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# Suspended Sediment Transport Revealed by Patterns in Turbidity and Electrical Conductivity Curves in Three Cave Systems in Missouri, USA.

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# SUSPENDED SEDIMENT TRANSPORT REVEALED BY PATTERNS IN TURBIDITY AND ELECTRICAL CONDUCTIVITY CURVES IN THREE CAVE SYSTEMS IN MISSOURI, USA.

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# ABSTRACT

In cave streams, the movement of sediment as suspended and bed loads are linked to the occurrence of precipitation events on the surface. During precipitation events, the discharge of the streams in the basin increases. As those surface streams flow into cave streams via sinkholes or fissures, the discharge in cave streams increase. In addition to changes in discharge, the response of the surface and cave streams to precipitation include changes in turbidity and electrical conductivity of the stream water.

Changes in turbidity (Tu), electrical conductivity (EC), and discharge (Q) of water in the cave stream can be used to infer sediment movement along cave systems. The types of movement are generally considered direct transfer, when surface sediment is introduced into the cave stream and that same sediment is carried through the entire cave stream during one flood even, resuspension of sediment from the cave stream bed, and deposition of sediment on to the stream bed. The probability of direct transfer is likely controlled by the length of the cave stream (with longer streams having a lesser likelihood of direct transfer except during extreme flood events). Resuspension is probably controlled by seasonality (snow and ice will not move sediment and will not cause an increase in discharge). Deposition is probably more common in longer streams as the sediment introduced from the surface travels through only a portion of the cave before the discharge decreases, allowing the suspended sediment to deposit along the cave stream.

Previous researchers developed a method to categorize the movement of fine-grained (suspended) sediment into three classes – direct transfer, resuspension, and deposition. These previous research projects were limited in the number of observations. In this study, the movement of fine-grained material as suspended sediment during rain events were classified based on differences in turbidity, electrical conductivity, and discharge within three cave systems in Missouri, USA. Using previously collected data, 208 flood events were identified and classified from three cave sites.

Resuspension of sediments during rain events was observed through all three cave sites for 45% of the flood events; whereas the direct transfer of sediments was observed for 1% of the flood events. Over 50% of flood events observed were too complicated to be place in the established classes. These responses exhibited several curve types during one flood event. The intensity of the flood event and the time between precipitation events did not correlate with the frequency of any of the classes. Seasonality did correlate with the observation of direct transfer with direct transfer being more common in the spring and fall that relate to spring thaw events and fall thunderstorms.

# 1. INTRODUCTION

## 1.1. General Background

Trace materials, such as led, zinc, and copper, are carried through cave systems by adsorbing to clay particles (Mahler and Lynch, 1999; Neill et al., 2004) and can be very harmful to the animals in the caves (Mahler et al., 1999). Bacteria and other contaminants can also attach to clay particles (Mahler et al., 2000; Dussart-Baptista et al., 2003; Massei et al., 2003). Water-borne diseases caused by bacteria can also be quite harmful to the aquatic life inside these cave systems as well as humans who may bathe in or drink the water (Mahler et al., 1999). Sediment deposition and contaminants adsorbing to the sediment flowing through the Tumbling Creek Cave stream is a likely factor contributing to the decline in the cave snail population (Elliot and Aley, 2005). Therefore, understanding the movement of sediment into and through the karstic systems is needed to help address ecosystem health questions.

Precipitation events control the sediment transport within cave streams that are linked to losing streams, as the increase in discharge in losing streams results in increases in discharge in the cave streams (Herman et al., 2012; Mahler and Lynch, 1999). Massei (2001) classified sediment transport through karst streams into resuspension, deposition, and direct transfer. After rainfall begins and discharge increases, the initial pulse of water can suspend finer grained materials (silts and clays) that had been previously deposited along the active stream channel and transport that fine-grained material farther down the cave stream or out to the cave as discharge at the spring (Mahler et al., 1998; Massei et al., 2003; Dussart-Baptista et al., 2003; Herman et al., 2008). New sediment from the surface can be brought in through the losing streams and into the cave stream (Massei et al., 2003; Dussart-Baptista et al., 2003). Under some high flow events and with short cave streams, sediment can be transported through the entire cave stream during one rain event. During smaller events or in longer cave streams, that fine-grained material might be deposited along the cave stream. Fine-grained sediment can reside along and in cave streams for hours or days (Massei et al., 2002; Broderick et al., 2017; Wicks et al., 2018) to many years (Kiernan et al., 2001; Broderick et al., 2017; Wicks et al., 2018) depending on the occurrence of storms, the velocity of water (related to discharge), turbidity, and sediment size or type (Herman et al., 2012).

Changes in three parameters can be used to infer if suspended sediment within the karst system was resuspended, deposited, or directly transferred: these are turbidity (Tu), electrical conductivity (EC), (Valdes et al., 2006) and discharge (Q) (Fournier et al., 2007). The velocity and volume of water delivered during a rain event determine the discharge (Fournier et al., 2007). Discharge is like Tu in the way that Q increases at the start of rain and then slowly falls back down to baseflow conditions after the storm.

Turbidity is the measurement of how cloudy the water is due to the number of suspended particles in the water; the higher the Tu, the murkier the water. Electrical Conductivity is a measure of the level of dissolved solids in the water. EC stream response is based on a mixing system that can be relatively simple with “new” or “event” water coming in from the surface and mixing with “old” or “pre-event” groundwater (Hooper et al., 1990; Evans and Davies, 1998; Massei et al., 2003), or have three (or more) components of water from the surface, ground, and soil (Hooper et al., 1990; Evans and Davies, 1998). Regardless of a two or three component system, the overall EC in the stream decreases rapidly during a storm event since the EC of rainwater is lower than the EC of water that is already in the system. Q is defined as the flow

rate, or the volume of water flowing past a point over a certain amount of time (Poehls and Smith, 2011).

During a rain event in a karst system, Tu increases with discharge while EC decreases (Figure 1). Increases in discharge have a shorter-term effect on Tu and a much longer effect on EC resulting in Tu reaching background levels more quickly than EC (Valdes et al., 2006; Massei et al., 2006). Increases in discharge control increases in Tu and thus changes in discharge and turbidity correlate. After precipitation events, baseflow conditions are reached within a day or so (depending on the intensity and duration of the precipitation event). EC is related to the concentration of dissolved ions in water and is thus linked to changes in chemistry. Rainwater and most surface waters have a low EC (very dilute waters); whereas water in a cave stream under baseflow conditions is likely in equilibrium with respect to calcite and thus has a higher EC. During flood events, the surface water with lower EC flows into the cave stream and in some cases through the cave. At the end of the event, the more slowly flowing water dissolved calcite in the wall-rock and the stream bed and slowly reaches equilibrium with respect to calcite, this climb to baseflow conditions may take hours to days.

Based on studies from a surface stream (Williams 1989), Valdes et al. (2005, 2006) reworked those finding for cave streams and proposed three classes of suspended sediment transport. Valdes et al. (2005, 2006) looked at correlations between the turbidity and conductivity of water in cave streams during precipitation events to infer different modes of sediment transport. The three classes are:

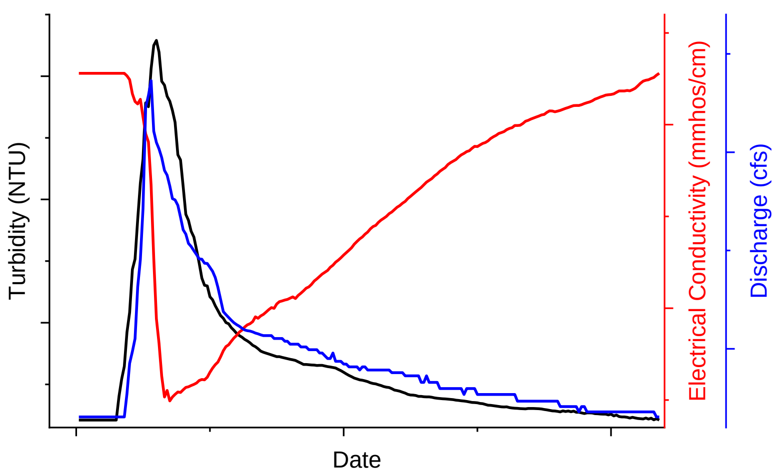


Figure 1. Example of a time series graph for a rain event. Shows how a rain event effects on Turbidity (black), Electrical Conductivity (red), and Discharge (blue) inside of a cave system.

(1) Class I: (C1) a simultaneous increase in Tu and decrease in EC, resulting in a single value curve,
(2) Class II: (C2) an increase in Tu before a decrease in EC, creating a clockwise loop curve, and
(3) Class III: (C3) an increase in Tu after a decrease in EC, forming a counterclockwise loop in the curve.

Each class would then represent one of the following suspended sediment transport modes respectively: direct transfer, resuspension, and deposition.

Fournier et al. (2007) used the same classes of suspended sediment transport in cave systems as Valdes et al. (2005, 2006); however, Fournier et al. (2007) used normalized variables to allow comparison between events and to quickly see the slope of the Tu-EC curves (i.e., whether $\alpha=1$ showing direct transfer, $\alpha>1$ showing a clockwise resuspension loop, or $\alpha<1$ showing a counterclockwise deposition loop). The discharge was added to the hysteresis curves to illustrate the hydrodynamic information needed to understand the importance of the transport properties (Fournier et al., 2007).

### 1.2. Observations and Hypotheses

In this study, data from three cave systems in Missouri, USA, Tumbling Creek Cave (TCC), Hunters Cave (HC) and Devils Icebox (DI), were used to reveal a pattern in the classes seen in the EC-Tu-Q curves. States in the midcontinent generally have winters with days below freezing, hot and dry summers, and two transitional seasons with heavy rainfall. In the winter, it could take longer for precipitation to seep underground stream due to the water and the ground freezing as well as snow cover can decrease the likelihood of sediment moving downstream. In the summer, the soil can become very dry and not allow water to infiltrate. Vegetation can also grow thick, keeping the soil from being eroded. The spring and the fall are known to have a higher number and intensity of rain events. The onset of these seasons should show a lot more sediment movement from the surface into the cave stream. C1 curves are expected to be seen in the spring and fall or times after little to no rainfall. C2 curves are expected in the winter and summer where there is less erosion or sediment movement on the surface. C3 curves are predicted to be seen during lesser intensity rain events where turbidity may not be very high, but new sediment could be coming into the cave system.

Observations and reasoning: 1) HC and DI have longer cave streams than TCC does, so surface sediment is likely to be carried into and through the entire HC or DI systems during one flood event. TCC, although shorter, is still nearly 1,000 meters long, so it is unlikely that surface sediment would be carried into and out of the TCC system, though the likelihood of the occurrence is higher than for DI or HC. 2) In TCC, sediment was seen throughout the cave stream and could be transported downstream if the discharge (velocity) increased. Also, after a large rain event, sediment was seen coating rocks at the natural entrance which does not regularly have water flowing through it. It is a reasonable assumption that sediment must be moving through the system and is not only being deposited on the stream bed since the cave stream is not overrun with sediment. Therefore, the primary hypothesis is

H: Sediment transportation within Tumbling Creek Cave, Hunters Cave, and Devils Icebox will be Class II (resuspension).

In addition, seasonal changes can alter the conditions of the soil that is available to be transported and having less precipitation, and lower velocity water movement can keep eroded sediment from washing downstream.

Observations and reasoning: 1) Seasonality: direct transfer is expected at the onset of the wet seasons (spring and fall) or after erosion from the surface stream has occurred but has not yet been carried downstream. Resuspension would be expected through every season and after

events that produced C1 curves or quickly following C2 curves when there would not be as much time for erosion to occur between events when there is a probability that more sediment has been brought into the cave. C2 curves are also expected compared to C1 curves in the winter and summer due to frozen basin conditions in the winter not allowing for mass erosion and transportation of surface sediment and during the summer when less intense rain events occur, and vegetation has rooted the sediment in place. Greater intensity rain events that can bring sediment quickly through the cave stream are expected to produce C1 curves; whereas lesser intensity rain events are expected to generate C2 curves since the velocity is predicted to be lower and the time shorter for sediment movement. 2) Not all rain events show simple single peaked events but may have several EC or Tu bumps throughout the rising and falling limbs of the time series graph.

Secondary hypotheses are that if there are multiple classes of suspended sediment transport seen throughout the cave streams, these classes would be due to the different intensities of rain events. C1 curves would be seen in the spring and fall, after more extended periods of no rain, and during intense rain events. C2 curves are expected to be observed closely following previous events and during less intense rain events. Multipeak events will be caused by many rain events overlain on top of each other and are predicted in the spring and fall (during the wet seasons). C3 curves are expected only during short and mild events with low velocities inside of the cave stream.

Finally, as this research is aimed at understanding suspended sediment transport in cave streams, preliminary work on tracing suspended sediment was undertaken in TCC using fluorescent microspheres and homemade sediment traps.

# 2. MATERIALS AND METHODS

## 2.1. Field Site Description

Tumbling Creek Cave (TCC) is in the Ozark Highlands of Taney County, Missouri (Maher, 2006) (Figure 2). This cave system developed within the Ordovician aged Cotter Dolomite (Maher, 2006). Dye tracing concluded that the catchment area for TCC is around 23.49 square kilometers (Elliot and Aley, 2005). The recharge area is isolated from most urban influences and is mainly privately owned with a fraction of the land used by the public (Neill et al., 2003). Forests of oak and hickory have previously dominated the area (Maher, 2006); however, during a 35-year interval between the 1960s and 1990s, pasture lands replaced much of the forested areas (Neill et al., 2003). The loss of forests led to an increased amount of erosion and sediment transported into the cave system, especially during storm events. Rehabilitation of the recharge area consisted of restoring 5.54 square kilometers of land to natural forests to reduce the amount of sediment moving into the caves stream and the turbidity within the water in the cave stream (Elliott and Aley 2005). Under normal flow conditions, water from TCC discharges into a few springs and eventually flows into Big Creek[1]. When the flow conditions are high, Tumbling Creek can feed around 15-20 different springs[1].

