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Connecting the Dots: A Communications Model of the North Texas Integrated Warning Team During the 15 May 2013 Tornado Outbreak

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On 15 May 2013, 19 tornadoes occurred across North and Central Texas, killing 6, injuring over 50, and causing more than $100 million in property damage. The majority of the impacts to life and property were the direct result of EF-3 and EF-4 tornadoes that affected the communities of Cleburne and Granbury. This study focuses on an examination of the North Texas Integrated Warning Team (IWT) communications through a thorough analysis of interactions between IWT members during this event. Communications from all members of the IWT were collected and organized so that a quantitative analysis of the IWT communications network could be performed. The results of this analysis were used to identify strengths and weaknesses of current IWT communications to improve the consistency of hazardous weather messaging for future high impact weather events. The results also show how effectively communicating within an IWT leads not only to more consistent messaging, but also to broader dissemination of hazardous weather information to the public. The analysis techniques outlined in this study could serve as a model for comprehensive studies of IWTs across the country.

1. INTRODUCTION

On 15 May 2013, 19 tornadoes occurred across North and Central Texas, killing 6, injuring over 50, and causing more than $100 million in property damage (NCDC 2013). The majority of the impacts to life and property from this outbreak were in the communities of Cleburne and Granbury. The Cleburne tornado, rated an EF-3, damaged dozens of homes along an almost 9 mile path. The Granbury tornado, rated an EF-4, was responsible for the outbreak's six fatalities as it moved along a nearly 3 mile path.

The warning system for hazardous weather, including events like the 15 May 2013 outbreak, consists of detecting an impending threat, providing information to those at risk, and enabling the at-risk population to make decisions for personal safety (Sorensen 2000). Agencies that perform the hazard identification and communication functions of warning systems are known as Integrated Warning Teams (IWTs). IWT members are most commonly identified as local emergency management and government officials, media representatives, amateur radio operators, and the National Weather Service (Doswell et al. 1999). IWTs work to provide a consistent message regarding a hazard because at-risk populations will not immediately take action in response to the first warning message they hear (Sorensen 2000), but will instead seek out additional sources of warning information to confirm the warning is true (Mileti and Sorensen 1990). Message inconsistency limits the ability of the at-risk population to personalize, or recognize the personal importance of, warning messages (Foster 1980). This, in turn, affects a much broader decision making process that culminates in the decision on whether or not to seek protective action; the protective action decision making process consists of identifying a threat, personalizing it, evaluating protection options and then making a decision on how to respond to the threat (Lindell and Perry 1992, 2004).

This study focuses on a formal examination of IWT communications with a thorough analysis of interactions between North Texas IWT members during the 15 May 2013 tornado outbreak. Understanding the interactions of an IWT not only serves to identify the strengths and weaknesses of current IWT hazardous weather messaging, but is an important step in building a resilient community. Community resiliency, or the ability to respond and

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recover from a disaster, is not solely based on the post-disaster decisions, but the decisions leading up to the event (Nigg 1995). Communications from all members of the IWT during the 15 May 2013 outbreak were documented so that a quantitative analysis of the IWT communications network could be performed for this event.

2. DATA AND METHODOLOGY

To perform a quantitative analysis of communications within the North Texas IWT (hereafter, simply IWT) during this event, the groups that compose the IWT had to be formally defined. In this study, the IWT is composed of four primary groups: The National Weather Service Forecast Office in Fort Worth, TX (hereafter NWS), the primary television broadcast media outlets in the Dallas-Fort Worth area Designated Market Area (hereafter referenced as "Media"), North Texas local emergency management officials (hereafter referenced as "EM"), and a Virtual Operations Support Team (hereafter, VOST) (http://vosg.us/history). Each member of this IWT had a common goal of providing hazardous weather information to the general public during this event. The public is also included as a group in this analysis, and is simplistically defined to include those individuals in North Texas not included in the IWT as defined above. This very generic definition of the public was made because the primary focus of this study is on internal IWT communications, and not a detailed analysis on response behaviors to the weather warning system as a whole.

All available communications were documented during this event, with the primary focus on collecting communications during the times of 1900 CDT to 2200 CDT, when 14 tornadoes, 6 instances of baseball sized or larger hail, and 7 instances of damaging wind were reported to the NWS (**Figure 1**) (NCDC 2013). Communications were collected from time-stamped, archived NWSChat logs (https://nwschat.weather.gov), NWS internal communications logs, and interviews with each NWS staff member that worked during this event. Media communications were documented minute by minute by reviewing archived tapes of coverage provided by the local ABC, CBS, NBC, and FOX affiliates of the Media. EM communications were documented by conducting semi-structured interviews with EM officials in Montague, Hood, and Johnson Counties. These EM officials also provided a timeline of internal communications and operations of their respective Emergency Operations Centers, including the activation of various methods of public notification of hazardous weather (i.e. Outdoor Warning Sirens, and the activation of "Reverse 9-1-1" type of technologies). Media, EM, and VOST communications that occurred within NWSChat were also documented, and VOST communications that occurred primarily on Twitter and Facebook were included in this study. Finally, communications that directly mentioned the NWS on Twitter (i.e. mentions of @NWSFortWorth), and any direct Facebook interactions between the NWS and Public were documented. To capture some idea of what message the public received during this event, door to door surveys were conducted near the tornado damage paths of the Sunset, Granbury, and Cleburne tornadoes. Only 29 individuals were available or willing to respond, so the Public survey results are not used directly as a point of analysis in this study but provide anecdotal context. Amateur radio communications logs and internal NWS communications logs were also used to document communications with trained spotters and storm reports that were received from the public. These methods resulted in 1229 unique pieces of information documented for analysis.

