures. The OGC compliant result data server is implemented with GeoServer deployed as a Java servlet in an Apache-Tomcat web server. The specific versions of the open-source tools used in this project are listed in Table 1.

7. GEODATABASE

The PostGIS geodatabase is used to store both surface features and results. For each surface feature type such as roads or building footprints, four tables are created. Individual tables hold the latest, newly, and formerly impacted features. Each updated collection of impacted features is stored separately in time history archive table. During non-flood conditions, all but the archive table will be empty. A simple naming convention is used to programmatically assemble table names throughout system processing. Table names are built by combining a surface feature's table name with the unique name of the effect and the purpose of the table. For example, the flood effect defines its unique name as "inundated". The latest collection of impacted railroad features would then be stored in a table named "inundated_railroads". This simple convention makes it easy

to add additional surface features for analysis and new effects. Appropriate tags are added to indicate purposes like archival and storing newly/formerly impacted features. The relevant names are passed along in the body of an event.

8. GEOPROCESSING

The default geoprocessing behavior is to calculate the intersection between an impacted area and surface features. Processing results are captured in an in-memory collection and attached to an "Intersected Features Event". If a new effect like a wild fire were modeled, intersection alone could be sufficient to establish an impacted feature. For flood effects the additional comparison with the DEM establishes if a particular feature is under water. Excluding the previously mentioned hydroconditioned areas, the relief of the 3 meter post-spacing DEM clearly reflects the excavated surfaces of both roads and railroads. This additional processing is handled through the creation of a specialized "Impact Analyzer" component (Figure 4). The DEM based analysis results in a roughly 10% reduction of intersected surface features. Flood effect processing also calculates the water depth of each inundated feature. Water depth is stored as a new attribute in each impacted feature. It is then used by the data server for symbolizing (Table 2) flood inundated features. Because water depth can vary over the geometry of a feature, it is calculated as the average depth of each inundated point. All geoprocessing is performed with GeoTools. Initial consideration was given to PostGIS for the intersection detection. Though PostGIS is fully capable, an SQL approach is less flexible for capturing intermediate collections than the GeoTools solution. GeoTools objects are much better suited for attaching to an event than are database queries. The limited scope of the prototype did not propagate alerts beyond the generation of newly and formerly impacted features events. In a full-featured production system, dedicated event handlers can easily be added to send individual notifications via email or text message.

9. DATA SERVER

Geospatial data interoperability makes it possible for information to be viewed by a wider audience than is possible with proprietary formats. The Open Geospatial Consortium (OGC) promotes interoperability through the definition of open format specifications. Specifications like WFS, WMS and KML are now supported by many geospatial applications. GeoServer is an OGC compliant data server that is used to provide system results in all three above mentioned formats. Setup with GeoServer is straightforward. Publishing new data layers takes only minutes. The majority of effort in this phase was expended on creating custom symbolization for impacted features. Data layers are symbolized using OGC Style Layer Descriptors (SLD). While not particularly complicated to create, all but the simplest styles require hand editing XML text. A multivariate symbolization was sought to reflect both the hazard of inundation and the water depth. The color red is commonly used to indicate danger or caution. A red hue is used to represent the hazard of inundation. A constant red hue with variations in lightness is used indicate water depth. Light

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to dark reds indicate shallow to deep water depths respectively. Details of the color scheme are listed in Table 2.

Table 2. The flood inundated feature color scheme specified in the SLD for impacted lines and polygons

Description	Hex Color	RGB Color
Feature outline	FF0000	255, 0, 0
Inundation depth ≥ 10ft	CB181D	203, 24, 29
Inundation depth ≥ 5 & < 10ft	FB6A4A	251, 106, 74
Inundation depth ≥ 2.5 & < 5ft	FCAE91	252, 174, 145
Inundation depth < 2.5ft	FEE5D9	254, 229, 217

The Red, Green, Blue (RGB) color definitions for this color scheme were provided by the ColorBrewer online application (Brewer, 2009). A fully red hue, with no green or blue in its RGB definition was used to outline inundated features. Symbolization examples can be seen in Figures 6-12.

10. RESULTS

Flooding occurs in the study area when Tar River water levels reach a height of 28ft above the NAVD88 vertical datum. Fortunately no such conditions occurred during project development. To demonstrate results, water levels were simulated by manually varying values from 45ft to 47ft and back to 46ft above the datum. The map in Figures 6 combines the base map in Figure 2 with the flooded area and impacted roads at the 45ft mark.
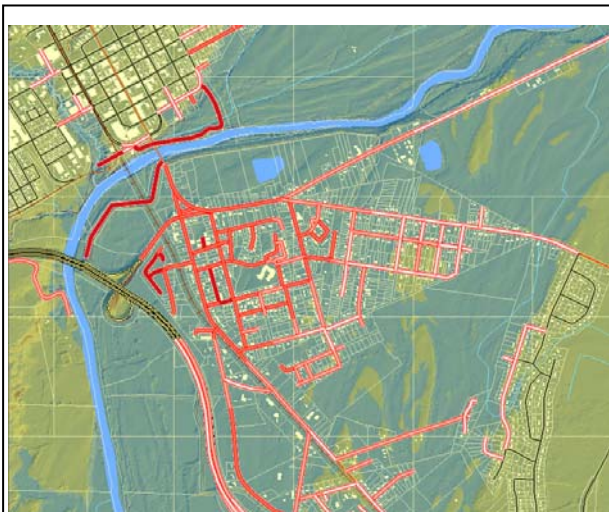

Figure 6. Impacted roads due to flood inundation. The Flood water levels are at 45ft above the vertical datum. The impacted feature legend is listed in Table 2.