TCC has a relatively simple morphology containing two main passageways that are interlocking and have a total length of 2,789 meters (Neill, 2003). The east to west passage is several meters above the north to south passage and is an old cave stream passage. The lower passage contains the active stream, Tumbling Creek, (Neill et al., 2003) which flows from the north to the south and is around 879 meters in length (Rossman, 2010).

The field study focused on a 100-meter reach of the cave stream. A v-notch weir is located at the upstream end of the 100-meter reach. On the upstream side of the weir, the velocity of water lowers causing water and sediment to pool, and at the downstream end of the weir, there is a small pool a few feet deep. During low flow, the pool releases only a shallow stream of around one to two inches deep of water downstream. The cave stream flows under a rockfall where it begins to widen to about a few meters wide and 15cm deep behind. As the stream continues, the width is relatively constant, and the ceiling height reduces to about one meter. Downstream, the water flows around a bend and under a footbridge, which causes the water to pool. On the downstream end of the footbridge, there are a lot of larger rocks from a rock fall that are distributed across the stream. A rockfall limits human-access to the downstream portion of the stream; however, water and sediment can move downstream. A second footpath leads to the downstream side of the rockfall where the width of the stream is more variable. The depth of water on the downstream side of the rockfall increases to a little over half a meter. As the cave stream flows over a dam, the depth of water is reduced. The upstream portion of the dam contains many chert boulders that have fallen from a ceiling collapse. Downstream of the dam is the end of the study reach.

Hunters Cave (HC) and Devils Icebox (DI) are in the Bonne Femme Creek watershed south of Columbia, Missouri (Lerch et al., 2005) (Figure 2). These two cave systems were developed within the 50-meter thick Mississippian aged Burlington Limestone (Osagean Series) (Wicks, 1997). The recharge area for both HC and DI is around 30 square kilometers and is covered in clay-rich Pleistocene age glacial deposits and loess (St. Ivany, 1988) as well as

[1] http://www.tumblingcreekcave.org/2_cave.html, accessed November 29, 2017

residual soils of the Weller-Bardley-Clinkenbeard association (USDA-NRCS, 2001). DI consists of one primary conduit that is 6,400 meters with several smaller conduits branching off with a total length of 10,760 meters (Lerch et al., 2005). The cave stream discharges to one main spring in Rock Bridge Memorial State Park, Missouri Department of Natural Resources, Division of Parks, before reaching Little Bonne Femme Creek. HC has a total length of 2,540 meters, and the main stream conduit is 1,250 meters. HC discharges into Bass Creek within the Three Creeks Conservation Area, Missouri Department of Conservation.

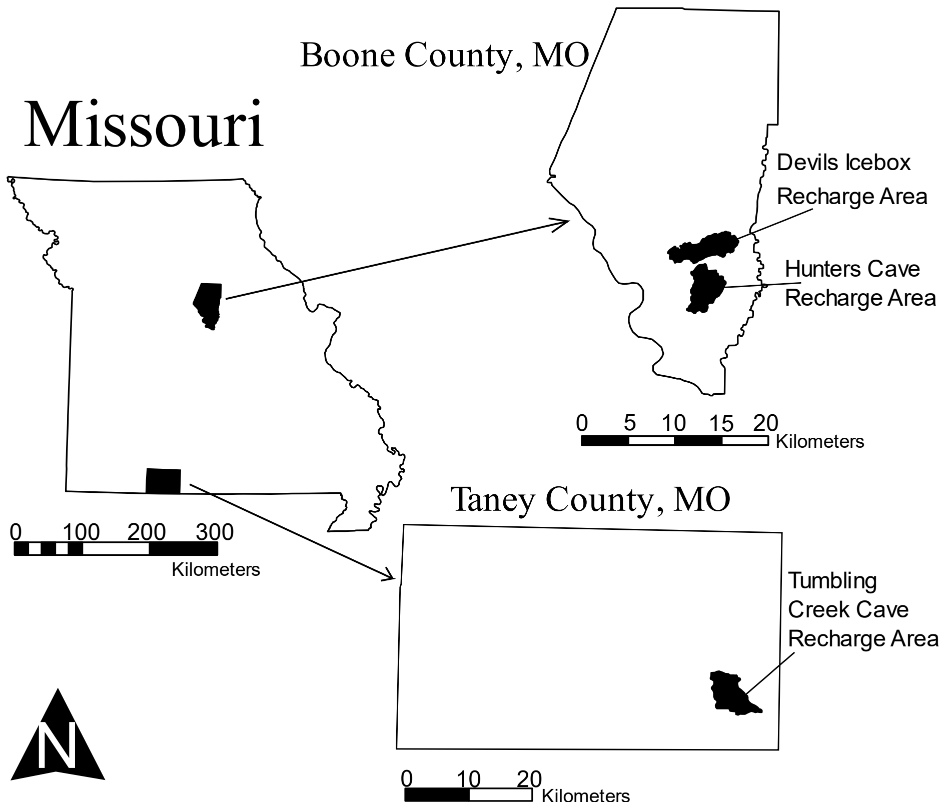


Figure 2. Map of Missouri modified from a USGS map showing counties of the three cave sites. Tumbling Creek Cave is in Taney County (redrawn from Rossman, 2010) while Hunters Cave and Devils Icebox are in Boone County (redrawn from Lerch et al., 2005).

### 2.2. EC-Tu-Q Classes

In all three caves, the data were collected by previous researchers and were made available for this study. For Tumbling Creek Cave, the data loggers are managed by personnel for Ozark Underground Laboratory. For Hunters Cave and Devils Icebox Cave, the data loggers were managed by Robert Lerch. Data files are available in the Mendeley Data web repository. Manufacturer and model of the probes are in Appendix A as is a brief description of how the probes function.

*2.2.1. Tumbling Creek Cave Curves*

Since 2002, a Campbell Scientific CR10X Datalogger managed by personnel from Ozark Underground Laboratory has been in place within the upstream pool of the v-notched weir of the TCC stream. For over ten years, the turbidity, water temperature, electrical conductivity, dissolved oxygen concentration, and stream discharge have been measured and recorded. Data from 2002 to 2015 were provided to the research group by the Ozark Underground Laboratory. Between the years of 2002-2007, measurements were recorded anytime between two minutes to an hour, though later data from 2014 on was measured on a 10-minute interval. Daily maximum precipitation data were collected near the cave site. Details of how the probes work is provided in Appendix A.

For this study, turbidity (Tu), electrical conductivity (EC), and discharge (Q) were used. One or more of the three major components (Tu, EC, and Q) were missing from several years of the data making them unusable, so only water years 2002-2007 and calendar years for 2014 and 2015 were analyzed for this study. For each calendar year, data files were cleaned up by removing all data other than turbidity, electrical conductivity, discharge, precipitation, date and time. A second step to vetting the data was to go through each flood vent and making sure there were no missing time or unexplained changes in Tu or EC (as seen in Figure 3 with an abrupt change in Tu within an 8-minute period). A third step in vetting the data was to remove spikes in turbidity from flood events that lasted for only 15 to 30 minutes that may have been caused by rocks fallings into the stream near the probes. Time series plots of the data were generated as an aid for incomplete records (for instance times where some of the data were missing due to battery failure). Flood events were chosen by looking for fluctuations above baseflow conditions. As the time of the precipitation events were not known (daily data), the precipitation data were added at 0:00 hour on the day it occurred. For each rain event, the hydrographs showing Tu, EC, and Q were plotted.

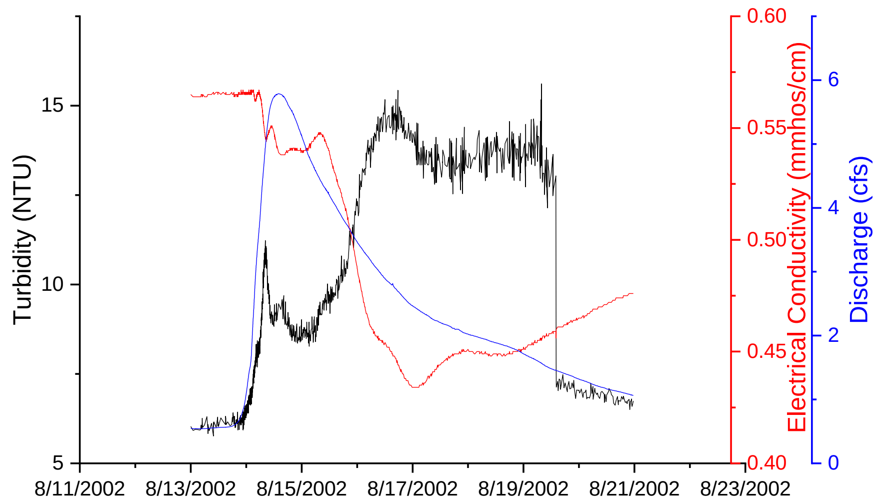


Figure 3. Time series graph showing a rain event from August 2002 in TCC and data logger malfunctions with the turbidity probe.

The data were then normalized according to equations 1, 2, and 3 (Fournier et al., 2007).

$$Tu_{normalized} = \frac{(Tu - Tu_{min})}{(Tu_{max} - Tu_{min})} \quad (1)$$

$$EC_{normalized} = \frac{(EC - EC_{max})}{(EC_{min} - EC_{max})} \quad (2)$$

$$Q_{normalized} = \frac{(Q - Q_{min})}{(Q_{max} - Q_{min})} \quad (3)$$

EC is normalized slightly different than Tu or Q since it responds inversely. Normalized EC is plotted against normalized Tu with normalized Q as circles on the curve. Figure 4 shows the models from Valdes et al (2006) and examples of the three different classes.

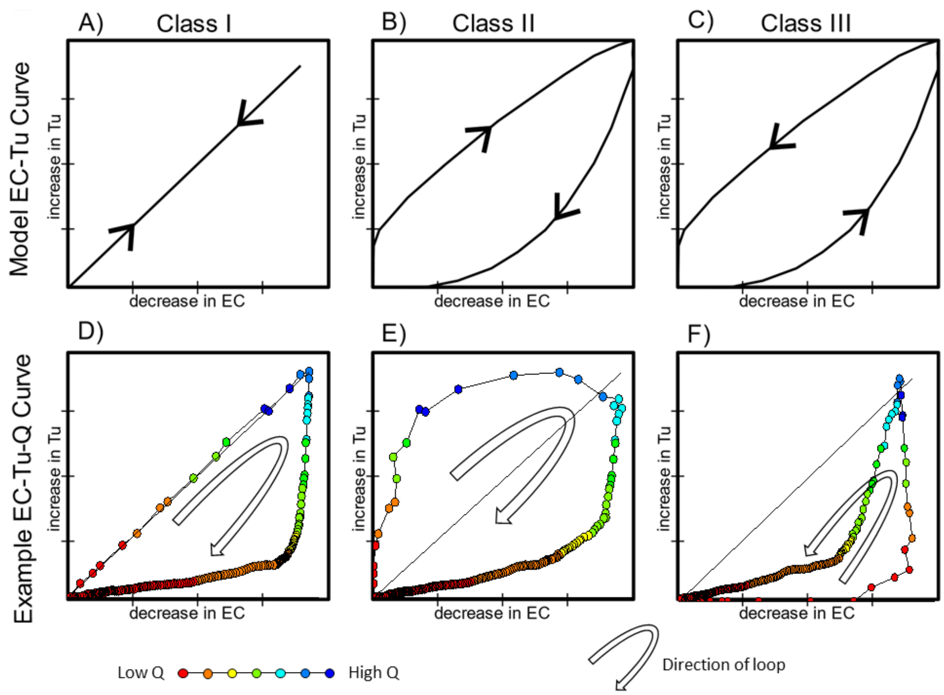


Figure 4. Models of EC-Tu curves redrawn from Valdes et al. 2006 (A-C) and examples of normalized EC-Tu-Q curves (D-F). Class I shows a single value curve (A,D) inferring direct transfer, class II shows a clockwise loop (B,E) inferring resuspension, and class III shows a counterclockwise loop (C,F) inferring deposition. Discharge is expressed as circles on the curve, lower discharge in red and greater discharge in blue.

*2.2.2. Devils Icebox and Hunters Curves*

For Devils Icebox and Hunters Cave, data from the middle of 1999 to late 2001 were available from Lerch. The sampling intervals were 5 minutes for discharge and 15 minutes for Tu and EC. For these two cave systems, discharge data were filtered to every 15 minutes. Following a similar procedure as used for data from TCC, hydrographs for each year were generated, and the data were vetted for missing data and spikes. Precipitation data were retrieved

from a NOAA site[2] in the nearby city of Columbia, Missouri. For each rain event, time series graphs and EC-Tu-Q curves were created.

[Discharge, electrical conductivity, and turbidity data from all three cave (TCC, HC, and DI) sites will be available on Mendeley in the near future].

### *2.2.3. Analysis of Classes*

Each flood event was numbered with the first number corresponding to the flood event, the second corresponding to the number rain event for the year, and the third corresponding to the month in which the flood event occurred (Figure 5). Each flood event was characterized as "good" (meaning that the Tu and EC data were clear, creating and a smooth, easy to identify curve), "okay" (when the Tu-EC data were not as clear, but a curve could still be identified), "poor" (for curves that data were harder to read and contained many bumps making the curves less accurate), and "bad" (for cures with missing data). The number of smaller peaks within the larger flood event were also noted (Figure 6 shows an example of a rain event with smaller peaks on the ascending limb). Each smaller peak on a complex EC-Tu-Q curve were given classes and if those matched other curves, those curves would be placed into a similar subgroup.