To analyze how various pieces of information were communicated within the IWT during the event, pieces of information were traced through the IWT in the same way that personal networks, or rumor networks can be modeled, with a digraph (Poole 2011, Uzzi and Dunlap 2005). There were numerous pieces of information that could have been tracked in this study, however the following items were subjectively chosen by the authors to document:

1. First NWS Tornado Warning for Hood County (that mentioned Granbury, the location of the EF-4 tornado that resulted in 6 fatalities)

2. NWS Tornado Warning for Johnson County that mentioned Cleburne (the location of a mile wide EF-3 tornado with no fatalities)

3. NWS Tornado Warning issued for the Cleburne tornado shifting to a northward track

4. NWS Tornado Warning for Tarrant County

5. The knowledge that the Cleburne tornado's track (Johnson County) was shifting north

6. The knowledge of a tornado debris signature in dual-polarization radar schematics on a supercell in Parker County

7. The report that the Cleburne tornado (Johnson County) was a "mile-wide wedge" tornado

8. The confirmation report of a tornado in Granbury (Hood County)

9. The confirmation report of a tornado in Pecan Plantation (Hood County)

10. The confirmation report of baseball sized hail in Granbury (Hood County)

11. The confirmation report of a tornado in the Millsap area (Parker County)

12. The confirmation report of a tornado near Sunset (Montague County)

13. Report of significant damage from the tornado in Granbury (Hood County)

To construct a digraph modeling the communication of each piece of information in the documented IWT interactions, each group (NWS, Media, EM, VOST, Public) was defined as a vertex, and a directed edge connecting vertices was defined to represent a successful communication of the piece of information (1-13, defined above) from one group or vertex to another. Utilizing this model, a 5x5 adjacency matrix, A, was created with each entry in the matrix assigned a 1 when it represented an edge of the digraph (i.e. for each entry in A, A_{ij} in the adjacency matrix, a "1" was assigned when the vertex in the i-th row successfully communicated with a vertex in the j-th column, otherwise a "0" was assigned). Because this communications analysis was modeled after a rumor network, the diagonal of each adjacency matrix (those cases where i=j) had to be zeros. That is, a group does not directly communicate with itself in this model.

Successful communication of a piece of information was defined as any communication of information items 1-13 that could be confirmed between members of the IWT with the data collected during this event. A successful communication had to be verified within 15 minutes of the piece of information entering the IWT by any means. The requirement for a direct communication to occur within 15 minutes of entering the IWT was subjectively defined by the authors, but was based on the advance tornado warning lead time goal set by the National Weather Service (NWS National Performance Measures, 2010). Each of the adjacency matrices created in this event are included as **Appendix A** at the end of this paper.

The collected data made the creation of the adjacency matrices straightforward for the most part; however, there were occasions where verification of a successful communication link was ambiguous. To reduce bias in the creation of the adjacency matrices, each of the authors independently created adjacency matrices for each piece of information (1-13) and then met to discuss discrepancies. The evidence used to assign each 0 or 1 entry had been documented, but is not included in this paper. The entries that were most contentious were those entries that resulted in the communication of a warning message directly to the public. Of particular interest: *Were the communications of tornado warnings from the NWS directly to the Public successful?*

The authors decided to assign this communication as a "0" in each adjacency matrix. The primary reason that this direct communication was decided to be unsuccessful was that the authors could find no evidence that the Public received a warning message directly from the NWS in all of the communications documented during this event. (**Figure 2**). Further support for this decision is provided in Trainor (2012), which strongly suggested that the general public does not typically receive a warning message directly from the NWS (**Figure 3**). The VOST, EM, and Media groups were "allowed" successful direct communications with the Public in this study because there was at least one piece of evidence indicating that the public successfully received a piece of information from each of these groups.

With all adjacency matrices created, the authors wanted to investigate how robust communications were within the IWT for the various pieces of information modeled in this study. First, the authors wanted to determine whether, given enough time, a piece of information would filter through the entire IWT. In rumor modeling, this is the same as determining if vertex *i* is connected to vertex *j* by a path of some length, *k*. This can be calculated by using the equation (Poole 2012)

$$A_k = \sum_{k=1}^{n} A^k \qquad (1)$$

where *n* is number of vertices. In this study, there are 5 vertices, so n=5, and A_5 was calculated for each adjacency matrix. The results of these calculations are included in **Appendix A** and are discussed in more detail in section 3. Each step, or iteration through this equation, *k* in equation 1, represents a 15 minute passage of time for the message to travel between groups. A "complete" rumor matrix is defined as an A_5 that contains no zero entries; that is, each group has received the same message from every other group after 75 minutes.

Second, the authors wanted to determine if there was a way to classify the relative importance of each group in communicating a particular piece of information during this event. As suggested by Poole (2011), the eigenvectors and eigenvalues for adjacency matrices can be broadly applied to rank which vertex (or in this study, IWT member) played the most important role in communicating a selected piece of information.

Based on the construction of adjacency matrices in this study, Perron's Theorem is generally satisfied (Poole 2011). Perron's Theorem requires that each adjacency matrix be a positive n x n matrix. Because adjacency matrices in this study could have all zero columns (meaning that vertex *j* never received a particular piece of information), Perron's theorem was not always fully satisfied. However, this does not prevent calculating eigenvalues or eigenvectors; it simply results in some trivial calculations, that is, some values of zero in the resultant eigenvectors. When Perron's Theorem is completely satisfied, this guarantees that there exists at least one positive eigenvalue with a corresponding positive eigenvector. More importantly, Perron's Theorem guarantees a unique eigenvalue of the adjacency matrix exists with a corresponding probability eigenvector that satisfies the equation

$$A\boldsymbol{r} = \frac{1}{\alpha}\boldsymbol{r} \qquad (2)$$

where ***r*** is an eigenvector corresponding to the adjacency matrix A, and α is the constant of proportionality (Poole 2011).

This allows the calculated eigenvector **r** to represent a unique ranking vector of A such that adding up the values of **r** will result in the value 1. Such a ranking gives insight as to which vertex, or IWT member in this case, played the most important role in communicating the piece of information modeled, based on its relative value in its associated ranking vector, **r**. The calculation of eigenvectors in this study utilized EISPACK software routines (Smith, et al. 1976, more recently online at: http://www.akiti.ca/). The results of these calculations are also included in Appendix A and are most meaningful as a ranking when there are no trivial results; that is, the vector **r** contains no zeros. The interpretation of the results of these calculations is also discussed in more meaningful detail in sections 3 and 4 of this paper.

