Spatial Patterns of Mortality Risk within a Tornado Path:
A Fine-scale Spatial Analysis of Spatial Video-collected Damage Data for the Newcastle-Moore Tornado of May 21, 2013

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ABSTRACT

The past few years have coincided with several catastrophic single and multiple outbreak tornado events. These have revealed that even with more advanced warning systems, and the availability of protective spaces such as safe rooms, a large tornado can still claim scores of lives and cause many more injuries. As a result, there is a need for more fine spatial scale research on a number of topics, including warning systems and response, evacuation, and the heterogeneity of building risk in a tornado. All of these research areas would benefit from fine-scale damage data from past events to understand contributing factors to morbidity and mortality. For example, by considering the building-to-building damage variation in previous tornado paths, patterns might be identified that can be translated to tornado-prone areas as policy actions[1](e.g., is the risk to life greater up or down slope, on the facing or opposite side of the street to an approaching tornado, and within or on the end of a city block?) Although we can surmise the importance of spatial situation and configuration, it is only recently that damage data has been collected or acquired that can advance this branch of hazards science. This report will present the preliminary findings of one such methodology applied to the Newcastle-Moore, Oklahoma tornado of May 20, 2013. More specifically, this report has the following objectives. First, to use the spatial video approach to post-tornado damage collection previously applied by the investigators to the Tuscaloosa, Alabama (4/27/2011) and Joplin, Missouri (5/22/2011) events. This will establish data for cross-comparison between three similar events. In addition, these data provide a baseline against which to measure recovery for the Moore area. The second objective is to perform fine-scale spatial analysis on the damage data to reveal patterns which can later be associated with secondary data, such as mortality locations, to identify patterns of enhanced and reduced risk within a tornado path.

BACKGROUND

Geographic Information Systems (GIS) and mobile mapping technologies have previously been used to associate damage with human outcomes (Hall and Ashley 2008, Curtis and Mills 2011,

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[1] Since the notable tornado of 1999, Cleveland County (which houses Moore) Oklahoma has been struck by several other tornadoes including two significant events (http://www.srh.noaa.gov/oun/?n=tornadodata-city-moore).

Curtis and Fagan 2013). The methodology proposed here varies from more commonly available data, such as might be utilized by and then made available through FEMA, in that these data are coded to a finer (ten category) standard scale which has now been applied in multiple events. In addition, these data are coded from an archival source allowing for re-investigation for validation or advancing different lines of inquiry. This is particularly important as spatial context around key locations may reveal far more than a single coded damage score. In general, therefore, this data collection approach is in keeping with the suggested need for fine-scale research into Enhanced Fujita Scale 4 and 5 sized tornadoes (Simmons and Sutter 2012). In this spirit, if we return to the second objective of this paper, the specific research question is, are there any spatially significant structures that received less damage than expected based on the surrounding damage landscape?

Assessing Damage after a Tornado: Moore, Oklahoma

During 2011, two tornadoes re-focused an already active hazards research community on the potential consequence for severe weather on urban areas. The largest number of tornado deaths since 1932 (324) for a single day occurred in the southeast of the United States on April 27. This was followed less than a month later (May 22) by the largest number of deaths attributed to a single tornado since 1947 in Joplin, Missouri (161 deaths) (National Weather Service 2011). In the space of less than one month, top ten tornado statistics so popular in high school and university classes had been rewritten. The concern amongst researchers was that, supposedly, all the secondary factors which can protect against a loss of life have improved over the last few decades: warnings systems, availability of safer structures and practices for sheltering, and also triage medicine. The 2011 loss of life re-emphasized that if conditions coincided in the worst way, then these types of catastrophic events were still likely to occur. As a result, a variety of suggestions and topics for debate were raised, such as finding spatial hot and cold spots in past tornado paths to find locations of where and where not to place critical infrastructure (Simmons and Sutter 2012). Extending this logic in a slightly different direction, are there spatial patterns identifiable in a damage path that can be used to develop regional critical infrastructure policy? In order to achieve this aim, fine-scale (at the building level) damage data are required, probably with additional ground-survey information allowing for the investigation of any revealed pattern.