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Rainevent | Number | | Date | T-EC Data | Bumps | Peaks | AvT | AvEC | Class | Keep | Bump Class | Group |
| 2 | 1 | 2002_1 | H | 8-13-02,8-20-02 | Bad | - | - | - | - | - | No | | |
| 3 | 2 | 2002_2 | H | 8-25-02,9-11-02 | Bad | - | - | - | - | - | No | | |
| 4 | 3 | 2002_3 | J | 10-30-02,10-31-02 | Good | 1 | 1 | - | - | **1** | Yes | | |
| 5 | 4 | 2002_4 | L | 12-13-02,12-14-02 | Okay | 2 | 1 | - | - | **1** | Yes | | |
| 6 | 5 | 2002_5 | L | 12-28-02,1-19-03 | Okay | 4 | 1 | - | - | **4** | Yes | 1,1,2 | |
| 7 | 6 | 2003_1 | A | 1-29-03,2-1-03 | Okay | 1 | 1 | 15 | 9 | **2** | Yes | | |
| 8 | 7 | 2003_2 | B | 2-11-03,2-18-03 | Okay | 3 | 2 | - | - | **4** | Yes | 2,2,? | |
| 9 | 8 | 2003_3 | B | 2-19-03,2-21-03 | Poor | 2+ | 2+ | 15 | 15 | **4** | Yes | 2,2 | |

Figure 5. Showing organization and classifications of EC-Tu-Q curves for each flood event graphed. Red showing vetted data, yellow showing point averaged data, and white are data that were original data.

If the data were too noisy to see a curve, Tu and EC data would be point averaged to smooth out the curves (Figure 7). If the data weren't very noisy, points would be averaged by 9 points (4 on each side), if the data were a little messier the points would be averaged by 15 (7 on each side), and if the data were extremely noisy but the data shows a general trend, then the points would be averaged by 25 (12 points on each side). The point average for the Tu and EC data were also written down in the spreadsheets for each cave site.

The EC-Tu-Q curves created from each rain event were classified according to the schemes of Valdes et al. (2006) and Fournier et al. (2007). If the flood event did not fall into any of those three categories, that flood event was added into a new fourth class, Class 4 (or other), that included events that could not be classified into a single class or that contained more than one class. Tallies of the number of rain events and flood events according to each class were made.

[2] https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily, accessed December 10, 2018

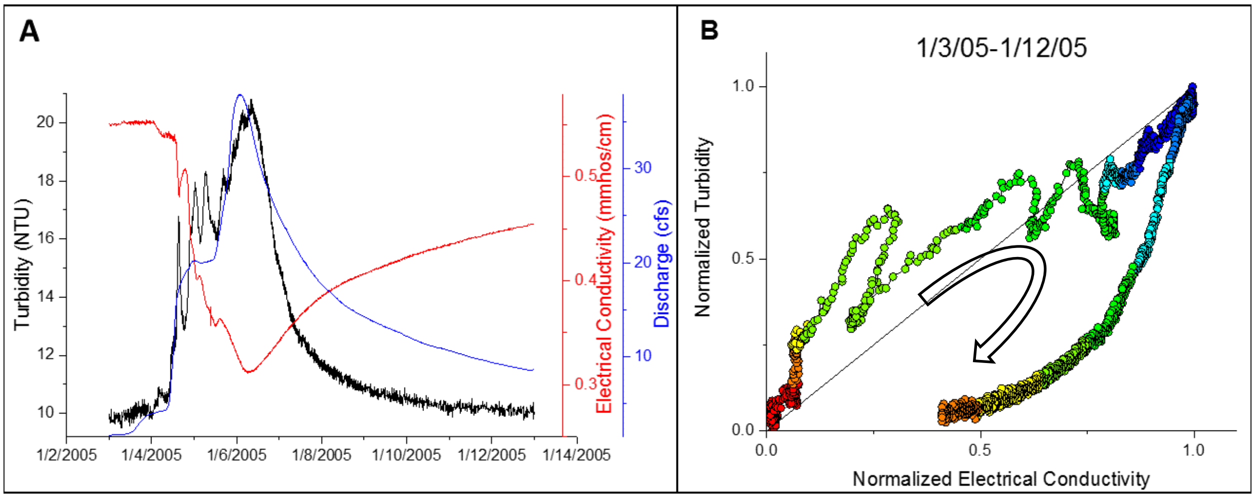


Figure 6. Example of a time series graph (A) and EC-Tu-Q curve (B) showing multiple smaller Tu and EC peaks during a rain event. Most of the smaller peaks occur on the ascending limb of the graphs.

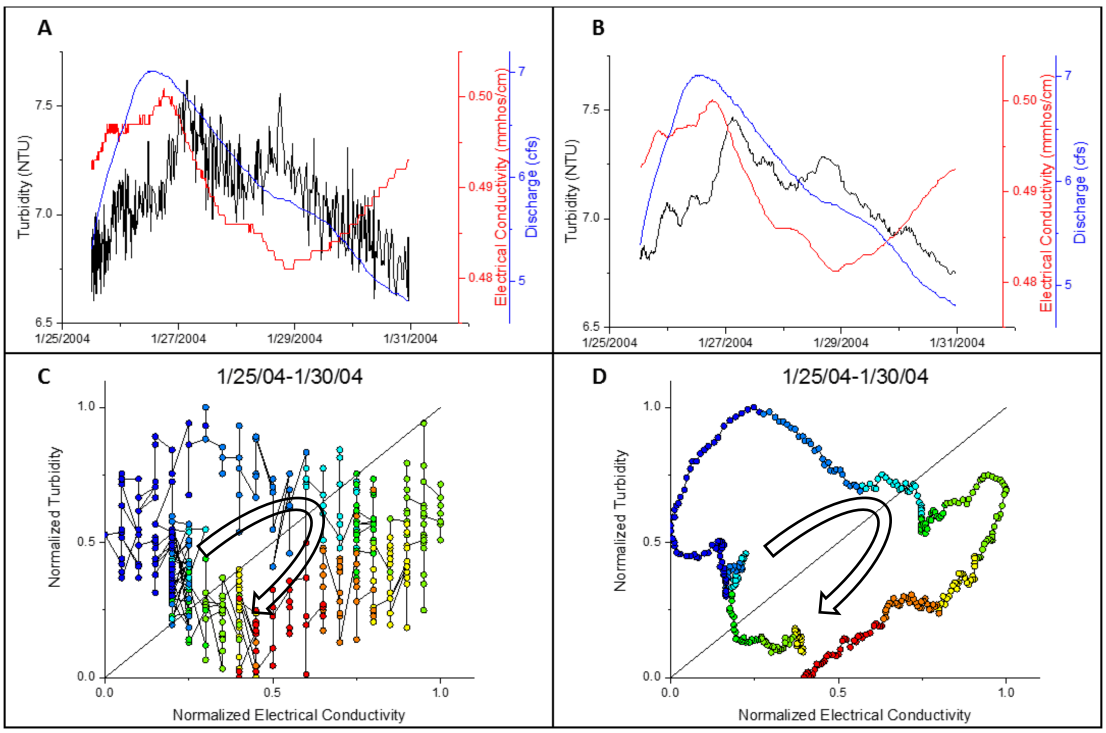


Figure 7. Example of a rain event from January 2004 showing the original data (A,C) which contained a lot of noise and the point averaged data (B,D) from the same event, smoothing the curve.

The air temperature for each rain event was used to determine ground thaw state after the winter (Figure 8). This information was gathered from a NOAA site[2] from Springfield, Missouri for TCC and Columbia, Missouri for DI and HC. The increase in Q and Tu were found for each rain event and if Tu and EC levels decreased back to near baseflow conditions before the rain event. The amount of rain that fell during the days of the event was added together and added to the document. A few rain events consisted of two or more nonconsecutive days without it being reflected in the Q data so that those events would be considered as one. Rain events may happen one after the other or have days to weeks in between which was noted for each event. Not every

day that contained precipitation resulted in a rain event but were also counted to be sure since it could change if the ground was already wet or not. Rainfall under 0.1inches was not considered enough rain to affect the system since it was observed that anything less than 0.1inch precipitation was never seen in any of the Tu, EC, or Q data.

Each of the suspended sediment transport classes were analyzed separately to see if any patterns occurred. C1 curves were analyzed first followed by C2 and C4. No rain events produced a C3 curve defined by Valdes et al. (2006) or Fournier et al. (2007). First, seasons would be checked to see where each class were more frequent than others. The intensity of storm events would be checked after by looking at the amount of precipitation and the increase in turbidity and discharge thinking maybe if a storm is greater than others it could cause a different reaction. Seasons and temperature would also be taken into account here if a more intense storm happened in the summer versus the winter if it would change the pattern. The last item checked was the time between rain events. The days between graphed rain events were checked through all of the different cave sites; however, at TCC, the time between smaller precipitation events that didn't appear to have any effect on Tu, EC, or Q would also be considered since the precipitation data were close to the cave. Another item checked here was if Tu and EC were able to fall back down to "base levels" before the next event or if they were still high from the previous event.

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Rainevent | Number | | Date | Class | Group | Temp | Q increase | T increas | Base T-EC | Precip | days_skip | o/a | DBP | RB | DSLR |
| 10 | 11 | 2003_6 | C | 3-19-03,4-5-03 | 2 | 2 | 35-69 | 5.15 | 4.894 | Yes | 1.19 | 2_Yes | On | 19 | Yes | 8 |
| 11 | 12 | 2003_7 | D | 4-20-03,4-22-03 | 2 | | 53-56 | 0.36 | 2.3 | Yes | 0.96 | 1 | On | 30 | Yes | 13 |
| 12 | 13 | 2003_8 | D | 4-24-03,4-30-03 | 4 | | 52-74 | 15.87 | 14.75 | No | 1.94 | 1 | After | 4 | No | 4 |
| 13 | 14 | 2003_9 | E | 5-16-03,5-25-03 | 2 | | 58-69 | 6.71 | 5.68 | No | 1.49 | 1 | On | 23 | Yes | 2 |
| 14 | 15 | 2003_10 | F | 6-2-03,6-4-03 | 2 | | 56-59 | 0.37 | 5.277 | Yes | 1.54 | 2 | On | 16 | Yes | 8 |
| 15 | 16 | 2003_11 | F | 6-12-03,6-17-03 | 2 | | 71-72 | 8.6 | 8.5 | Yes | 1.93 | 2_no | On | 10 | Yes | 5 |
| 16 | 17 | 2003_12 | H | 8-2-03,8-4-03 | 2 | | 74-79 | 0.3 | 3 | Yes | 3.12 | 1 | After | 52 | Yes | 12 |
| 17 | 21 | 2003_16 | J | 10-10-03,10-11-03 | 2 | | 62-66 | 0.007 | 2.3 | Yes | 1.99 | 2_no | On | 27 | Yes | 5 |
| 18 | 22 | 2003_17 | K | 11-6-03,11-12-03 | 4 | 4 | 35-62 | 0.486 | 1.2 | *Yes* | 1.5 | 2_no | After | 28 | Yes | 6 |
| 19 | 23 | 2003_18 | K | 11-16-03,11-24-03 | 4 | | 28-59 | 29.4 | 29.9 | Yes | 3.85 | 2_yes | On | 11 | Yes | 4 |

Figure 8. Kept rain events throughout all cave sites. New information: air temp., amount increase for Q and Tu, if Tu and EC values started at baseflow levels, total precipitation, and time since last rain event (DBP). For TCC only: number of days of rain, if variables changed on or after rainfall, precipitation prior to event (RB), and time between any prior precipitations (DSLR).

The shape of the different curves was not always alike, even in the same class. So, within each class, curves that have a similar shape were also analyzed together. There were a handful of C4 curves produced by rain events that were potentially C3 curves, but since it was uncertain, they were still considered as C4 curves with a subgrouping of potential C3.

After going through and looking at the classes, months were looked at next to see if a wetter year could cause the classes to shift. First, precipitation was graphed on the Y-axis against time, showing when and how much rain fell during each month per year. The y-axis was set up to 5 inches of rain to see the days of precipitation with little rain better. There were a few days of rainfall that did pass the 5 inches over the years, but they were just taken note of to know which they were. Each year was looked at separately and together starting with January. It would be inspected to see how many rain events occurred during that month, how cold it was/ would the ground be frozen over for long, and how much rain fell during the rain events. Once each month was checked, they would be compared to each other from different years to see if something happened differently during that month to cause one curve over the other.

Another thing looked at was the time between storms. The time between the peaks of the graphed rain events were looked at as well as if Tu and EC were at baseflow levels before the event. There were also the days of precipitation that didn't seem to effect Tu, EC, or Q but may have wetted the ground enough before the next rain event, so both the days between peaks and days between the last day of precipitation regardless if it affected Tu, EC, or Q was looked into. Also, there were a handful of events throughout the years at every cave system that could not be graphed since the data were not always complete and contained missing days or one of the three factors (Tu, EC, or Q).

## 2.3. Field Test

### *2.3.1. Microspheres*

An initial trip to Tumbling Creek Cave in the spring of 2018 was used to plan for a preliminary test of using sediment tracers within the cave stream. A total of 12 samples of soils and of suspended sediments were taken. Seven from the surface which included the main discharge spring, another at a karst window, and a third from the natural cave entrance where fine-grained sediment was deposited on top of boulders from a previous rain event. Five samples were from inside of the cave stream before and after a v-notch weir and also near a footbridge.