Lastly, the authors assigned a directed communication path to each non-trivial documented communication in this study. These communications were not as strictly defined as they were in the creation of the adjacency matrices. These paths were assigned not only to documented successful communications, but intended communications as well (i.e. if the NWS intended a message to go to the public, it was counted here). Communications within groups were also allowed, if for example, media members were speaking directly to one another, or if a different NWS office relayed a report to the NWS office in Fort Worth. These communications were collected in one large matrix that represents a sort of histograph of communications between various members of the IWT and the public (**Figure 4**). This matrix was created to provide some insight as to the composition of all of the documented communications in this study (the authors did not include all 1229 pieces of communication in this paper, so this is a way to visualize the distribution of communications collected).

3. INTEPRETATION OF DATA

Once the matrices were constructed and the analysis completed as described in section 2, the interpretation of the matrices showed some interesting results which are described in this section. Select matrices were chosen for discussion in this section.

a. Confirmed tornadoes

The matrices for information flow concerning the confirmation of tornadoes (A.8, A.9, A.11, and A.12) generally showed that these pieces of information were communicated amongst all members of the IWT.

For both A.11 and A.12, the rumor matrix was complete when k=2 in Equation 1, and the information was shared multiple times between members of the IWT. For matrix A.9, the rumor matrix is nearly complete when k=3, but further iterations confirm that the EM community never shared the tornado confirmation report with other members of the IWT (the rows in the A^k matrices representing EM remain zeroes for all values of k). The matrix analyses in these instances support the idea that the more groups that share information into the IWT, the easier, faster, and more complete the information reaches all members of the IWT.

Matrix analysis of A.8 had the most negative results as the information only appears to be received by the EM and Public members (i.e. all other columns are zero vectors). In this case, the tornado was reported to the emergency manager by a member of the Public, but the information was never shared further within the IWT. Analysis of this matrix confirms that this information oscillates between these two IWT groups (see A_5 in Appendix A.8) but never fully makes it through the IWT. A Media member also showed live footage of the tornado, and a VOST group shared information about the tornado on social media, but neither group directly shared this information with the other members of the IWT through other communication methods (i.e, direct communication, or via NWSChat). The communication of this information within the IWT would have been critically important as this tornado was the violent EF-4 that resulted in 6 fatalities near Granbury. Caution must be taken in this case as it appears the information successfully makes it to the Public, but the "Public" in this case is only a small set of people composed of county spotters. This skews the implied results in some ways, and highlights a weakness in the broad definition of the "Public" in this study, as it appears that the general public (i.e. those directly impacted by the tornado) received this message, when the door to door survey results indicate that this was likely not the case. No one surveyed near the tornado damage path in Granbury indicated that they had advance knowledge of a confirmed tornado as the storm approached. The matrix calculations in this case strongly suggest that when information is not shared freely within the IWT, the information essentially perishes. This can result in a lack of consistent messaging from various IWT members, or in a lack of communication of critical information by the IWT in general.

b. Tornado damage in Granbury (Hood County)

The results from tracing the information regarding significant damage from the tornado in Granbury through the IWT were significantly positive across all groups. The information about the damage almost completely infiltrated the IWT when k=2 and the rumor matrix was complete for k=3. Not only was it complete, but most of the IWT received the information multiple times (see A_5 in Appendix A.13). In this example, all members of the IWT played a strong role in sharing and communicating this piece of information. This case demonstrated that the more members of the IWT that share information within the IWT structure, the more completely and quickly this information is shared with the Public.

c. Comparison of the confirmed tornado in Granbury vs. report of significant damage from the tornado in Granbury (Hood Co)

The adjacency matrices and matrix analysis for the confirmation of the tornado in Granbury (A.8) and the report of significant damage from the tornado in Granbury (A.13) reveal two different IWT communication approaches when A_5 for each matrix is juxtaposed. When information is not fully shared through the IWT as in A.8, the risk of providing an inconsistent message increases. A_5 for matrix A.8 shows that the NWS, Media, and VOST groups never receive this message from other members of the IWT. Without having confirmation of ground truth, other members of the IWT may be prone to making assumptions, and then sharing those assumptions with their partners and followers.

However, when the information is fully shared among all members of the IWT (A.13), a dramatic amplification of the communication of the message was observed. This increases the likelihood that a consistent message is received and shared by all members of the IWT, resulting in a higher degree of confidence that the information is true. This makes the information more reliable in general, and thus easier to act upon. As research by Lindell and Perry (1992, 2004) discussed, threat confirmation plays a large role in the Public's protective action decision making process. Information that is reliable can cut down on the amount of time it takes to confirm a valid threat, cutting down on the amount of time it takes to make a decision to take protective action. A_5 for A.13 also showed that the Public had multiple opportunities to receive this message, increasing the chances that this message was received multiple times, from multiple sources. During interviews with the Public downstream of this tornado, a few residents specifically stated that receiving the information about damage in Granbury from multiple sources helped spur their plan to take protective action. Of those surveyed downstream of this thunderstorm, 33% received this piece of information, while no one reported that they had received a message of a confirmed tornado near Granbury before the tornado directly impacted that community. These results provide strong circumstantial evidence that consistent messaging within the IWT makes it more likely that the intended audience receives the message being communicated.

d. Tornado Warning Matrices

Similar results were discovered for all of the tornado warnings that were investigated for this analysis (A.1 - A.4). The matrices seem to show that the NWS is consistently the primary detector and only source for warnings within the IWT. The Media, EM, and VOST played a large role in disseminating the warning information to the Public. When k=2 (A_2) for these matrices, the Pubic had received the NWS warning information indirectly at least two or three times. The Public never received the warning directly from the NWS (in this model) which demonstrates the important role other members of the IWT have in further communicating warning information. The 29 door-to-door surveys indicated that no one reported that they received a direct warning message from the NWS, even though those conducting the surveys identified themselves as NWS meteorologists. This does not provide definitive evidence that the Public does not receive warnings directly from the NWS, but these results do seem to provide strong circumstantial evidence of that conclusion. The results of these matrix calculations also show that NWS partnerships with IWT members must be strong if a warning message is going to be communicated to the public. While the warning message does get to the public, the message must first go through non-NWS members of the IWT. These members have the ability to filter or change the message if the warning decision is not communicated effectively from the NWS, potentially resulting in a different message getting to the Public.