In 2013, on May 21st the EF5 rated Newcastle-Moore tornado resulted in an approximately 14 mile, 1.1 mile maximum width damage path. The town of Moore, Oklahoma has previously been hit by significant tornadoes, of particular note being the 3rd May 1999 tornado which killed 36 and injured another 583 and has since been widely studied by academicians (McCoy and Stumpf 2002, Brown, et al. 1999, Brooks and Doswell III 2002, Burgess, et al. 2002, Hammer and Schmidlin 2002, Speheger, et al. 2002). By comparison the 2013 tornado was less catastrophic, but still killed 23 and injured 377. This report focuses on the spatial patterns of damage data collected in the days following this event.

Spatial Aspects of Damage Assessment

From a spatial perspective, maps of Fujita or Enhanced Fujita scale damage tend to be overestimates because the purpose of the classification is to identify evidence for the strongest wind field in (usually) a coarsely drawn area. The contours found in the results maps of Figures 2 to 4 illustrate this point. There have been a few attempts to create more spatially specific intensity patterns, for example as intra-urban damage maps (Speheger, et al. 2002). In this case, the authors used a GIS to spatially summarize the previous Moore tornado for 3 May 1999, from a variety of sources including ground surveys, videos, radar, and aerial photography. Their resulting cartography was spatially detailed with varying widths of wind speed intensity overlaid onto house outlines. The detail found here was unique and subsequently evolved into several other investigations (Rae and Stefkovich 2000, Burgess, et al. 2002, Yuan, et al. 2002). Wurman et al. (2007) used these data for development of disaster scenarios for sub-neighborhood scale major metropolitan areas, most notably Chicago, Illinois. Their approach overlaid varying intensity tornado paths onto city maps and aerial photography, before assigning mortality estimates based on a combination of fine scale damage and census data. Their estimates, which were in the thousands, have since been questioned (Blumenfield 2008, Brooks, et al. 2008, Wurman, et al. 2008).

Tornado injury studies have also understood the importance of being able to link morbidity and mortality with actual damage locations, and even collect data to this end, though little to no spatial research tends to result (Glass, et al. 1980, Brown, et al. 1999). Associated spatial descriptions tend to be coarsely drawn, such as differences between towns, or inside and outside of the path, or between urban and suburban areas.

Just as Speheger and colleagues (2002) stimulated more fine-scale tornado investigation, so it is hoped the introduction of a standard approach to collecting data, and a standard way to code damage for multiple events, will also spillover into different associated research disciplines. The Tornado Injury Scale (TIS), was developed by Curtis as a health risk evolution of the traditional EF scale (Curtis and Fagan 2013). Utilizing the 10 point degree of damage scale used by field teams for residential coding, the TIS also includes apartments or condominiums. This is because the purpose of the TIS is not to estimate wind speed (and therefore assign a tornado "size") but to identify the potential for injury or loss of life. The TIS scale is as follows (Curtis and Fagan 2013):

1 = No visible damage
2 = Minor visible damage (usually loss of roof tiles, guttering, etc.)
3 = More substantial roof loss and / or boarded windows and doors
(The above three scores, though causing damage, are unlikely to result in loss of life especially if the resident is not proximate to an outer wall that might be penetrated by projectiles.)
4 = Large sections of roof material are lost as are less rigid sections of the house such as the collapse of car ports
5 = The building has shifted on its foundation and / or sizeable holes have been knocked through walls or the roof
(Scores of 4 and 5, though not necessarily injury-causing carry more of a mortality risk (though slight under normal precautions) as part of the outer shell may have been penetrated.)
6 = The roof has been removed
7 = Exterior walls have collapsed
(Both 6 and 7 result in considerable damage to the home that can easily result in injury or loss of life. This is especially true for the upper reaches of a 7 score if multiple walls have collapsed. A building crushed by a tree would also score a 7.)
8 = All exterior walls have collapsed leaving just a few inner walls standing

9 = The entire structure has been reduced to rubble
10 = Even the debris has blown away leaving just dirt or a concrete slab
(Scores 8 to 10 are likely to result in injury or death unless there is an inner reinforced storm room or basement.)

Figure 1 presents two examples of TIS scores 5 to 9 for the 2013 Newcastle-Moore tornado. Each image is extracted from Contour Storyteller software which allows for the mapped display of the spatial video. The upper right inset map displays exactly where each video frame was taken, and for this example all images come from a two block area.