Lighter to darker reds indicate shallower to deeper inundation levels respectively for each impacted feature. The water depth to color relationship is listed in Table 2. Water levels rising from 45ft to 47ft reveal newly impacted road features. Figure 7 maps the flooded area at 47ft and the newly impacted road features if a 1ft rise in water levels occurred. Figure 8 highlights formerly impacted roads as the flood waters recede from 47ft to 46ft. Figures 6-8 were created using ArcMap and impacted features limited to roads for the sake of clarity.

Impacted road layers are served through a WMS feed from the result data server. WMS servers turn data request from client applications into images. Since the results are continually updated by the system, simply referencing the WMS layer is sufficient to get the latest information.
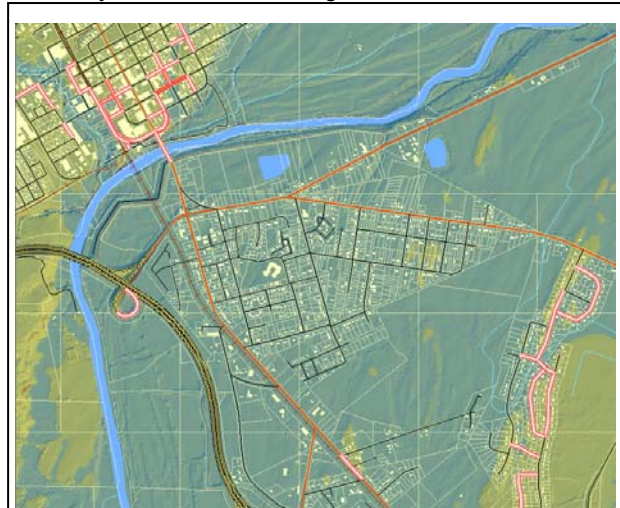

Figure 7. Newly impacted roads when flood levels rise from 45 to 47ft above the vertical datum.

Visualizing the results revealed a missing data preparation step. Feature types like property parcels and building outlines, can be definitively represented by a single feature.
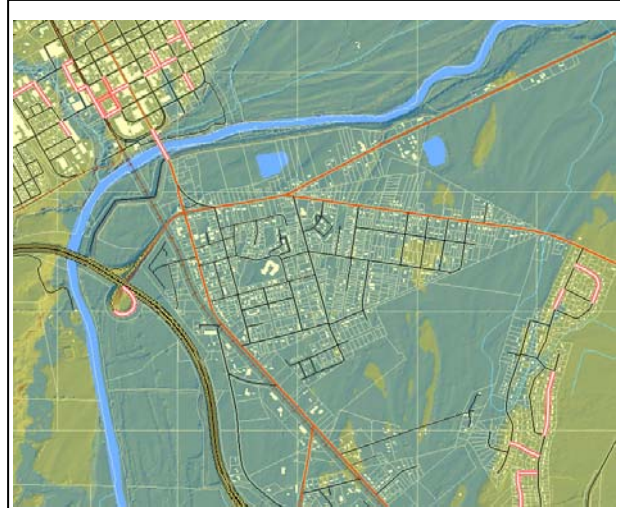

Figure 8. Formerly impacted roads when flood waters recede to 46 from 47ft above the vertical datum.

When an effect influences that feature, a change in symbolization clearly establishes its impacted state. The same is not true of feature types like roads or railroads where multiple lines are connected to form a network. The boundary between lines can be arbitrarily set without changing the overall network. With roads, feature lines that cross intersections can give misleading results. If a small portion of a long road is impacted (Figure 9), the entire feature will be highlighted. This could incorrectly eliminate a navigable road. A solution is to divide feature geometry into segments that better serve a routing purpose. During the data preparation

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phase, lines can be split (Figure 10) so a feature doesn't extend through an intersection and unnecessarily eliminate a valid transportation route.
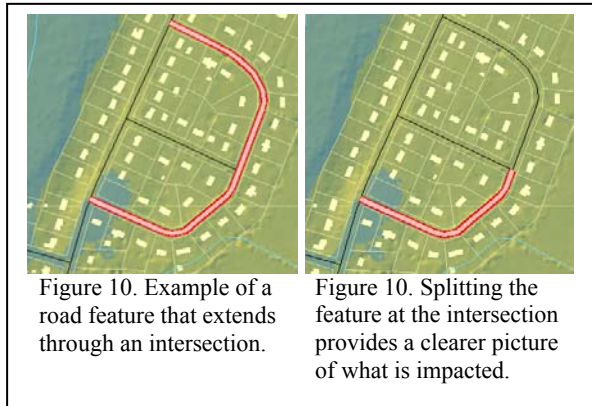

Figure 10. Example of a road feature that extends through an intersection.