The samples were sieved using a 600-micrometer. A small scoop of each sieved sample, around 0.5 mL, was then placed into 50 mL plastic centrifuge tubes. 40 mL of $NaPO_3$ solution (Sodium Hexametaphosphate) was added and stirred to defloculate the sediments. A stir ball was placed inside of each test tube and set on a vortex for around ten seconds before samples were run through the machine to make sure that the samples were evenly mixed. A Beckman-Coulter Lasercize (LS 13-320SW Laser Diffraction Particle Size Analyzer Single Wavelength) was used to measure the size distribution of each sample.

In addition, several of the samples from both inside of the cave stream as well as from the surface were analyzed to check for any fluorescent materials that are native to the basin and cave stream. In the laboratory, samples were checked first under ultraviolet (UV) and royal blue (RB) lights to check for fluorescence.

After the initial analysis of the samples from the basin, fluorescent green polyethylene microspheres were used to mimic the sediment. These microspheres had a diameter of 26-32 microns and a density of 1.025g/cc. The microspheres fluoresced at 505 nm with UV (365 nm) and RB (470 nm) excitation. A small pinch of the microspheres less than a millimeter thick was set in a dish of water and placed under the RB light to check their fluorescence.

Since the density of the microspheres was that of water, a biocompatible surfactant was added to make sure they mix with the water instead of float to the top. 100 mL of de-ionized water was measured in a 250 mL beaker and then heated on a hotplate until boiling. The water was let to boil for five minutes before adding the surfactant. After removing the beaker of water from the hotplate, 0.1 grams of Tween80 was measured out and slowly added to the hot water. The solution was mixed with an immersion mixer for around 30 seconds on and off to sufficiently mix the water and surfactant. The solution was let out to cool before being used. The one gram of fluorescent green polyethylene microspheres was split into two centrifuge vials (0.5 grams per vial). Once the Tween80 solution was cooled, two mL of the solution was added on top of each of the vials of microspheres. Both vials were capped and placed into a centrifuge for a total of 10 minutes ensuring that all of the microspheres were wetted. After centrifuging, the

vials were let to sit overnight to allow the bubbles on top to settle. Most of the microspheres sank to the bottom of the vial; however, a few microspheres were trapped in the bubbles at the top of the water.

### *2.3.2. Sediment Traps*

Sediment traps were created next in the hopes to collect sediment and microspheres carried through the TCC stream. The traps were created using PVC pipes and PVC caps. Two initial sediment traps were constructed with the pipes being around 60cm long and a diameter of around 10cm. Rounded caps were placed on the back of the PVC tubes with a 5/32 hole drilled near the top of the back of each cap to allow water to flow out. The front of each pipe was also capped, one using a screw on cap and the other a flat cap. The front caps had a 5/32 hole drilled in the center to allow water and sediment to flow into and through the pipes. This design was based on a suspended stream sediment sampling method by the British Geologic Survey[3]. The idea with these pipes is that the inlet is much smaller than the diameter of the pipes, so the velocity of the water will decrease, and sediment will precipitate inside of the pipe. Two more holes were drilled on the top side of each PVC pipe, one near the front and one near the back. The front hole was used to be able to attach a thin nylon rope to the pipe and a tree or rock, so the tube would not be washed downstream when the velocity of the stream increases during a rain event. The back hole was used to allow air to leave the tubes when submerging in the stream. Once all the holes were drilled, and the traps put together, the test traps were taken to a stream on the LSU campus to be tested out. The sediment traps were held underwater until all of the air was released, and the pipes settled on the bottom of the stream. One trap was placed roughly in the center of the stream and the other closer to the stream bank a few meters down from the first sediment trap. The upstream trap did not remain submerged in the stream, so large rocks were added to the top of the pipe. Both traps were set out facing upstream and were then tied off to trees to prevent them from being washed downstream.

The traps were left in the stream for two days before they would be collected and analyzed for sediment. After the two days, the traps were retrieved from the stream during which the holes on either end of the sediment traps were covered while being pulled up as horizontally as they could from the stream in hopes to keep as much of the water and sediment inside of the traps before the examination. The water was slowly poured out to try to keep as much sediment stuck inside at the bottom. Once most of the water was poured out of the traps, they were checked for the amount of sediment that was still available.

After the experiment with the sediment traps, two more traps were made using mainly the same material as the other two and holes drilled in the same locations to allow water and sediment to enter the pipe. The caps on the two new traps had the same rounded back and a flat top like one of the previous traps. The trap that had the screw on cap was kept as is. The two traps that were used as testers in the stream before TCC were washed out to get most of the sediment that was stuck inside out before placing them in the cave stream.

### *2.3.3. Field Test*

At Tumbling Creek Cave, a small portion of the cave stream, around 100 meters, near the middle of the system was used to test out the sediment traps and microsphere movement during

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[3] https://www.youtube.com/watch?v=PnSm4hNAJ4Q, accessed September 2018

base flow conditions (Figure 9). The first sediment trap was placed a meter down from the edge of the pool on the downstream side of the weir where the microspheres were introduced into the stream (Figure 10A). This trap was placed in shallow, quick moving water with the top third of the trap sticking above the water. Three more sediment traps were placed around twenty to twenty-five meters down from one another in the stream and tied off to rocks nearby to keep them from flowing downstream. The second trap was fully submerged only with the addition of rocks. The third trap was completely submerged farther downstream near the footbridge (Figure 10B). Trap fourth trap was placed ~10 meters downstream of the third sediment trap and downstream of a rock fall. The water in this area was the deepest of all four reaching just below the knee under low flow conditions.

The two tubes of 0.5 grams of fluorescent green polyethylene microspheres were slowly released in the stream at the downstream end of the v-notch weir. The flow velocity of the stream during this experiment was at baseflow. A flashlight with an RB light was used to monitor the movement of microspheres in the stream. An initial release of microspheres was halted when problems with the flashlight arose. The remaining microspheres were released about 2 hours later.

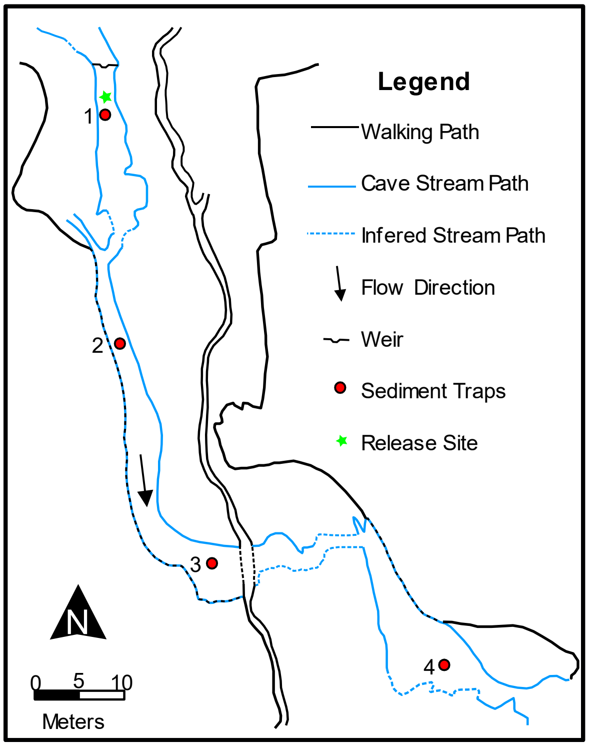


Figure 9. Image modified from cave survey in Thomson and Aley, 1971, showing extent of testing site at Tumbling Creek Cave. The entire length of the reach for this study is ~100m.

The sediment traps were set out in the cave stream for two days to allow them to have time to collect sediment and microspheres during base flow. Around 24 hours after placing the sediment traps and releasing microspheres, the stream was walked with the RB light to look for fluorescent microspheres starting from the first sediment trap. The walk ended a few meters down from the third trap and not continued to the last due to the battery on the light dying. After around 45 hours from the initial release of microspheres, the stream was rechecked, this time starting from downstream to upstream to hopefully not dislodge any microspheres from upstream

and creating misleading results. After this, each of the sediment traps were picked up from the water with both holes covered to lose as little water as possible placed into their own bags to be brought back to the lab to be analyzed for the fluorescent microspheres found in the tubes.

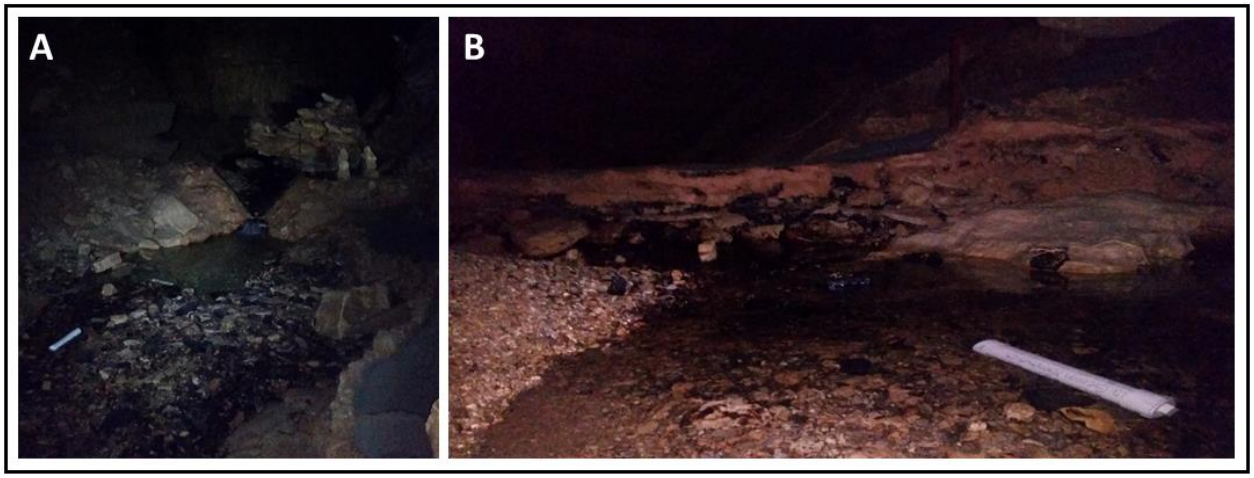


Figure 10. 2 of the sediment traps inside of TCC. Sediment trap 1 (A) is placed on the downstream side of the weir after the pool of water in an area where the water is shallow (photo taken facing upstream). Sediment trap 3 (B) is placed on the upstream side of the footbridge where water pools up before going through (photo is taken facing downstream toward the bridge).

While transporting the sediment traps back through the cave system, the bags continuously ripped due to the weight of the water inside the traps and from potentially rubbing against any sharp rocks and speleothems within the cave. The traps and bags were carried out of the cave and up to the field house where unfortunately by then nearly half of the water and possibly sediment that was collected in each of the traps were lost. The traps were also then placed an hour later into heavy-duty contractor bags to try to keep from losing any additional water or sediment.

Once back in the lab, each bag was separately brought into a dark room to check on the number of microspheres that were captured with each tube using the RB flashlight. Fluorescent particles found inside each bag and tube were then placed in dishes to be analyzed under a microscope to check for roundness.

# 3. RESULTS

## 3.1. EC-Tu-Q Classes

### *3.1.1. Creating Curves*

The main class seen throughout all cave sites was resuspension with several being direct transfer. There were no simple deposition events seen in any of the systems during any years analyzed. Although the main class seen was C2, nearly half of the curves produced were not simple enough to be placed in one of the previous classes. These curves were placed into a new class and were considered C4, other. Most of the C4 curves contain several of C1 or C2 curves meaning that there were probably several peaks or fluctuations that occurred throughout the rain event which caused different curves over the event, and there were also a handful of events that were just too messy to place into anything else and did not contain any real curve.

A total of 208 rain events and EC-Tu-Q curves were analyzed between the three cave systems: 91 from TCC, 47 from DI, and 70 from HC (Figure 12). Years 2003 and 2015 had the highest number of rain events whereas years 2002, 2007, and 2014 had the lowest number of events (seen from Tables 1, 2, and 3). Along with calculating the number of classes in each year in the different cave systems, the different classes from each rain event were plotted and looked at for each month (Figure 11). Since TCC had more years of data than HC and DI, it shows a greater number of all of the classes. HC and DI have many rain events that match up time-wise, but the rain events do not always produce the same curve in both cave systems.

Since there is no temporal overlap between the TCC data and that from DI or HC, rain events could not be analyzed for the same event. However, events recorded from HC and DI show similarly shaped EC-Tu-Q curves in nearly half of the flood events. Yet, a single rain event has observed to result in a simple C1 curve in DI and can show a more complex C4 curve in HC. The number of flood events observed in HC does not match to the number observed in DI (seen in Tables 2 and 3). This could be due to missing data from one cave system but not the other or to the fact that one basin received rain when the other did not, even though the two basins were geographically close.