Unfortunately, the warning information was never fully shared by all groups of the IWT (see A_5 for A.1 - A.4). In these cases, the information essentially stopped moving by k=2 (A_2) meaning it didn't have as much residence time within the IWT structure as most other pieces of information tracked in this study. Comparing these official warning matrices with the ground truth matrices (A.7 - A.13), we see that ground truth reports are communicated through the IWT much more effectively and completely. It can be inferred that ground truth reports in general help keep a message about hazardous weather moving through the IWT and to the Public, more so than just the warning message alone. In addition, as we have seen in the previously discussed matrices, as more members of the IWT communicate the message, the more people have access to the information, thereby increasing the chances of the Public receiving the intended message.

e. Ranking Vectors

The ranking vectors were an important part of this project too, and provide insight into which groups were most effective at communicating each piece of information. Certain patterns were detected among the ranking vectors that enabled the authors to divide the associated information and matrices into three different groups for analysis: Official Warning Information, Hazard Detection, and Ground Truth.

Matrices A.1 - A.4 that conveyed tornado warning dissemination were considered "Official Warning Information". The NWS ranked as the main communicator of this information in all four of these matrices, which is consistent with its role as the only official source of the warning.

Matrices A.5 and A.6 were considered "Hazard Detection" pieces of information. Once again, the NWS ranked as the main communicator of this information, but the EM group did play a role in

A.5 as they were also one of the first to confirm the tornado was moving north via damage reports. The NWS was primarily conveying this information based on radar trends.

The final matrices (A.7 - A.13) were grouped as "Ground Truth" pieces of information, and consisted of ground truth reports from the field. The Media, Public, and VOST groups ranked highest as the most influential communicators in these instances, indicating that these three groups are the primary information spreaders for "Ground Truth" information. In nearly all the ranking vectors for A.7 - A.13, the VOST group was at or tied for the top spot. The NWS is a secondary receiver of this information, as usually the NWS is not out actively spotting or tracking these storms in the field. What the ranking vectors seem to show in these cases are the important roles that non-NWS groups have in the IWT. The Media, Public, and VOST groups were key to sharing information, and when they shared the information with other groups in the IWT, the information effectively and quickly spread through the entire IWT, giving the Public multiple opportunities to receive this information. As mentioned above, it seems critically important for these ground truth reports to be communicated by the IWT in a timely manner during hazardous weather events. The communication of the warning itself seems to have very little residence time in the IWT, while the communication of ground truth reports resonates throughout the IWT.

4. CONCLUSIONS

The analysis of IWT communication during the 15 May 2013 tornado outbreak revealed complex interactions amongst IWT members. The results from this analysis suggest several interesting factors from this particular IWT. First, the National Weather Service plays an important role of a detector of weather information, but is not necessarily disseminating this information directly to the public. Second, when members of the IWT do not communicate internally, there is an increased risk of the public receiving an inconsistent message from the IWT. The mathematical analysis of the communication within the IWT reinforces the idea that the IWT plays a critical role in the NWS hazardous weather warning program. Indeed, the results of this study seem to strongly show that a warning message will not effectively get to the Public without other members of the IWT!

Specifically, the analysis showed a clear signal that an official warning by itself has a relatively short life within the IWT. In very few steps, the initial message that a warning has been issued stops being communicated within the IWT and likely to the Public as well. In contrast, ground truth information communicated to all IWT members resulted in a very long residence time within the IWT and gave the Public multiple opportunities to receive hazard information. These results highlight the importance of an IWT that communicates well internally. The faster that hazardous weather information is shared with all members of the IWT, the faster and more frequently this information becomes available to the Public to take action on. The matrix analysis in this study shows a clear message that individual IWT members communicating hazard information only to the Public does not lead to effective communication.

Communication between IWT members is essential for a truly consistent message. Why is this important? This study showed two cases which had different outcomes depending on the internal communication within the team. The first case is the confirmation of the Sunset tornado (Matrix A.12). In this case, the tornado was reported by spotters and was communicated to the IWT through NWSChat. Within minutes, each broadcast media outlet, the NWS, and VOST were communicating messages about a confirmed tornado near Sunset, Texas. In the case of the deadly EF-4 Granbury tornado, information about a confirmed tornado in Granbury was not communicated by the NWS to any partner, as the information was not known by the NWS at the time because the confirmation was not shared internally with all members of the IWT. Fewer opportunities to receive information leads to less opportunity to personalize and confirm the threat, which may lead to a delayed or ignored response by the Public to seek protective action. Sorensen (2000) describes an information void created during "rare or unfamiliar events" that necessitates "repetitive warning messages" to satiate this gap. The Public is actively seeking information during an event, but differences in IWT approaches to that communication may limit information exposure to the public and, consequently, public response.

Nurturing an IWT is hard work. Relationships must be built, trust must be gained, and everyone's role must be understood before high impact weather events occur. When the time comes, these relationships are put to the test with each member having essentially the same goal, and fulfilling a crucial role. This study began with the idea of tracking information through the IWT to see what relationship exists with the data. The adjacency matrices and the in-depth look at the data from the 15 May 2013 tornado event show when the IWT communicates well, the end users of weather information receive several consistent pieces of information in return. Conversely, this study suggests that IWT communication needs additional development. Traditionally, the NWS has issued warnings, the media has broadcast the warnings, and the emergency management community has made decisions on where to direct resources based on this information. This study shows when the IWT members are communicating efficiently, the system works quite well. The rumor matrices show that when there are breakdowns in communication between IWT members, the message which ultimately leaves the IWT is far from complete and leads to less message availability for the Public. Further study is needed to determine the reasons why communication breakdowns occur, as the case could simply be an assumption that the communication has already occurred.