Figure 10. Splitting the feature at the intersection provides a clearer picture of what is impacted.

Figures 6-8 demonstrate the visualization of impacted roads in the popular full-featured GIS application ArcMap. Google Earth is widely used for its ability to navigate worldwide imagery, terrain and map data in a 3D virtual globe setting. Figure 11 shows impacted road, railroad, building outline and parcel features in Google Earth over a backdrop of Google Earth supplied imagery. Data displayed in Google Earth must be in the KML format. The KML specification was originally developed by Keyhole, Inc. before being purchased by Google in 2004. The KML specification is now managed by the OGC. Many in the general public are not likely to have dedicated geospatial applications installed on their computers. They are likely to have access to a computer with an internet connection. In these cases a webpage may the best opportunity for disseminating and visualizing results. Figure 12 is an example of results being displayed in a simple browser-based client. This web client uses another open-source product called OpenLayers for the client side mapping capabilities. It combines system results with imagery supplied by Microsoft's Bing Maps. Though different applications,
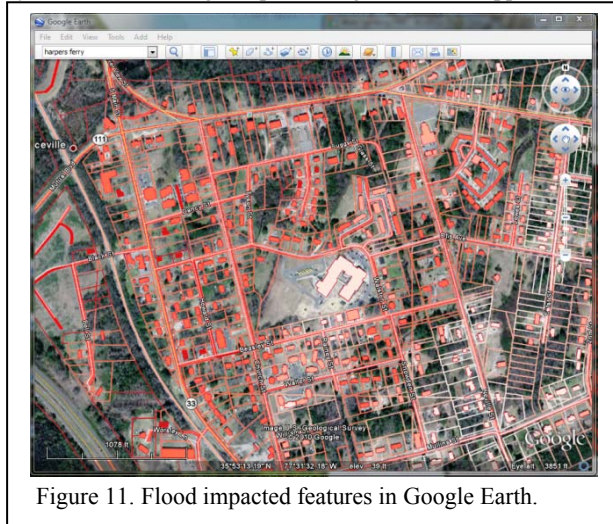

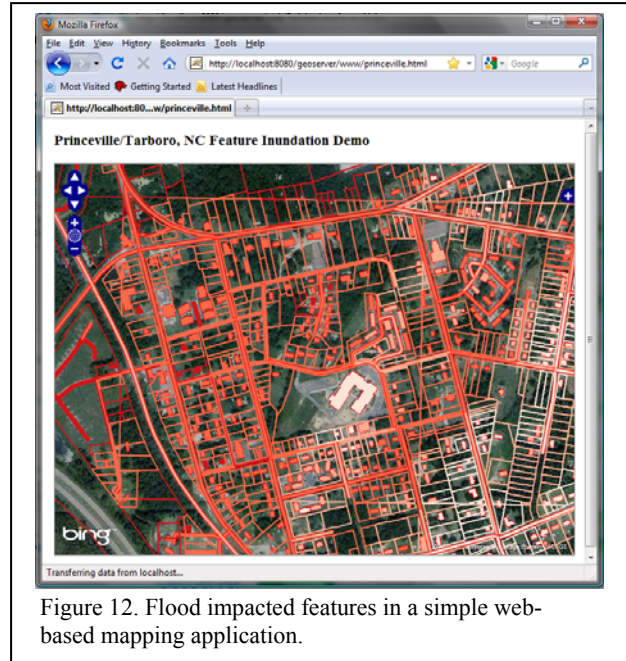Figure 11. Flood impacted features in Google Earth.

Figure 12. Flood impacted features in a simple web-based mapping application.

the results are symbolized equally in all the examples shown in Figures 6-8. The demonstration of results in ArcMap, Google Earth and a browser-based client illustrate the benefits of data interoperability.

11. CONCLUSION

This paper documents how continuous automated monitoring of features in a flood zone, combined with direct alerting can improve flood mitigation efforts. It further demonstrates that open-source tools are a valid development solution. From geodatabases and geoprocessing to geospatial data servers, open-source products are a viable implementation option. Data interoperability with multiple geospatial applications is possible using open formats. This helps to maximize the availability of critical information, satisfying the goal of increased awareness. But the scope of this project was limited to a proof of concept prototype. For a full-featured system additional capabilities are needed. Maximizing warning times in advance of a flood requires a reliable forecasting mechanism. The river gauge approach has limited coverage and forecasted flood data cannot currently be accessed programmatically. Though not a focus of this project, follow on efforts should include reliable flood forecasting techniques with full river basin coverage. A complete system should also address the scalability required to monitor a full river basin, entire state, or larger geographic area. The final piece to a complete system is the development of mechanisms to register and manage alert subscriptions.

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