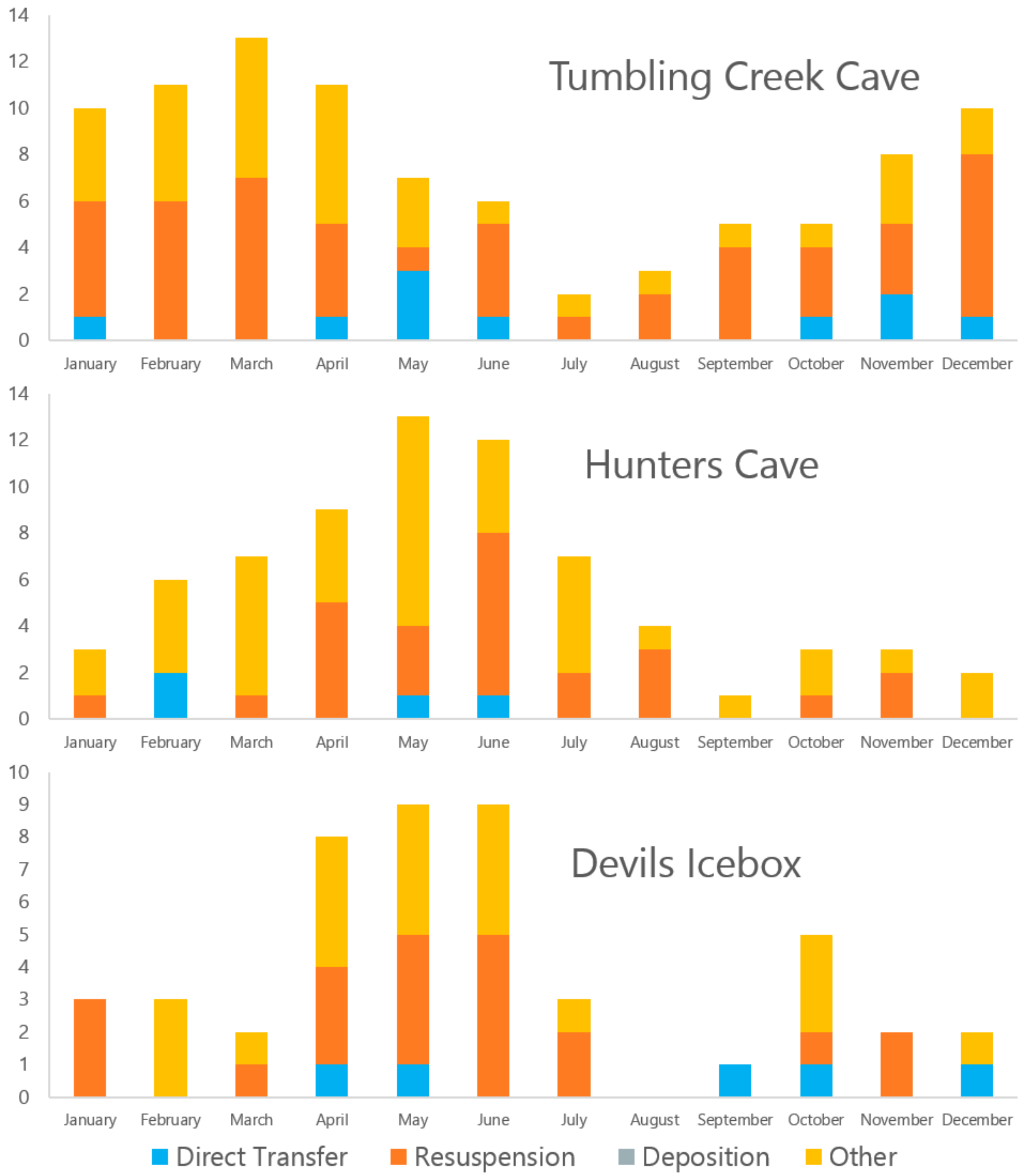


Figure 11. Classes graphed from TCC, HC, and DI on a calendar year. C1 is direct transfer, C2 resuspension, C3 deposition, and C4 other (being the complex curves).

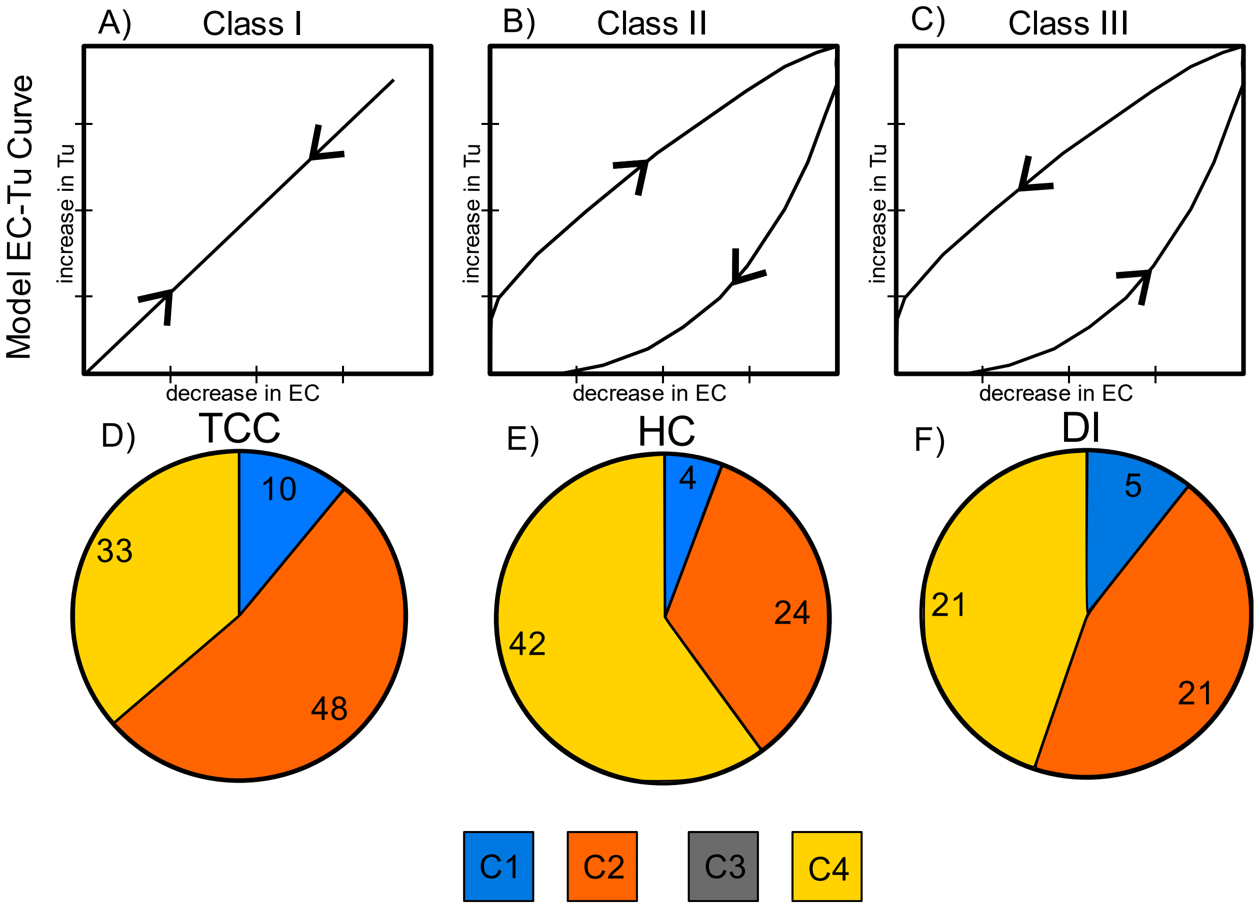


Figure 12. A-C are the model EC-Tu curves redrawn from Valdes et al. (2006) to show the general shape for each of the proposed classes. D-F show the number of rain events in each class produced from all three cave sites.

Table 1. Curves from Tumbling Creek including the total curves created for each year and the number that are C1, C2, C3, or C4.

| TCC | Total Events | Class I | Class II | Class III | Class I, II, III | Class IV |
|---|---|---|---|---|---|---|
| 2002 | 3 | 2 | 0 | 0 | 2 | 1 |
| 2003 | 18 | 0 | 13 | 0 | 13 | 5 |
| 2004 | 12 | 1 | 8 | 0 | 9 | 3 |
| 2005 | 12 | 1 | 8 | 0 | 9 | 3 |
| 2006 | 13 | 3 | 7 | 0 | 10 | 3 |
| 2007 | 9 | 3 | 4 | 0 | 7 | 2 |
| 2014 | 9 | 0 | 4 | 0 | 4 | 5 |
| 2015 | 15 | 0 | 3 | 0 | 3 | 12 |
| Total | 91 | 10 | 47 | 0 | 57 | 34 |

Table 2. Curves from Devils Icebox including the total curves created for each year and the number that are C1, C2, C3, or C4.

| DI | Total Events | Class I | Class II | Class III | Class I, II, III | Class IV |
|---|---|---|---|---|---|---|
| 1999 | 10 | 1 | 4 | 0 | 5 | 5 |
| 2000 | 13 | 2 | 6 | 0 | 8 | 5 |
| 2001 | 24 | 2 | 11 | 0 | 13 | 11 |
| Total | 47 | 5 | 21 | 0 | 26 | 21 |

Table 3. Curves from Hunters Cave including the total curves created for each year and the number that are C1, C2, C3, or C4.

| HC | Total Events | Class I | Class II | Class III | Class I, II, III | Class IV |
|---|---|---|---|---|---|---|
| 1999 | 13 | 1 | 4 | 0 | 5 | 8 |
| 2000 | 30 | 1 | 11 | 0 | 12 | 18 |
| 2001 | 27 | 2 | 10 | 0 | 12 | 15 |
| Total | 70 | 4 | 25 | 0 | 29 | 41 |

*3.1.2. Class I Curves*

While TCC contains the most C1 curves, DI and HC do have several themselves. The seasonality factor shows C1 curves produced in the spring and the fall, with very little in the winter and none in the summer (Figure 11). TCC contains C1 curves in April, May, and June and then again in October, November, and December. HC shows C1 curves in May and June but not in the fall. DI also has spring C1 curves in April and May and fall curves in September, October, and December. There are a few obscure C1 events that appear in the winter at TCC and HC (January and February respectfully). Though DI and HC both have C1 events in spring, DI contains several C1 events in fall while HC does not, so C1 curves from site to site do not always match up.

The intensity of rain events varies within this class throughout all three cave systems (Figure 13). In TCC, less intense events are seen in the fall, winter, and summer with medium events in winter and spring, and the large C1 events in spring, fall, and winter. HC and DI show similar results with storm intensity. DI shows C1 curves with the highest overall Q and Tu increases, though HC does not show quite the same results even though these two systems are close to each other.

In TCC C1 curves are seen to occur after the previous peak from 5 to 60 days, but no longer than 16 days of no rain. The average C1 curve happened around a week or less from the previous day of precipitation but over two weeks from a day where we could see any fluctuations in the EC, Q, or Tu data. Another thing checked was if Tu and EC data were able to get back to base flow conditions by the time of the rain event and for the majority of C1 curves, they appear to have. There were some that might have gotten relatively close and a few that were still falling before the next event occurred. HC and DI C1 curves are seen anywhere from a couple of days to two weeks after the previous rain event that caused an EC-Tu-Q curve. For HC, Tu and EC were

back at baseflow conditions before the two later spring events with lesser intensities, though baseflow conditions were not back before the larger events. Before the two larger events for C1 curves in DI, EC and Tu had not returned to baseflow conditions, though for the others they had.

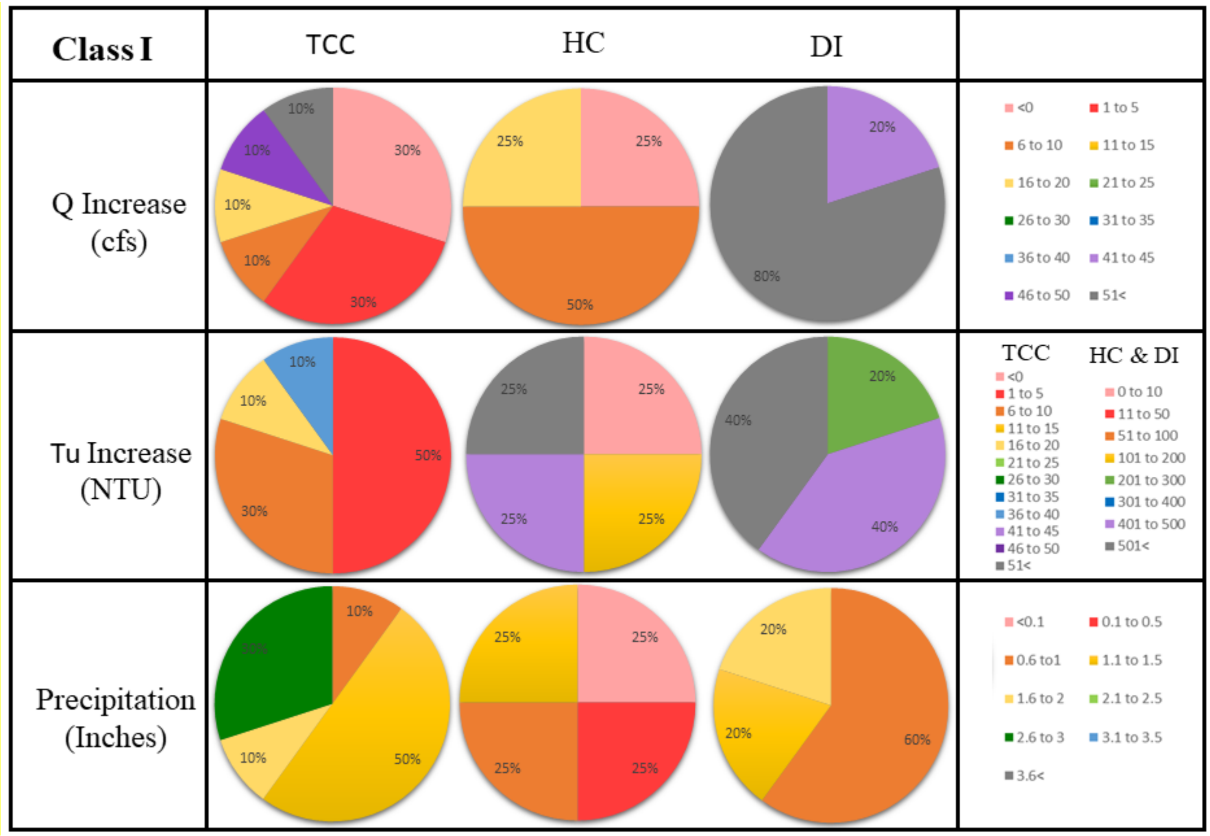

Figure 13. Class I, direct transfer, curves from all three caves. First three pies show the increase in Q during different rain events, then the increase in Tu, and amount of precipitation. Tu increases on average much less at TCC compared to DI and HC, resulting in a different scale for that one chart.