For TIS 5, the first building shows damage and holes to the exterior shell, including a sizeable puncture in the wall. The second TIS 5 image has a large section of damage at the roof-wall intersection. For TIS 6, both images show homes where the roof has been removed. For TIS 7, the two images show the range for this score; the first building has lost its roof and sections of exterior wall, while the second has suffered multiple failures to exterior walls. For both TIS 8 images the majority of the outer shell has been destroyed leaving just an interior section. The visual damage for TIS 9 and 10 would be a debris pile or just a concrete slab.

For comparison purposes with other damage scoring systems, such as used by FEMA or associated research (Wurman, et al. 2007), the 10 TIS classes can be aggregated into four: unlikely loss of life (TIS 1 to 3), possible loss of life (TIS 4 & 5), serious risk to life (TIS 6 & 7), and extreme risk to life (TIS 8 to 10).

Spatial Video

Spatial video is a form of mobile mapping that merges a video image with GPS coordinates. Different systems have previously been employed by the authors (Mills, et al. 2008, Curtis, et al. 2010, Mills, et al. 2010, Curtis and Mills 2011), with the technology varying from having an external proprietary GPS receiver encoding locational information as an audio stream onto the video through an external unit, to an extreme sports camera, the Contour +, which has an internal GPS tagging the video stream. There are several benefits to this last system including image quality, the small size of the camera, and the relatively low cost. In addition, the software used to display both video and GPS path (Storyteller) is freely available; the GPS path is visible in a Google map interface as long as the user has an Internet connection. The relative ease of download and display also has field implications as it allows for the image and GPS signal to be checked at the end of each collection day. The work done in the GIS Health and Hazards lab at Kent State University is focused on maximizing the transferability of geospatial tools and approaches to a wide array of users, so the potential for this type of spatial video unit to incorporate field collaborators, and to be able to widely share video is appealing. There are more sophisticated units, for example ImageCat (http://www.imagecatinc.com/), producing more precise locational tagging, and certainly more research-useful software, but these systems are far more expensive and involve additional training. To reemphasize, the approach detailed in this report can be used by any collaborator, even people outside of academia to collect and code data, which means potentially more data from disparate locations can be used to build a tornado spatial data warehouse.

METHODS

A two-person team arrived in Oklahoma City on May 29th, eight days after the tornado had touched down. On May 30th the team was joined by a local collaborator from the Center for Spatial Analysis in the Department of Geography at the University of Oklahoma. Using printed sheets of damage aerial imagery as a guide, the team went to the western edge of the tornado path outside Moore, Oklahoma. Seven cameras and two spatial video systems were arranged around the vehicle. On either side of the car, fixed to window mounts, were two Contour + 2 cameras with inbuilt GPS recording functionality, and two Panasonic PV-GS500 video cameras. An additional Contour + 2 camera pointed forward. Each of the PV-GS5000 cameras was connected to a Red Hen Systems Global Positioning System (GPS) with aerial mount which output a coordinate signal onto the audio track of the video tape. The kit was completed with a Garmin eTrex GPS. In total there were eight different GPS tracks being recorded, and at least three video images being captured on either side of the vehicle.

The majority of the damage path in Moore was collected during the 30th. Drive speed was approximately 15 to 20mph. In the evening of the 30th the video were downloaded from the Contour + 2 cameras and viewed in Storyteller software to ensure video image quality and the GPS track were recorded properly. On the 31st the team returned to the damage area and collected roads that had been impassable the previous day (because of debris being cleared or utilities being reestablished) or where errors had been detected in the first data collection run. On returning to the GIS Health and Hazards Lab (GHH) at Kent State University, the Panasonic PV-GS500 tapes were digitized and archived, and coding began with the Contour + 2 video. In general the quality of the image is better from the Contour camera, but the Red Hen system had been used for the Joplin tornado so it had also been used for possible later comparisons between tornados with the same system[2].