A strong IWT is critical for the warning system to have the full beneficial impact. Information sharing between the partners of the IWT not only aids in the hazard detection and management processes, but maximizes the quality and frequency of information that makes it to the public for input into their protective action decisions. The lack of communication has been shown to be an impediment to this process. Research suggests that those who do not receive a warning are significantly less likely to take protective action (Balluz, et al., 2000; Blanchard-Boehm and Cook 2004). While this study confirms this concept, the study also suggests that a NWS warning alone is not enough to ensure protective action is taken. However, effective, timely communication within an IWT has the ability to greatly amplify the messaging of hazardous weather information to the Public, which increases the likelihood of people seeking protecting action, resulting in stronger community resiliency to weather disasters.

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REFERENCES

Balluz, L., Holmes, T., Kiezak, S., Malilay, J., & Schieve, L. (2000). Predictors for People's Response to a Tornado Warning: Arkansas, 1 March 1997. Disasters, 24(1), 71-77.

Blanchard-Boehm, R.D. & Cook, M.J. (2004). Risk Communication and Public Education in Edmonton, Alberta, Canada on the 10th Anniversary of the 'Black Friday' Tornado. International Research in Geographical and Environmental Education, 13(1), 38-54

Doswell III, C.A., A.R. Moller, and H.E. Brooks, 1999: Storm Spotting and Public Awareness since the First Tornado Forecasts of 1948. Weather and Forecasting, 14, 544-557

Foster, H., 1980. Disaster Planning: The Preservation of Life and Property. New York: Springer-Verlag.

Lindell, M.K., and R.W. Perry. 1992. Behavioral Foundations of Community Emergency Planning. Washington, DC: Hemisphere Publishing Corp.

Lindell, M.K., and R.W. Perry. 2004. Communicating Environmental Risk in Multiethnic Communities. Thousand Oaks, CA: Sage.

Mileti, D.S. and J.H. Sorensen, 1990: Communication of Emergency Public Warnings. ORNL-6609, Oak Ridge National Laboratory.

NCDC, 2013. Storm Data. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801-5001.]

Nigg, J., 1995: Disaster Recovery as a Social Process. Newark, DE: Disaster Research Center, University of Delaware.

NWS National Performance Measures, 2010: http://www.nws.noaa.gov/cfo/program_planning/doc/FY-11%20Nat.%20Perf.%20Measures%20-%20With%20Preliminary%20Hurricane/FY-11%20Nat.%20Perf.%20Measures%20-%20With%20Preliminary%20Hurricane_files/textonly/slide1.html Storm-based tornado warning lead time.

Poole, D., 2011: Linear Algebra A Modern Introduction (Third ed.). Trent University. 728 pp.

Poole, D., 2012: Linear Algebra A Modern Introduction (Third ed.) Student Solutions Manual. Trent University. 540 pp.

Smith, B.T., J. M. Boyle, B. S. Garbow, Y. Ikebe, and V. C. Klema, 1976: Matrix Eigensystem Routines--EISPACK Guide. Mathematics of Computation, 30 (133), 188-189.

Sorensen, J., 2000: Hazard Warning Systems: A Review of 20 Years of Progress. Natural Hazards Review, 1(2), 119-125.

Trainor, J., 2012: The Importance of an Integrated Warning Team. Keynote Presentation. 1st North Texas IWT Conference, Arlington, TX.

Uzzi, B., and S. Dunlap, 2005: How to Build Your Network. Harvard Business Review, 83(12), 53-60.

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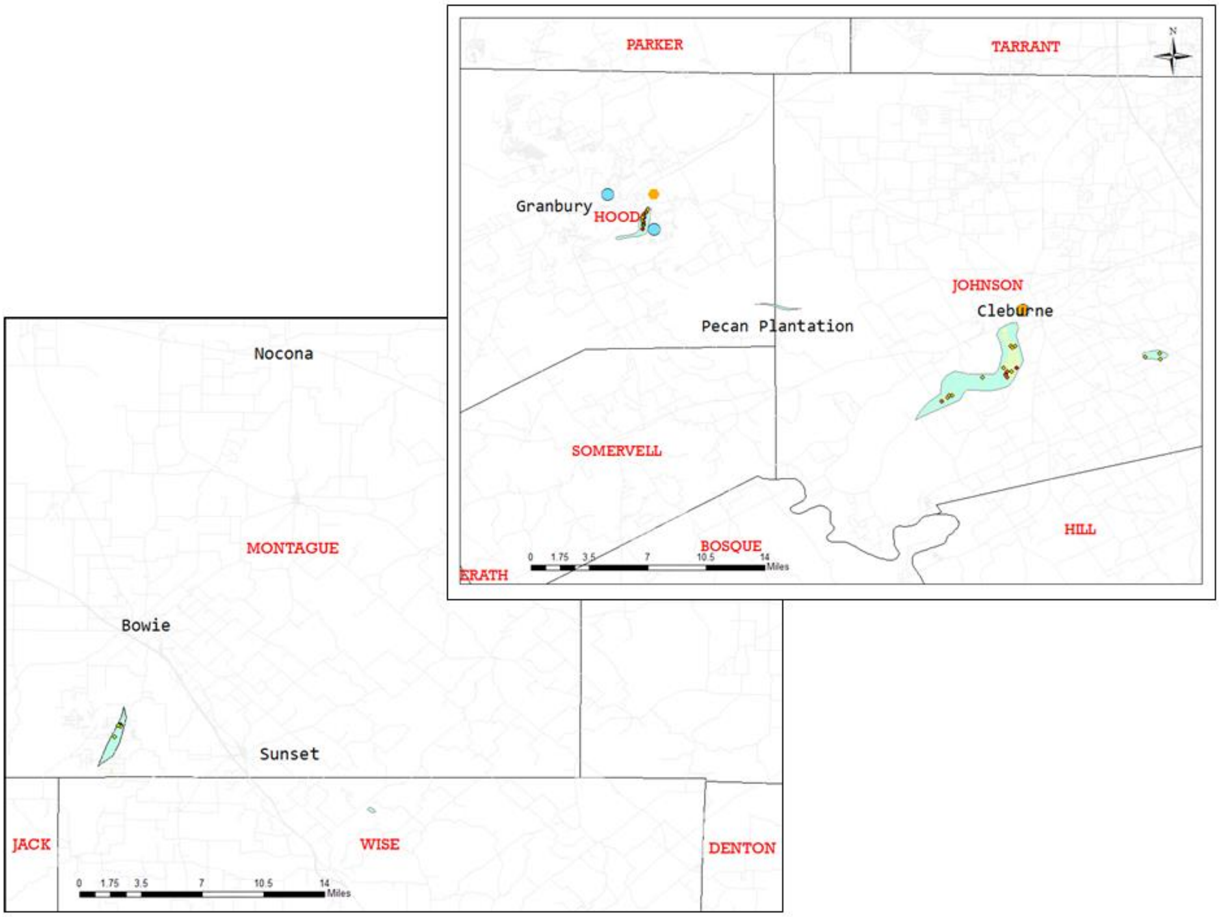