### *3.1.3. Class II Curves*

C2 curves are seen in all three cave systems with the highest percentage in TCC. Over half of the rain events in TCC produce C2 curves (53%), and in DI C2 curves are seen nearly half of the time (45%). HC shows a greater amount of C2 curves than C1 curves; however, they are not the most abundant curve seen in this cave system (at 34%). C2 curves are also seen throughout every month or season (Figure 11).

The intensity of rain events varies within this class throughout all three cave systems seen by the range of different precipitation amounts (Figure 14). TCC shows C2 curves produced from mainly higher amounts of precipitation events with Q and Tu increasing overall much less than the other two systems. HC and DI show C2 curves from, on average, less amounts of precipitation with greater amounts of discharge and turbidity during these events.

C2 curves from TCC have occurred a day or two after a previous event that shows EC, Tu, and Q fluctuations to around three weeks. Even looking at the last day of precipitation, this varies a lot as well. Rain may have fallen as little as a few days to two weeks before the event meaning that the ground might have been drier between some events than others. Looking at Tu

and EC data to see if they have got back to base levels here are also entirely random. Sometimes they have fallen back to base before the storm, and sometimes they have not, but usually, they are close. DI and HC show C2 curves occurring between a few days to around a week from the last EC-Tu-Q curve. Tu and EC on average had not returned to baseflow conditions but may have gotten close.

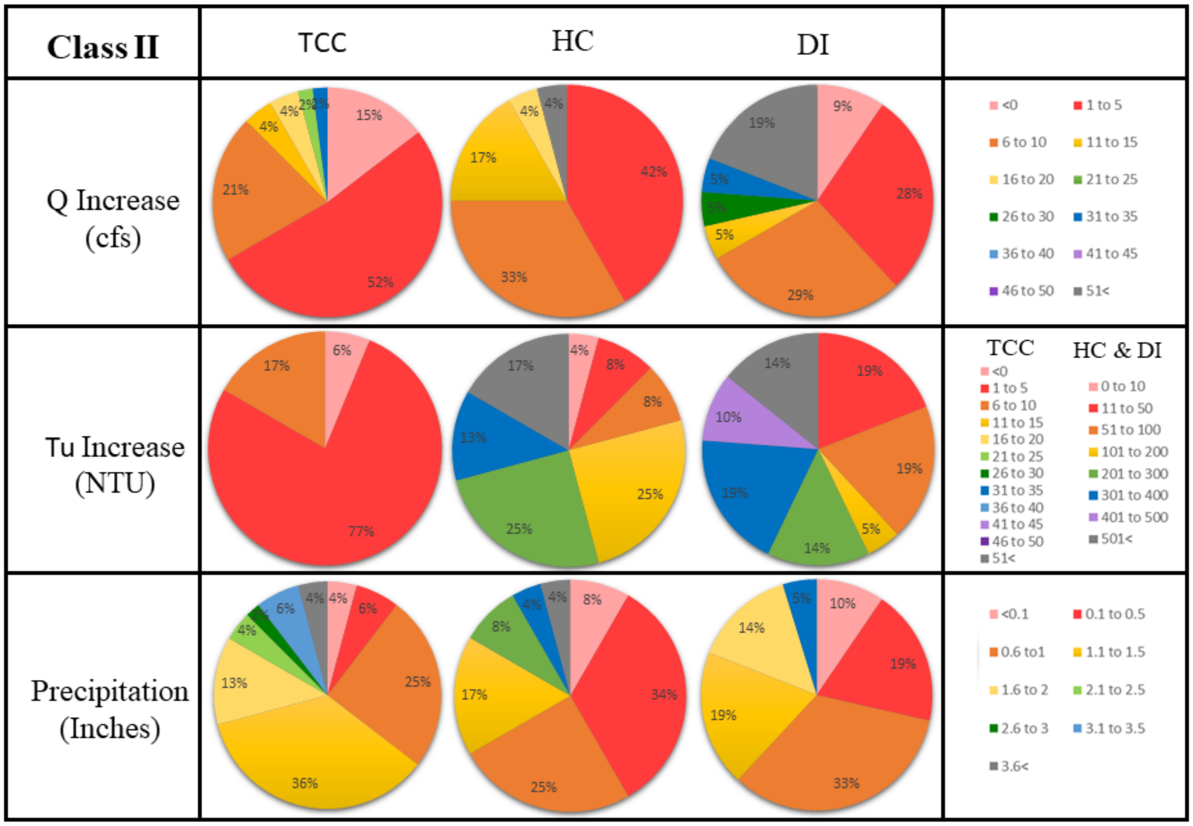

Figure 14. Class II, resuspension, curves from all three cave sites. First three pies show the increase in Q during a rain event, then increase in Tu, and amount of precipitation. Tu increases on average much less at TCC compared to DI and HC resulting in a different scale for that chart.

### *3.1.4. Class IV Curves*

C4, other, curves are seen throughout TCC, HC, and DI nearly half of the time with HC showing the most and TCC having the least (Figure 12). In TCC, the percent of C4 curves to C2 curves is nearly the same in all of the seasons except for fall. In the fall, there are less C4 curves observed (Figure 11) than any other. For DI all seasons have the same percent of C4 to C2 in each season, but in HC there are many more C4 curves than any other type across every season (Figure 11).

In TCC, rain events showed C4 curves produced by a range of different intensity storm events with the amount of precipitation varying between of all three systems as well. In general, rainfall was greatest in TCC than DI or HC that produced C4 curves; however, the turbidity was on average much less (Figure 15).

The time between rain events also varies just the same as the rest of the classes. A C4 curve can occur immediately following a previous event or days to weeks of no rain seen in

TCC, HC, and DI. Tu and EC regularly neared baseflow conditions prior to these events in all three systems with some events occurring while Tu and EC were still well above baseflow levels.

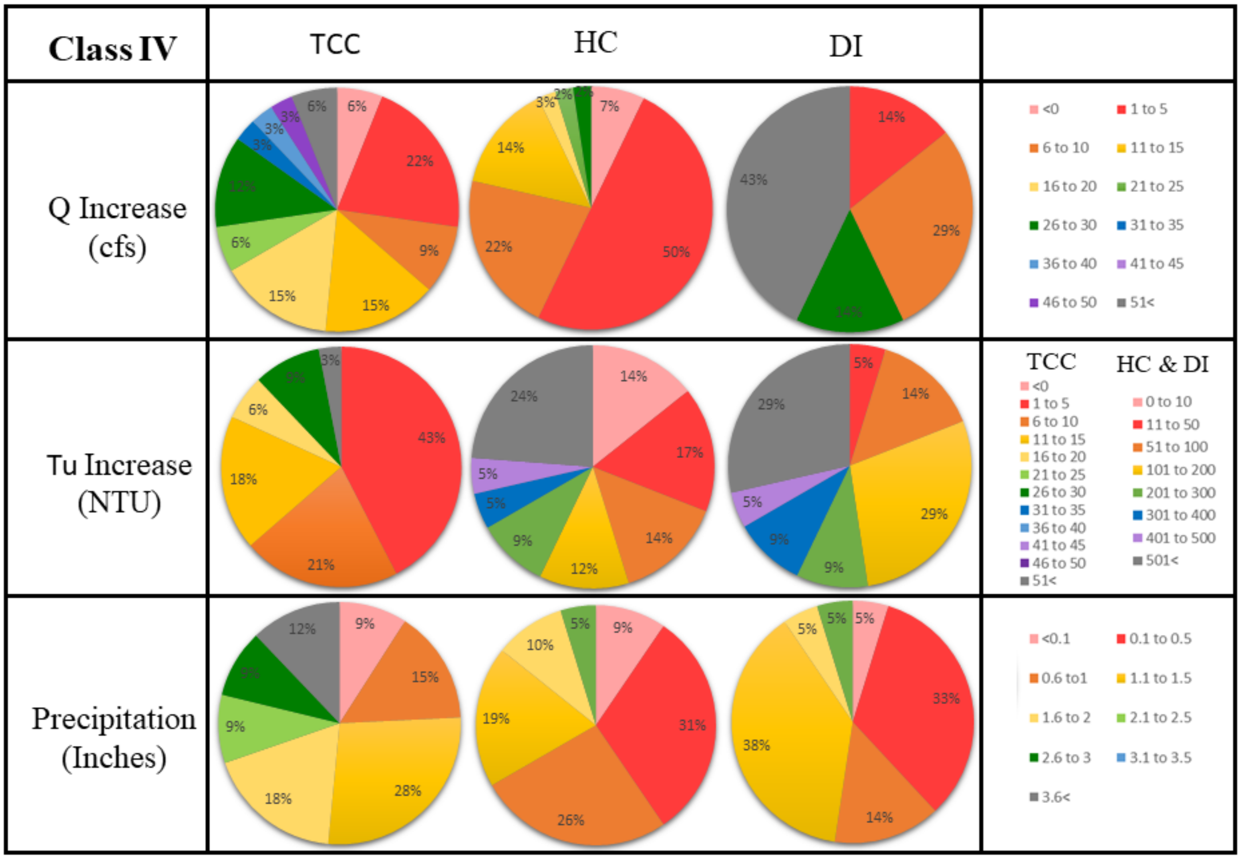


Figure 15. Class IV, other, curves from all three cave systems. The first three pies show the increase in Q during the rain events, then the increase in Tu, and the amount of precipitation. Tu increases on average much less in TCC compared to DI and HC resulting in a different scale for that chart.

### *3.1.5. Class II and Class IV subclasses*

Several curves within C2 and C4 showed similar shapes to one another and were placed into subclasses. In C2, there are several curves from all three cave sites that look alike with turbidity having two bumps with conductivity only having one (Figure 16A). Having more than one peak makes the overall curve still have a clockwise loop, but with two bumps when turbidity increases, decreases and then increases again with EC rising slightly during the fall of Tu. These events are also seen throughout all three cave systems and the seasons. This shape could not be distinguished from any of the other C2 curves with intensities ranging from small to medium and occurring on an irregular basis after different rain events from a few days to over a week.

From HC, several C4 curves could be potential C3 due to having a slope less than one but without a counterclockwise loop which has occurred from a variety of rain intensities seen in any other C3 curve (Figure 16B). These curves are only seen scattered throughout spring 2000-spring 2001 at HC and are seen in several different seasons. Intensity and volume of the rain event vary for these curves as well along with the time between the previous rain events. This shape is not seen in any of the DI data, but there is only one curve seen like this from May 2004 in TCC.

Another C4 group containing curves staring as C1 or C2 and changing into a counterclockwise loop before Tu end EC fall back to baseflow conditions (Figure 16C). There are only a handful of these curves seen, and they show no differentiation from the other classes in their seasonality, the intensity of storms, and time since the previous rain event.

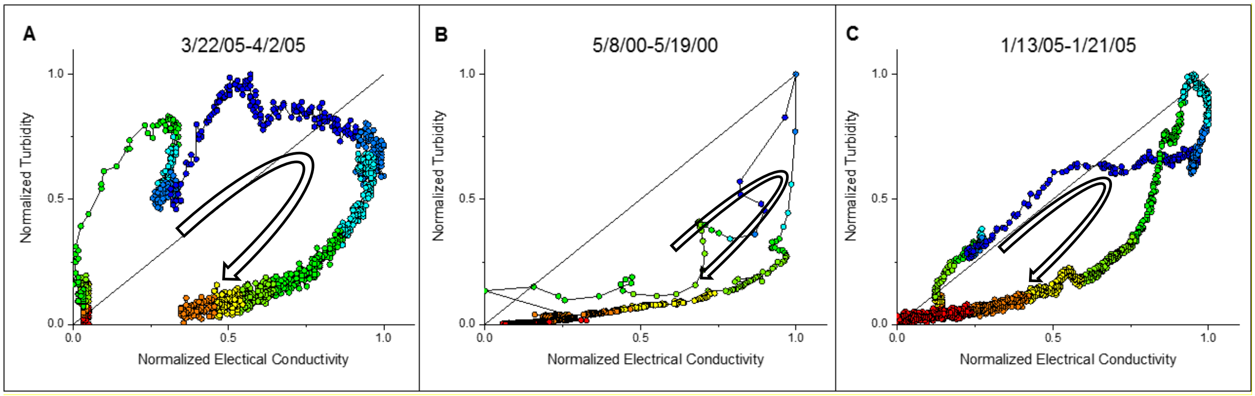


Figure 16. EC- Tu-Q curves produced by rain events from TCC in March-April 2005 (A), HC in May 2000 (B) and TCC in January 2005 (C).

## 3.2. Field Test

### *3.2.1. Sediment Trap Testing*

During the second day the traps were out, a rain event occurred in Baton Rouge, Louisiana causing the water level to rise and become very turbid. After the rain event had passed and the water settled again, the sediment traps were covered in a thin layer of sediment. One of the traps became partially coated on its side by sediment that was deposited next to the trap during the rain event with the front of the trap still exposed. The second trap had been tossed around during the event and had turned a bit to face the bank walls. Muddy water and sediment were seen inside of both traps once pulled out of the stream.

### *3.2.2. Microspheres in Tumbling Creek Cave*

The initial sediment analysis from the TCC stream and basin produced a chart with mean sediment sizes as well as the percent of the sample for specific micron sizes from the smallest around 0.375 microns to about 200 microns. The average size for all twelve of the samples was then averaged together to produce a mean sediment size around 60 microns. Two of the twelve samples had averages of 167.775 microns and 294.278 microns which were over a hundred microns greater than the other ten samples. After taking out the two outliers, the average for the other ten samples was closer to 26.33 microns, meaning that would be the size of microspheres used for this experiment.