The video of damage was coded and digitized within Google Earth. This was for three reasons. First, Google Earth is freely available, which is important as a mandate of GHH is to develop methods which are as transferable. Secondly, Storyteller software uses the same imagery as Google Earth which makes digitizing easier because of spatial feature recognition. Thirdly, the digitization process within Google Earth allows for the mixing of feature types (points, lines and polygons) in a data table-free dialogue box, and features can easily be added, moved, re-edited and deleted. This was important in capturing different aspects of the damage path beyond just building assessment scores. In other words, the coder is not constrained by pre-determined attribute fields. Every building on the video was coded as a point with an associated TIS, before being imported into ArcGIS 10.1 and converted into a shapefile. Once in the GIS, the damage point file was investigated using a localized measure of spatial autocorrelation which would identify damage "hotspots" and also reveal outliers in the coding.

RESULTS

Approximately thirty-five hours of Contour +2 video (five cameras), and fourteen hours of PV-GS5000 video (two cameras) was collected on the 30th May. On the 31st May, a further eight hours of Contour + 2 video (four cameras) was recorded to complete the majority of the tornado

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[2] Two additional benefits of the Red Hen system are that the video can be played directly within Arc GIS 9.2, and that the camera image has no wide-angle distortion. In general, though, the Contour system provides the easiest, cheapest and smallest approach for disaster-related spatial video work.

path in Moore, Oklahoma. On returning to the GHH lab, two students coded one of the Contour+ 2 cameras[3] using the TIS as developed for Joplin (Curtis and Fagan 2013). Each student coded approximately one-third of the path individually, and then both coded the final third independently in order to compare layers for consistency. Curtis provided oversight of all students' coding to maximize inter-rater reliability.

Each video was coded using a two monitor computer approach, with Storyteller software running on one monitor, and building TIS being digitized into Google Earth as a point on the other. After coding, all digitized points were imported and merged in ArcGIS 10.1. Table 1 provides a summary of all code structures. Figure 2 displays these scores mapped out across the tornado path. The buildings are color-coded with a red ramp to show their TIS. These are overlaid on contours generated by the National Weather Service (NWS) survey teams[4]. Only the two highest intensity contours are colored (orange for EF4 and red for EF5). The inset map shows one section of the path to illustrate how structures with the highest damage were found mainly in the EF4 (and above) contour, but that there was potentially life threatening damage outside of these two contours. Similarly, there is some variation between building damage within the EF4 contour. This can be seen in Figure 3 which further details the path in and around the EF5 section with each building's TIS now being labeled. Although most of the buildings received a TIS of 9 or 10, there are a few 7s within the EF4 contour. This variation in damage could be the difference in surviving the tornado. Also of concern is that there are some structures that receive a TIS 9 outside the EF4 contour which raises the question as to the accuracy of the spatial video code, the accuracy of the NWS survey team, or the spatial "fuzziness" introduced by contouring these data. A major advantage of using the spatial video is that these homes, and the surrounding neighborhood, can be revisited for validation purposes.

In order to further investigate such fine-scale variation, a local spatial autocorrelation analysis was performed using a local Moran's i function in ArcGIS 10.1[5]. This analysis identifies both hot and cold spots of TIS, but more importantly, it identifies outliers; LH are buildings that had a lower TIS than other surrounding structures, and HL had a higher TIS than the immediate neighborhood. Table 1 again summarizes these results, with the majority falling in the HH and LL categories, with 14 buildings being significantly worse (higher TIS) than their surrounds, and 42 faring significantly better. Both of these values should be further investigated to establish exactly why these outliers occurred. Figure 4 displays the same inset area map from Figure 2, but this time with buildings coded according to their local Moran's i score. The LH buildings (structures that performed significantly better than their surrounds) have been exaggerated as larger pale blue circles.

DISCUSSION

Since 2011 there have been several significant tornadoes in the United States. It is widely accepted that more fine-scale spatial research is needed in understanding how such events can still lead to such a heavy loss of life. In order to achieve this aim, researches need fine-scale damage data, ideally by building, for multiple prior events. Although high resolution aerial

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[3] The remaining video has been archived for potential future coding projects

[4] Available as a GIS shapefile at: http://www.srh.noaa.gov/oun/?n=events-20130520

[5] Inverse distance and Euclidean distance options were selected to conceptualize the spatial relationship.

photography offers many advantages, especially in terms of cost savings and expediency, there is still concern as to the accuracy of this source alone[6].

The spatial video system presented in this report provides an alternative solution for a detailed fine-scale recording of such catastrophic events. Indeed, this tool also provides the neighborhood context that others have suggested is necessary (Ashley 2007).