Figure 1 - A map of some of the significant severe weather events that occurred across North Texas from 1900 CDT to 2200 CDT, on 15 May 2013. Tornado tracks for the tornadoes discussed within this paper have been outlined in light green polygons. Individual damage indicators rated by NWS storm survey teams are included in these polygons as small circles. Circles that occur outside of polygons are either baseball sized or larger hail reports (shaded light blue) or non-tornadic wind damage reports (shaded orange). County names are included in "all-caps" as red text, and city names are labelled as black text.

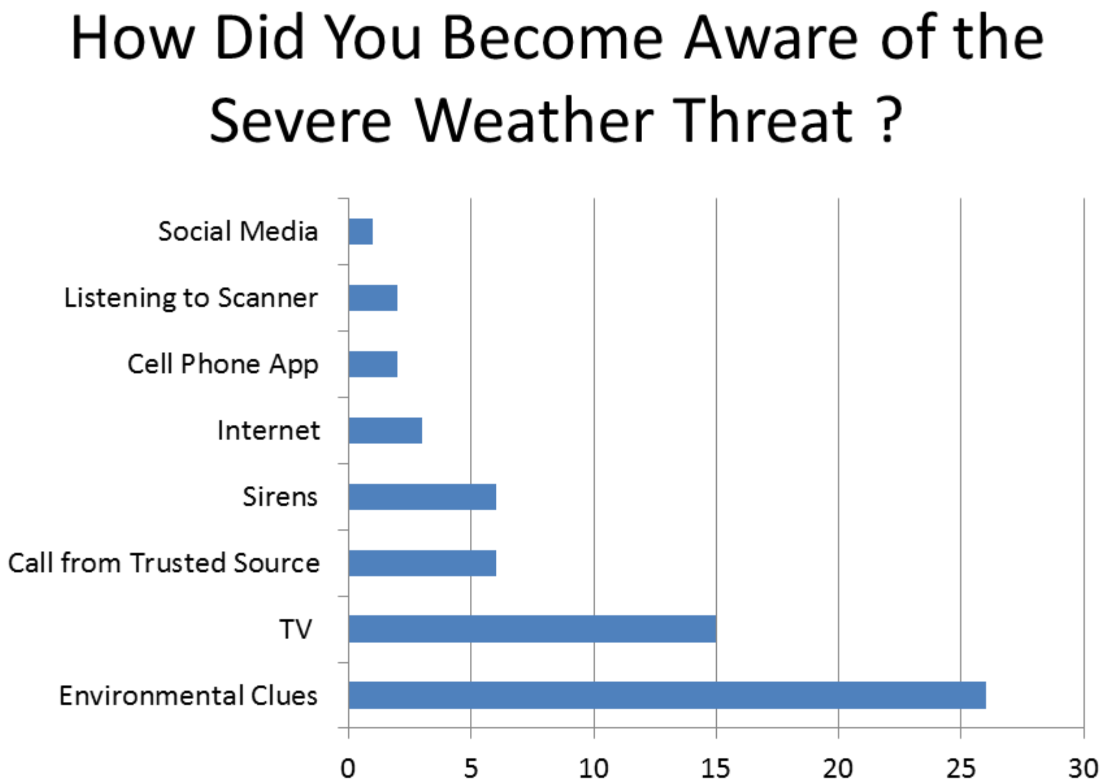

Figure 2 - The results of door to door surveys conducted by the NWS with members of the general public near the tornado damage paths affecting the communities of Granbury, Cleburne, and Sunset on 15 May 2013. There were 29 unique respondents, and these are the responses given to the open ended question, "How did you become aware of the severe weather threat before severe weather occurred near your location?" Multiple responses were allowed and explain why the total responses are greater than 29. "Sirens" are outdoor warning sirens, and environmental clues included responses such as "winds got stronger", "skies got darker", "hail got larger", "I heard a strange noise", etc.