After the initial test in the surface stream, the sediment traps were brought to Tumbling Creek Cave to be tried out to see if they would be able to capture microspheres. After 24 hours, the stream was walked with the RB and microspheres were found throughout the stream in small concentrations from the first sampler and past the third. The microspheres were found stuck on rocks, some on the bottom of the stream, and also some floating through the stream (though these may have been knocked off the floor or rocks from disturbing the water as it was walked through

upstream). At the upstream end of the footbridge, a big pool of microspheres was found swirling between rocks before they made their way through the holes in the footbridge. Many of the microspheres throughout the cave stream seemed to be floating through the water or deposited on nearby rocks with the less amount found on the bottom of the stream bed. The farthest downstream checked during this time was a few meters down from the third sediment trap and a rock fall. Here, microspheres were still spotted, some flowing through openings in the rock fall downstream.

The cave stream was walked again around 45 hours after the initial release of microspheres as the sediment traps were collected. The upstream section appeared to have some microspheres still moving through with most stuck-on rocks. The downstream portion of the stream around five meters past the fourth sediment trap (at a dam that was built in the stream to keep crawfish from infesting the upstream portion and eating the endangered Tumbling Creek Cave snail) had a lot of microspheres deposited on the bed and rocks around the upstream section of the dam. The downstream part of the dam also had quite a few microspheres flowing through and sitting on the stream bed. The group of fluorescent microspheres that were swirling up near some rocks before the footbridge were mostly all gone from the second to third day, with a few microspheres still stuck around the bridge.

### *3.2.3. Checking for Microspheres*

Most of the water and sediment seeped out through the bags by the time they made it to the lab. In bag one there was half a cup of water trapped in the bottom. Inside the tube, there was no water and no sign of any sediment, though there was a cluster of microspheres scattered throughout the first few inches of the tube. Microspheres were also seen loosely scattered throughout each of the bags that surrounded the sediment trap. Trap two was also empty of any water thought there was some sediment that was stuck to the inside of the PVC pipe. A few microspheres were found within the first few inches of the tube, but not nearly as many as the first sediment trap. The bags themselves had a little bit of water and sediment pooled at the bottom of the bag that was first surrounding the tube. Inside of the small pool of water, there were three microspheres found and inside of the bags themselves, there were many more scatted around. Some water and sediment were seen in the bags surrounding trap three as well. Inside trap three, several microspheres were found as well as scattered throughout the bag. Trap four had a little sediment stuck in the bottom of the tube and also showed a few microspheres inside of it as well as in the surrounding bags.

The green fluorescent materials were confirmed to be spheres under the microscope.

# 4. DISCUSSION

## 4.1. General Findings

Most simple rain events produce C2 curves which was expected with several that were C1. While C2 curves are seen throughout all seasons, C1 curves are usually found in the spring and the fall in these three cave systems (with a few exceptions of C1 curves in the winter). Since C1 curves are often produced in the spring and fall, it is possible to say that seasons might play a role in the curves produced. The other factors checked, the intensity of the rain event and the time interval between rain events, did not show any significant correlations to the classes. Overall, the intensity of rain events did not affect the class produced, with intense rain events seen more regularly from C2 and C4 curves opposed to C1 which was first thought.

Even though DI and HC are two systems that are relatively close to one another, they did not always produce the same curve for the same rain event. This was something that was really unexpected and the cause for this is unknown. Perhaps the rain event affected each basin differently, with one basin receiving more rain than the other, though without precipitation data from each of these sites it is hard to tell.

Rain events did not regularly produce simple curves as expected. In general, rain events at these three cave systems did not show single peaked curves, but instead had many smaller peaks on the ascending limbs. While resuspension was seen in each system more often than direct transfer, around half of all the rain events seen in TCC, HC, and DI ended up in the new class created, C4. These rain events showed curves that were more complex than a single peaked rain event with one dominant class. Instead, C4 included the curves that had several humps which could either result in a curve showing more than one of the previous classes (C1, C2, and C3) or they could show a curve that was too complex that no previous class could be picked out from. There were no definitive C3 curves seen from any of the cave systems, although there is a grouping of C4 curves in HC that may show some similarities to C3 curves.

Rain events from each class were analyzed, starting with C1. In 2006 (at TCC), several rain events produced C1 curves that occurred under different conditions during different times (EC-Tu-Q curves shown in Figure 17). The event January 29th showed a rain event that created a C1 curve with precipitation around 1inch, so the month had been relatively dry and cold before this event. There had been some previous rainfall throughout January but in total less than 0.75 inches. Q increased slightly around 0.27 CFS and Tu around 3.6 NTU. Later that year at the end of November, another C1 curve was seen but under very different conditions. Here, the amount of rainfall was around 2.76 inches following a period of 2 weeks with several days of mostly light rain. Two days passed over 0.5 inches with one over an inch of rain. So, before the November 30th event, the ground should have been wet. Q increased around 65 CFS and Tu 37 NTU.

Comparing these two rain events, there are no similarities to say what could cause a C1 curve. This is not the case for every rain event that produced a C1 curve. Some do show some similarities, but since there are only several C1 curves seen throughout all of the cave systems it is harder to find a pattern when there are also differences stopped.

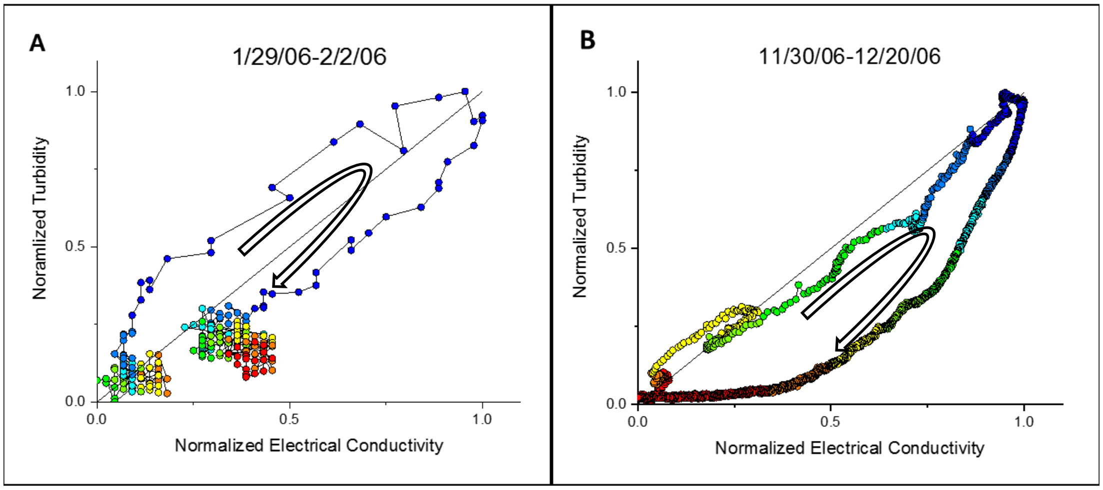


Figure 17. EC-Tu-Q curves produced by rain events from January-February 2006 (A) and November-December 2006 (B) showing a slope of 1, predicting direct transfer of sediment in the system.

Several C2 curves were compared with each other from 2003 (from TCC) that show different seasons, intensities, and times between rain events (EC-Tu-Q curves seen in Figure 18). January 29th shows a C2 curve after around a month of little to no rain. The ground was potentially still frozen, and it rained 0.58 inches increasing Q .37 CFS and Tu 1.17 NTU. May 16th's C2 curve is seen during the wet season following a month-long time of storms with precipitation for this event at 1.5 inches increasing Q 6.7 CFS and Tu 5.7 NTU. Lastly, August 2nd shows a C2 curve following a period of little to no rain (though more than the January event) with precipitation around 3.2 inches increasing Q .3 CFS and Tu 3 NTU. Even just looking at this smaller section of C2 curves, there was nothing that could link them together.

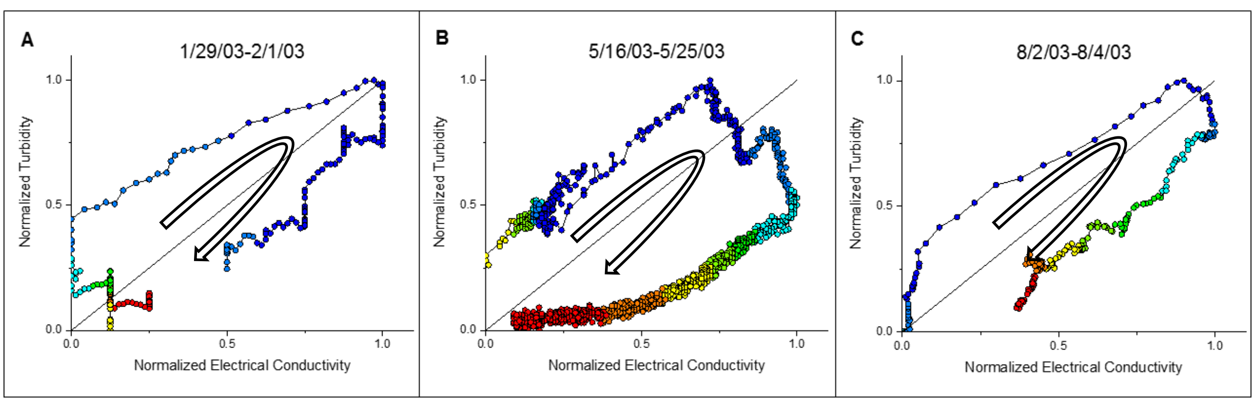


Figure 18. EC-Tu-Q curves produced by rain events from January-February 2003 (A), May 2003 (B), and August 2003 (C) from TCC showing a clockwise loop predicting resuspension of sediment in the system.

Since these rain events producing C2 curves are some of the most common, there can be similarities from curve to curve (and between cave systems) but there are also differences.

A couple of C4 curves from TCC were analyzed together to see if there is something that can be found that is similar. February 11th, 2007, a C4 curve occurs 12 days after any previous precipitation and over three weeks of the prior event showing changes in EC, Tu, and Q (Figure 19A). Rainfall was around 1.7 inches increasing Q 24.7 CFS and Tu 11.5 NTU. June 18th, 2015 shows a C4 curve created after a time of a lot of rain with that event having 3 to 4 inches of

rainfall (Figure 19B). Q increased 59.5 CFS and T 29.4 NTU. These more complex events are seen after times of no rain or a lot of rain and during any season just like the previous classes.

Since C4 curves are wildly different from one another, it is much harder to find patterns. If a curve does not fit into one of the previous three, they would be put in C4 which means it contains curves that show several humps or just something that is unexpected.

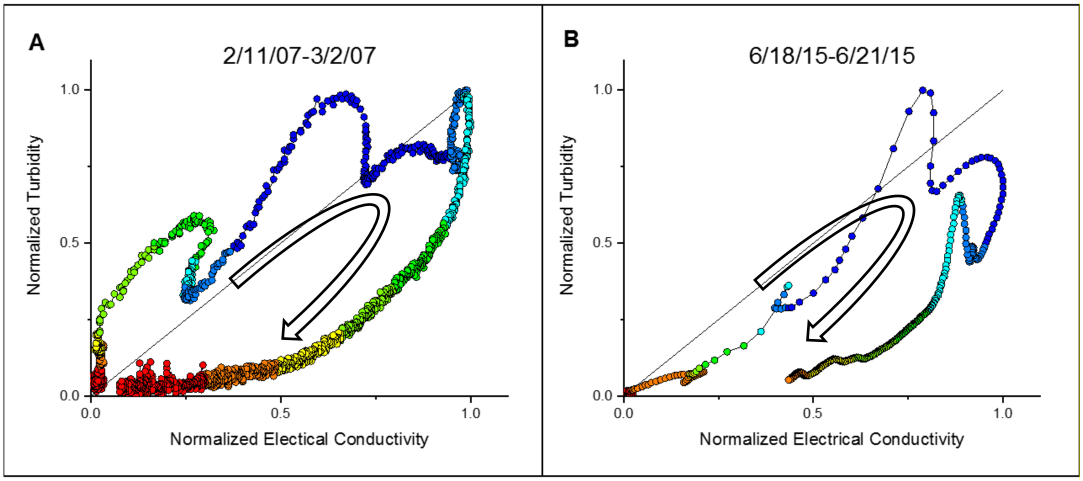


Figure 19. EC-Tu-Q curves produced by rain events from February-March 2007 (A) and June 2015 (B) from TCC showing several incomplete curves including both Class I and Class II or undefinable curves.

Rain events were also chosen throughout the years during similar times of the year with similar conditions before each rain event. Eight rain events were chosen for this comparison throughout the years at TCC in January, on January 29th 2003, on January 25th 2004, and another January 29th 2006 (Table 4). These three rain events occurred around the mid to late January season with some colder than others. The 2003 and 2004 rain events had at least one day that was below freezing hinting that the ground was most likely frozen for at least some of these rain events, though it was also likely for the ground to be frozen during the 2006 event as well. There was no prior rainfall (PRF) for at least a week for all the events, discharge and turbidity increased around the same amount, though precipitation amounts did vary a bit. The first two rain events had precipitation around half an inch while the third was over an inch for the event. There were no significant differences spotted between these events other than the amount of precipitation. The 2003 event and 2004 event both produced C2 curves while the later produced a C2 curve.

The second group of rain events was compared to one another from the spring seasons at TCC, one on May 2nd 2004, one on April 22nd 2005, and one on April 25th 2007 (Table 5). Each rain event occurs during the same time of year in different years with many similarities. In the spring, the ground should have thawed, and vegetation should begin to grow strong. This time of year is generally a lot wetter, with rain events occurring very soon after each other. These three rain events, however, are after a time when there had not been any significant amount of rainfall (anything over 0.1 inches) within the past week. All three rain events show a similar amount in precipitation, increase in discharge, and an increase in turbidity. The only differences found within this group are the curves that are produced. The first event produced a C1 curve, the second a C2, and the last a C4 (and a very complicated one where no classes could be deciphered from it).