In their analysis of the Joplin, Missouri tornado of 2011 using a similar method, Curtis and Fagan (2013) identified several general damage patterns within the path of destruction, including a distance decay of damage away from a source area, modified by variations in the spatial configuration of the physical geography, and the situation of each building with regards the direction of the tornado and surrounding structures. Their suggestions for further analysis mirror the goals suggested by Simmons and Sutter (2012) that there is still much to be revealed about within path spatial variation in risk (based on previous damage). This report has advanced such fine scale investigation by including another catastrophic tornado path, Moore, Oklahoma, and by using a local Moran's i analysis which not only identifies hotspots of damage within the path, but also reveals outliers – both buildings that outperform, and underperform their immediate neighbors.

As a result of this report there are five next steps: To revisit each outlier building within the video to identify whether the initial coding of the TIS is correct, and then to extract other building aspects form different sources (such as construction type using Google Street View) to identify possible building characteristics that lessen, or increase risk. Secondly, other contributing factors need to be identified, such as the situation of each outlier with regards the direction of the tornado, where the building is on a street segment, and any localized variations in relief. Thirdly, the same analysis will be performed on the Joplin, Missouri damage path and the two analytical outputs and localized findings compared. To reemphasize the benefit of spatial video, this comparison between tornados is possible because the locational video is archived. We can virtually re-drive the damaged streets. Fourth, the same damage and mortality / morbidity analysis will be conducted in Moore to link damage patterns to an actual human outcome. Finally, for any other significant tornado, if funds can be acquired, the same spatial video data need to be recorded so that an archive of as many events, of all sizes, and for different locations can be made available for future research.

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[6] FEMA commissioned New Light Technologies / ImageCat for rapid damage assessment from remotely sensed sources following the 2011 tornadoes in Birmingham and Tuscaloosa, Alabama and Joplin, Missouri. Combining high resolution pre- and post-disaster imagery with remotely sensed imagery resulted in a reportedly high accuracy rate. On-the-ground survey data was also used to validate findings, though there still remains no academic paper detailing these events.

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Table 1: A summary of TIS coded structures taken from the spatial video for the Moore, Oklahoma tornado of May 21st, 2013. Only TIS scores of 5 or greater are reported. Traditionally, the scores are collapsed into 6 & 7 as considerable damage, and 8 to 10 as catastrophic damage (TIS 5 being provided as a comparison to 6).

TIS 5	TIS 6	TIS 7	TIS 8	TIS 9	TIS 10	HH	HL	LH	LL	Total Coded Structures
178	135	189	129	363	107	870	14	42	1081	3395

Figure 1. Example TIS Scores from the Newcastle-Moore, Oklahoma tornado

Figure 2. TIS coded structures taken from the spatial video for the Moore, Oklahoma tornado of May 21st, 2013.