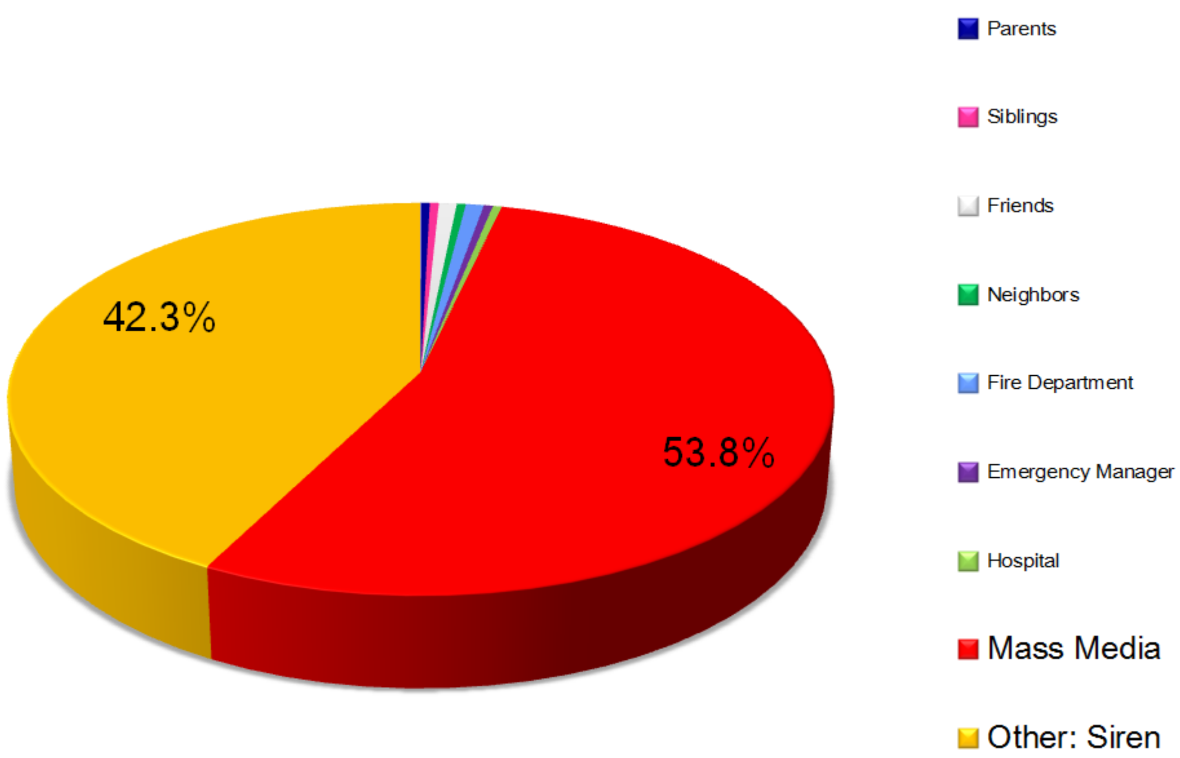

Figure 3 - The results of research conducted by Trainor (2012). In a public response survey, for those individuals that indicated they had received a tornado or severe thunderstorm warning in their region (169 responses), where did they receive this information from?

	NWS	Media	EM	Public	VOST
NWS	4	113	133	115	114
Media	40	16	19	461	15
EM	49	32	49	28	32
Public	66	76	36	28	30
VOST	26	21	21	46	0

Figure 4 - The results of the histograph approach to documenting all communications that were analyzed in this study from 1900 CDT to 2200 CDT. While this information was not used as a direct point of analysis in the study, it offers a look at the break down of the communications analyzed to construct the adjacency matrices.

Appendix A

Example

Matrices in this appendix will be displayed in the following format:

#. The piece of information or "rumor" being tracked through IWT communications, listed in the order presented in the paper. The related matrix mathematical results follow.

Adjacency Matrix:

	NWS	*Media*	*EM*	*Public*	*VOST*
NWS	__	__	__	__	__
Media	__	__	__	__	__
EM	__	__	__	__	__
Public	__	__	__	__	__
VOST	__	__	__	__	__

A_5: (results displayed here)

A_5: Organized like the adjacency matrix, but showing the results of equation 1, where k=5.

Ranking Vector: *NWS*, *Media*, *EM*, *Public*, *VOST*

Ranking: Listing, in order, the ranking of importance from the vector (left).

Note: Any notes of importance noted in the calculation of A_5 or the ranking eigenvector.

The construction of the Adjacency Matrix is discussed in the body of the text, as well as the calculation and meaning of the Ranking Vector (eigenvector). The ranking is listing the order of the groups in terms of how they are numerically ranked in the Ranking Vector. The higher the ranking, the more important that group was in the communication of the information being tracked through the IWT. Intermediate calculations are not included for brevity, but are available from the authors upon request.

1. First NWS Tornado Warning for Hood County that included Granbury and Pecan Plantation

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 0 & 1 & 1 & 2 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Ranking:

1. *NWS*
2. *Media*
2. *EM*
2. *Public*
2. *VOST*

Note: The calculation for A_k for k>2 is equal to A_2 as A^k for k>2 results in zero matrices. For the ranking, the NWS ranks first, with all other members tied for last place.

2. First NWS Tornado Warning for Johnson County that included the city of Cleburne

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 0 & 1 & 1 & 3 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Ranking:

$$\begin{matrix} 1. & NWS \\ 2. & Media \\ 2. & EM \\ 2. & Public \\ 2. & VOST \end{matrix}$$

Note: The calculation for A_k for k>2 is equal to A_2 as A^k for k>2 results in zero matrices. For the ranking, the NWS ranks first, with all other members tied for last place.

3. NWS Tornado Warning for the Cleburne tornado shifting north.

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 0 & 1 & 1 & 2 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Ranking:

$$\begin{matrix} 1. & NWS \\ 2. & Media \\ 2. & EM \\ 2. & Public \\ 2. & VOST \end{matrix}$$

Note: The calculation for A_k for k>2 is equal to A_2 as A^k for k>2 results in zero matrices. For the ranking, the NWS ranks first, with all other members tied for last place.

4. NWS Tornado Warning for Tarrant County

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 0 & 1 & 1 & 3 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Ranking:

$$\begin{matrix} 1. & NWS \\ 2. & Media \\ 2. & EM \\ 2. & Public \\ 2. & VOST \end{matrix}$$

Note: The calculation for A_k for k>2 is equal to A_2 as A^k for k>2 results in zero matrices. For the ranking, the NWS ranks first, with all other members tied for last place.

5. The knowledge that the Cleburne tornado was moving north (instead of southeast).

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 2 & 16 & 3 & 15 & 5 \\ 0 & 2 & 0 & 3 & 0 \\ 3 & 16 & 2 & 18 & 5 \\ 0 & 3 & 0 & 2 & 0 \\ 0 & 2 & 0 & 3 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 0.5 \\ 0 \\ 0.5 \\ 0 \\ 0 \end{matrix}$$

Ranking:

1. *NWS*
1. *EM*
2. *Media*
2. *Public*
2. *VOST*

Note: For the ranking, the NWS and EM groups are tied for first, while the Media, Public, and VOST are all tied for last.

6. Knowledge of a tornadic debris signature in southern Parker County.

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 0 & 1 & 1 & 2 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

Ranking:

1. *NWS*
2. *Media*
2. *EM*
2. *Public*
2. *VOST*

Note: The calculation for A_k for $k>2$ is equal to A_2 as A^k for $k>2$ results in zero matrices. For the ranking, the NWS ranks first, with all other members tied for last place.