Another pair of rain events that were checked against each other were again in spring, May 10th 2006 and May 10th 2015 from TCC (Table 6). These two events occurred around the same time/ season although in different years. They show similar amounts of time between the rain events that caused the curve as well similar intensities, but they produced two different curves (one C1 and the other C4). One thing here is that the amount of precipitation for each event are different, so there could be something going on with precipitation that is causing one rain event to produce one curve while the other produces a different one.

Table 4. Three events in January from different years at TCC showing rain events with similar conditions (intensity, season, and time interval between events) that produced different classed curves.

| Date | Temp (Fahrenheit) | Q (cfs) | Tu (NTU) | Precipitation (inches) | PRF (week) | Curves |
|---|---|---|---|---|---|---|
| **1/29/2003** | 30-45 | 0.37 | 1.167 | 0.58 | No | C2 |
| **1/25/2004** | 12-34 | 1.71 | 0.7 | 0.48 | No | C2 |
| **1/29/2006** | 40-53 | 0.273 | 3.6 | 1.11 | No | C1 |

Table 5. Three rain events from the spring from different years in TCC showing similar intensities, rain amounts, time of year, and time between rain events producing different curves.

| Date | Temperature (Fahrenheit) | Q (cfs) | Tu (NTU) | Precipitation (inches) | PRF (week) | Curves |
|---|---|---|---|---|---|---|
| **5/2/2004** | 48-71 | 1.7 | 4.6 | 1.2 | No | C1 |
| **4/22/2005** | 45-55 | 1.4 | 4.1 | 1.1 | No | C2 |
| **4/25/2007** | 51-71 | 2 | 3 | 1.22 | No | C4 |

Table 6. Two rain events in May from different years at TCC with similar intensities, rain amounts, time of year, and time between rain events producing different classed curves.

| Date | Temperature (Fahrenheit) | Q (cfs) | Tu (NTU) | Precipitation (inches) | PRF (week) | Curves |
|---|---|---|---|---|---|---|
| **5/10/2006** | 54-60 | 20.15 | 9.2 | 1.43 | Yes | C1 |
| **5/10/2015** | 57-72 | 21.86 | 9.614 | 3 | Yes | C4 |

## 4.2. Limitations

### *4.2.1. Previous Studies*

Field testing for the classes has been very limited with Valdes et al. (2006) looking at 16 total springs or wells for 5 cave sites all located relatively close to one another for two different rain events, one in December 2002 and the other January 2003. Each site had a slightly different cumulative rainfall amount, though the rainfall hyetographs generally have the same shape.

Valdes et al. (2006) also observed events with the lowest cumulative rainfall resulted in the highest response in Tu and EC and concluded that cumulative rainfall is probably not responsible for the differences in the curves but instead must be due to internal differences and hydrodynamic functioning (White, 1988). For the second event, one of the sites showed a C1 curve while the others were generally C2 in which Valdes et al. (2006) concluded that the transport processes at this site are different from the others. Unfortunately, there was no graph produced at this site for the first event, so it is unknown if that system would behave like it did in December and January. Fournier et al. (2007) also only looked at three rain events for one cave system in December 1999, April 2000, and November 2000. The December and November graphs showed two peaks in turbidity, potentially due to the rainfall stopping and starting again, while the April event only showed one peak. The December event produced three curves, first a C1, then C2, and finally C3, April produced only a C1, and November showing a C2 followed by a C1. Neither of these two studies addressed C4 curves, which it is probable that they just never came across any.

Comparing the results from this study to Valdes et al. (2006), they show mainly the same observations. Generally, C2 curves are created. During the second event, even though the cave systems are relatively close to one another in the study by Valdes et al. (2006) one system showed 4 curves, two were C2, one was C2 followed by C3, and the last was two C1 curves. In this study, HC and DI are two systems that are near each other, but they don't always show the same curves. The results from Fournier et al. (2007) also showed similar things to this study. First off, both showed simple C1 curves in the spring. In Fournier et a. (2007), C1 curves can be followed by C2 curves and C2 curves can be followed by C1 curves, meaning that the time between rain events doesn't seem to affect the curve created. This was also seen in this study. The differences from the rain events from Fournier et al. (2007) and the ones from this study is that their rain events produced full curves of each class when there are several seen during the rain event. In this study, one curve is generally seen with humps that could be different classes if looked at by themselves.

#### *4.2.2. Precipitation Data*

Precipitation data were given as daily data, so it was unknown when rain fell or if it was constant or sporadic. Precipitation data was also only received from TCC and not the other two cave sites which were taken from a nearby city (Columbia, Missouri) making this data less accurate as well.

Without better resolution precipitation data, it would be impossible to assume that if rain fell harder or softer throughout the day that it would produce different curves. Tu, EC, and Q data are all given generally in 10-15-minute intervals. Using daily data for Tu, EC, and Q to match precipitation would not be possible because it does not give enough detail for each rain event since the basins for each of the cave systems looked at, especially TCC, are small (Figure 20). A cave in a large basin may show more detail in daily data since there is a larger area to collect precipitation and can show the effects for an extended period; however, having a smaller basin means it won't be affected as great and will return to baseflow relatively faster. Still looking at precipitation, it was also noticed that not every rain event caused changes in Tu, EC, and Q.

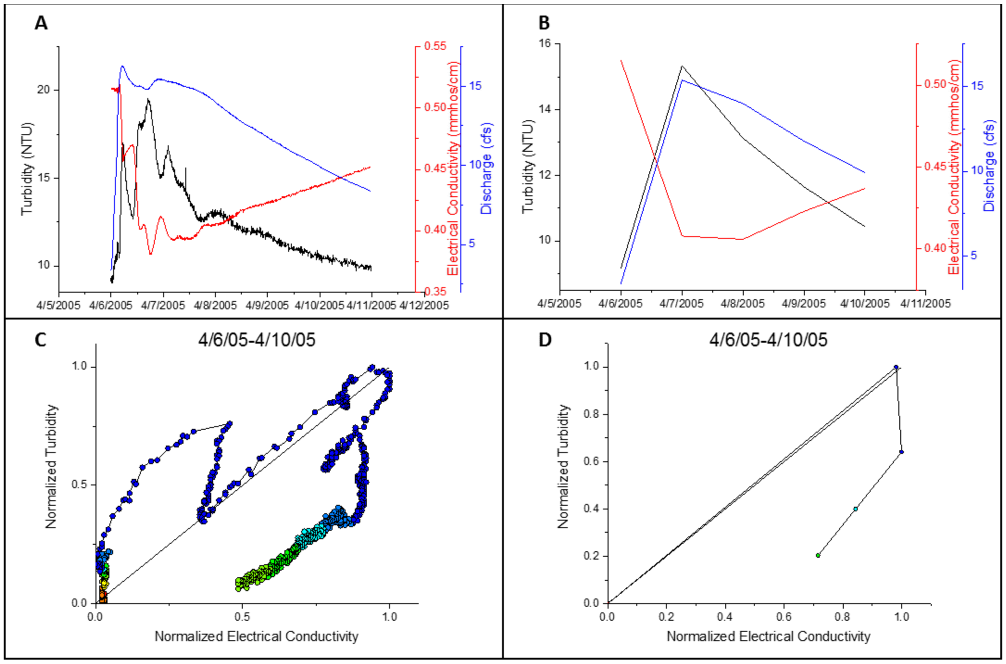


Figure 20. Figures A and C show time series and EC-Tu-Q curves of a rain event in TCC from 2005 with data from every 2-4 minutes for Tu, EC, and Q. B and D show the same event with daily data for Tu, EC, and Q to match precipitation.

### *4.2.3. EC Two or Three-Component Mixing System*

EC is based on a mixing system that can be relatively simple with "new" or "event" water coming in from the surface and mixing with "old" or "pre-event" groundwater (Hooper et al., 1990; Evans and Davies, 1998; Massei et al., 2003), or have three (or more) components of water from the surface, ground, and soil (Hooper et al., 1990; Evans and Davies, 1998). Regardless of a two or three component system, the overall EC in the stream decreases rapidly during a storm event when any new water mixes with the water that is already in the system.

It also is unknown if any of the cave systems in this study are a two or three component mixing system for EC. Surface water and soil water generally affect different sides of the EC curve with surface water important on the rising limb and soil water on the falling limb (Sklash and Farvolden, 1979), though this isn't always necessarily the case (Evans and Davies, 1998). Having a two or a three-component mixing system could potentially change the way that EC is acting. Having a three-component mixing system could make EC change in a way that is not expected, perhaps having it decrease faster or slower, seeing several more bumps or increasing back to base flow at a slower rate. This can then affect how the curves that are produced from the rain events look, and maybe they won't look like the general C1, C2, and C3 patterns that have been discussed. If a cave system also has more tributaries than another that might delay water from entering the system or increasing the amount at a faster rate could cause EC to change and again not act the way to produce simple C1, C2, or C3 curves.

### *4.2.4. Relatively Short Data*

The data received from DI and HC were both under three years of data. This made it a more difficult to see any patterns across the years at these sites; however, data from TCC consisted of several years.

### 4.3. Microspheres

Using only a smaller portion of the cave stream to test the microsphere movement was decided on due to a limited amount of time for the research and in hopes to collect significant data. Also, since this test was done during a time of slow flow conditions, the microspheres were not expected to make it through the entire cave stream over a few days. The number of microspheres for this experiment was also not sufficient enough to be released at the sinkhole and expected to be seen/ collected throughout the cave stream.

A few changes should be made for previous studies with the sediment traps so that the probability of capturing everything from the tubes would be higher. The tubes will be created smaller in both diameter and length; this would make them easier to remove from the water when filled and also could be placed and sealed inside of larger tubes so that no water or sediment will be lost or leaked out. The next test will also preferably take place during a storm event to capture the movement of the microspheres and the sediment during an event to then be able to compare with the sediment transport classes using the proposed methods by Fournier et al. (2007). Sediment within Tumbling Creek Cave is easily moved, with the microsphere tracer test confirming that some sediment even moves during low flow conditions, so it would make sense to see sediment suspended from the cave stream bed for most of the events that were looked at.

# 5. CONCLUSIONS

Direct transfer, resuspension, and deposition of fine-grained (suspended) sediment are the three main types of transport seen within karst systems and can be inferred by changes in turbidity, electrical conductivity, and discharge. 208 flood events were analyzed from three different cave sites (TCC, DI, and HC) to reveal patterns in the EC-Tu-Q curves created. Only half of the flood events could be placed in the classes proposed in previous studies while the other half were not seen as simple curves. Complicated flood events, perhaps caused by sporadic rainfall, created curves that were not easily classified as direct transfer, resuspension, or deposition and were considered as other. The majority of simple curves created were classified as resuspension curves with several direct transfer curves seen over each year. No simple deposition curves could be seen, though that does not mean there is no deposition occurring in these cave streams.

There was a slight seasonal effect as direct transfer was noted mainly in the spring and fall. Resuspension events occurred throughout the year without being more abundant in one season than another. Other curves can be seen throughout the year as well that were not solely direct transfer, resuspension, or deposition.

HC and DI are two cave systems whose basins are next to each other and generally showed similar precipitation events over the years. Even though these two systems are close, the EC-Tu-Q curves created from the same precipitation event only showed the same class around half of the time. A simple direct transfer curve can be observed in DI while a more complex curve with several peaks on the ascending limb can be observed in HC.

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# APPENDIX

The three parameters that were recorded at each of three caves were turbidity, specific conductance, and stage.

Turbidity: Turbidity data were given in Nephelometric Turbidity Units (NTU) which is a light-scattering method for measuring low levels of turbidity (Poehls and Smith, 2011).

Stage: Stage is measured using a pressure transducer that measures the depth of water above the probe. This depth is converted to discharge using a rating curve (Discharge plotted against stage).

Specific Conductance (also referred to a conductivity, electrical conductivity, or specific electrical conductance): Specific Conductance is measured as a voltage drop across a 1-cm spacing (gap) in the sensor cell through which the water flows. The voltage is converted to conductance (milliSiemens or equivalently millimhos). Conductivity is obtained by multiplying the conductance by the cell constant of the probe (provided by the manufacturer). Specific conductance is conductivity corrected to a temperature of 25 degrees C.

| | Depth | Specific Conductance | Turbidity |
|---|---|---|---|
| Tumbling Creek Cave | Campbell Scientific OBS+3 sensor | Campbell Scientific CS547A probe | Campbell Scientific OBS+3 sensor |
| Hunters Cave | Hach Company | Yellow Springs Instrument 6920 Sonde | Yellow Springs Instrument 6920 Sonde |
| Devils Icebox | Hach Company | Yellow Springs Instrument 6920 Sonde | Yellow Springs Instrument 6920 Sonde |

For this study, three components of the datalogger were looked at; the turbidity sensor (a Campbell Scientific OBS 3+ sensor), the specific conductance meter (a Campbell Scientific CS547A probe), and a pressure transducer.

# VITA

Caroline Mierzejewski graduated from the University of Illinois, Urbana – Champaign with a bachelor's in science from the department of Geology in May 2017. She was part of an undergraduate thesis project that was working on examining and describing an orthopteran fossil specimen to figure out if it was a new species. A native of Illinois, Caroline ended up at Louisiana State University as a graduate student to obtain a master's degree in Geology and Geophysics. Here she has been studying under Dr. Carol Wicks, researching karst hydrology and sediment movement in cave systems. After graduation, Caroline hopes to pursue a career in education, teaching others about the Earth and geology.