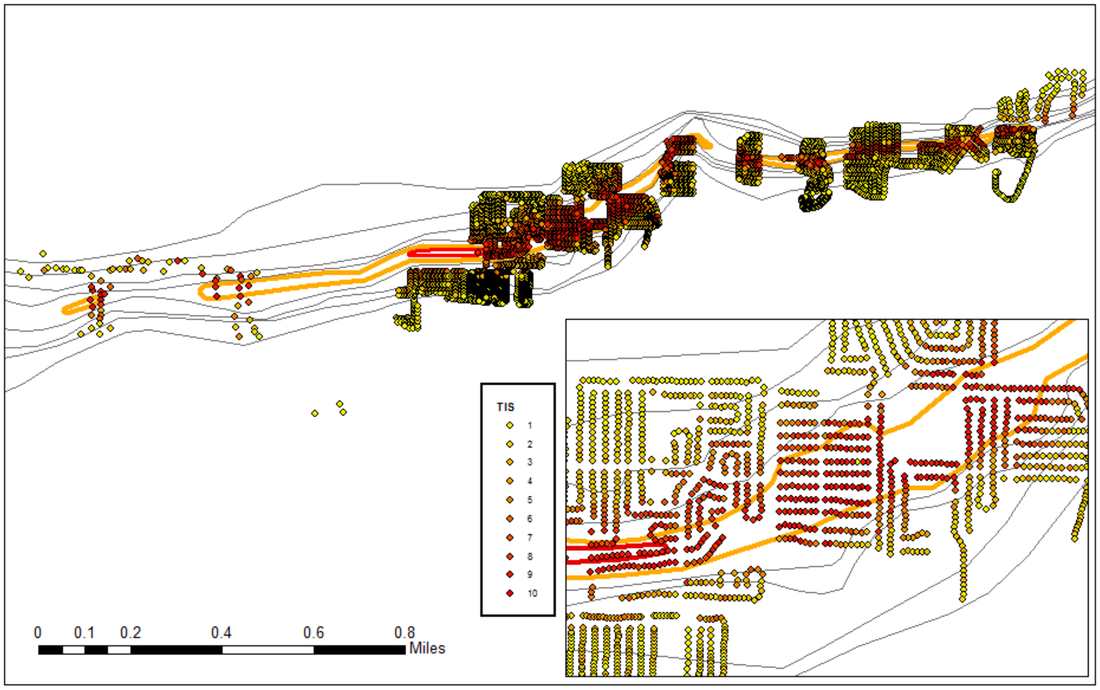

Figure 3. TIS coded structures within the EF4 and EF5 Moore, Oklahoma tornado path of May 21st, 2013

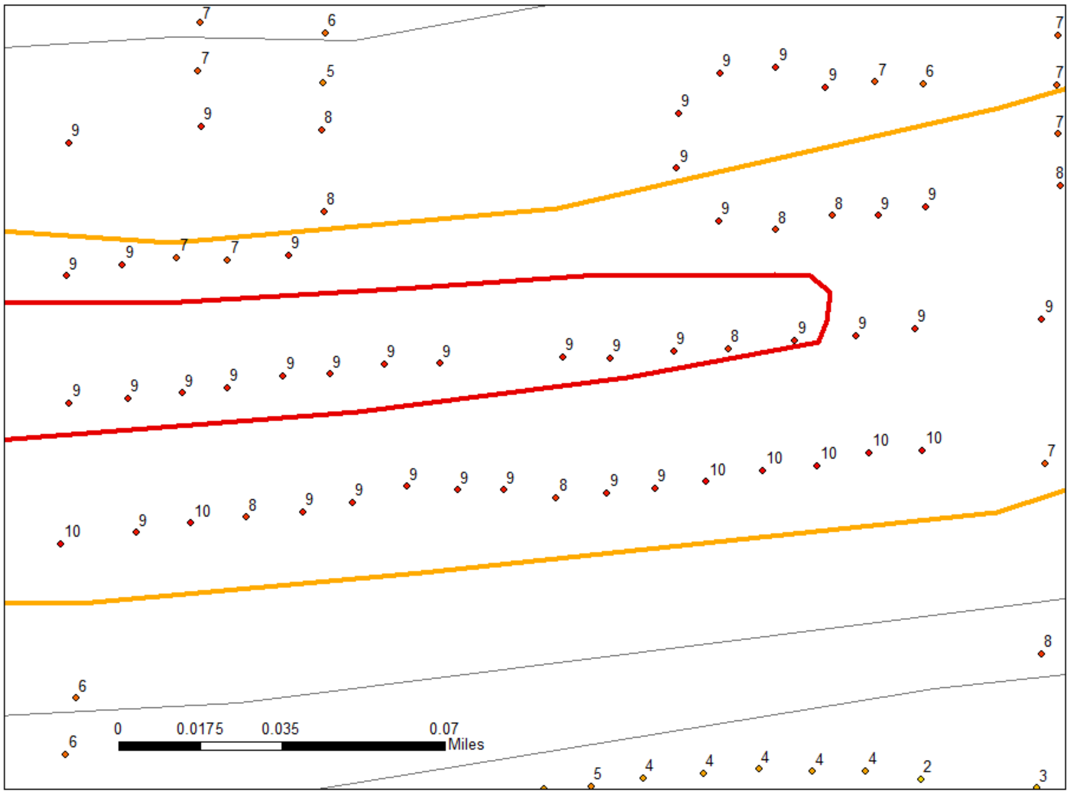

Figure 4. Local Moran's i analysis of TIS coded structures within the Moore, Oklahoma tornado path of May 21st, 2013.