7. The report that the Cleburne tornado is a mile-wide wedge tornado.

Adjacency Matrix:

$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \end{matrix}$$

A_5:

$$\begin{matrix} 2 & 12 & 5 & 9 & 3 \\ 0 & 2 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 2 & 0 \\ 3 & 12 & 5 & 12 & 2 \end{matrix}$$

Ranking Vector:

$$\begin{matrix} 0.5 \\ 0 \\ 0 \\ 0 \\ 0.5 \end{matrix}$$

Ranking:

1. *NWS*
1. *VOST*
2. *Media*
2. *EM*
2. *Public*

Note: For the ranking, the NWS and VOST are tied for first place, while the Media, EM, and Public are tied for last.

8. The confirmation of a tornado in Granbury.

Adjacency Matrix: $\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$ A_5: $\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 3 & 0 \\ 0 & 0 & 2 & 3 & 0 \\ 0 & 0 & 3 & 2 & 0 \\ 0 & 0 & 2 & 3 & 0 \end{matrix}$

Ranking Vector: $\begin{matrix} 0 \\ 0.25 \\ 0.25 \\ 0.25 \\ 0.25 \end{matrix}$ Ranking: 1. *Media* 1. *EM* 1. *Public* 1. *VOST* 2. *NWS*

Note: For the ranking, the Media, EM, Public, and VOST groups are tied for first, while the NWS is last. As noted in the discussion, the “Public” group is somewhat misrepresented by county spotters that were communicating with a county EM.

9. The confirmation of a tornado in Pecan Plantation.

Adjacency Matrix: $\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{matrix}$ A_5: $\begin{matrix} 8 & 5 & 5 & 8 & 5 \\ 9 & 6 & 6 & 7 & 6 \\ 0 & 0 & 0 & 0 & 0 \\ 5 & 4 & 4 & 4 & 4 \\ 4 & 2 & 2 & 3 & 2 \end{matrix}$

Ranking Vector: $\begin{matrix} 0.3146 \\ 0.3427 \\ 0 \\ 0.2068 \\ 0.1359 \end{matrix}$ Ranking: 1. *Media* 2. *NWS* 3. *Public* 4. *VOST* 5. *EM*

10. Report of baseball sized hail falling in Granbury.

Adjacency Matrix: $\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{matrix}$ A_5: $\begin{matrix} 14 & 15 & 15 & 15 & 15 \\ 9 & 8 & 8 & 9 & 9 \\ 0 & 0 & 0 & 0 & 0 \\ 18 & 18 & 18 & 17 & 18 \\ 21 & 21 & 21 & 21 & 20 \end{matrix}$

Ranking Vector: $\begin{matrix} 0.2381 \\ 0.1429 \\ 0 \\ 0.2857 \\ 0.3331 \end{matrix}$ Ranking: 1. *VOST* 2. *Public* 3. *NWS* 4. *Media* 5. *EM*

11. Confirmation of a tornado near Millsap.

Adjacency Matrix:
$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{matrix}$$

A_5:
$$\begin{matrix} 50 & 51 & 51 & 36 & 51 \\ 25 & 25 & 25 & 19 & 25 \\ 44 & 43 & 43 & 32 & 44 \\ 69 & 69 & 69 & 50 & 69 \\ 69 & 69 & 69 & 51 & 68 \end{matrix}$$

Ranking Vector:
$$\begin{matrix} 0.1962 \\ 0.0981 \\ 0.1699 \\ 0.2679 \\ 0.2679 \end{matrix}$$

Ranking:
$$\begin{matrix} 1. & VOST \\ 1. & Public \\ 3. & NWS \\ 4. & EM \\ 5. & Media \end{matrix}$$

Note, the rumor or information has been communicated from all groups to all groups by A_2 (there are no zeros in A_2), which is 1 iteration or 30 minutes after the rumor was introduced to the IWT. In reality, there may be little motivation to continue to communicate this piece of information after this point, but calculations were taken out to A_5 for consistency. For the ranking, the VOST and Public are tied for first, with all other groups ranked in the order they appear above.

12. **Confirmation of a tornado near Sunset**.

Adjacency Matrix:
$$\begin{matrix} 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{matrix}$$

A_5:
$$\begin{matrix} 54 & 74 & 55 & 45 & 55 \\ 26 & 35 & 26 & 22 & 26 \\ 55 & 74 & 54 & 45 & 55 \\ 74 & 100 & 74 & 61 & 74 \\ 74 & 100 & 74 & 62 & 73 \end{matrix}$$

Ranking Vector:
$$\begin{matrix} 0.1929 \\ 0.0922 \\ 0.1929 \\ 0.2610 \\ 0.2610 \end{matrix}$$

Ranking:
$$\begin{matrix} 1. & VOST \\ 1. & Public \\ 3. & NWS \\ 3. & EM \\ 5. & Media \end{matrix}$$

Note, the rumor or information has been communicated from all groups to all groups by A_2 (there are no zeros in A_2), which is 1 iteration or 30 minutes after the rumor was introduced to the IWT. In reality, there may be little motivation to continue to communicate this piece of information after this point, but calculations were taken out to A_5 for consistency. For the ranking, the VOST and Public are tied for first, while the NWS and EM are tied for 3rd, and the Media ranked last.

13. Report of significant damage from the tornado in Granbury.

Adjacency Matrix:

0	1	1	0	1
1	0	1	1	1
1	0	0	0	0
1	1	1	0	1
1	1	1	1	0

A_5:

90	69	91	44	69
121	90	121	61	91
31	22	30	16	22
121	91	121	60	91
121	91	121	61	90

Ranking Vector:

0.1875
0.2500
0.0625
0.2500
0.2500

Ranking:

1. *VOST*
1. *Public*
1. *Media*
4. *NWS*
5. *EM*

Note, the rumor or information has been communicated from all groups to all groups by A_3 (there are no zeros in A_3), which is 2 iterations or 45 minutes after the rumor was introduced to the IWT. In reality, there may be little motivation to continue to communicate this piece of information after this point, but calculations were taken out to A_5 for consistency. For the ranking, the VOST, Public, and Media are tied for first, followed by the NWS and EM groups, respectively.