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Editorial

Generation and Propagation of an Urban Flash Flood and Our Collective Responsibilities

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0 INTRODUCTION

Destructive flash flooding is a growing global problem, with dangers being particularly acute in densely populated urban areas. The intensity of rainfall events is increasing, creating high runoff rates that are further accelerated by high impervious cover, channelized streams, and storm sewers. Intense storms of only a few hours duration can cause the water levels of small urban streams to rise more than 3 m/h. Dangers and damages are magnified in such areas because large populations are uninformed yet proximal to small flashy streams, particularly where roads, homes, and businesses have been built in their floodplains.

The record flash flood of July 26, 2022 in St. Louis, Missouri provides an illuminating example of the issues at hand. The community of University City was hardest hit, as this town of only 35 000 residents experienced a fatality, >$30 M in damages, and had >300 homes condemned. Early morning rescues of >50 citizens by University City's first responders and others by citizen Samaritans prevented many additional fatalities. The worst flooding occurred along the upper River des Peres (uRdP), recently identified as the flashiest stream in Missouri for its size (Criss, 2022). As discussed below, underlying problems include extensive impervious area, historical development of floodplains, and local governments that have promoted new floodplain developments and projects that increase impervious cover, magnifying both flood levels and potential damage.

This report will present what may be the most detailed record yet available of the generation, progress, and inundation zone of a highly destructive urban flash flood. This unique record underscores the great dangers, damages and frequency of urban floods, and the multiple responsibilities that governments, professionals and individuals must collectively share to minimize their impacts.

1 HYDROGEOLOGIC DESCRIPTION

Most of University City is located within the watershed of the upper River des Peres. This stream heads in the community of Overland located immediately to the west, and runs generally ESE along its ~10 km-long thalweg, more than half of which has been straightened and channelized with cement or rock walls and bottom. The stream then enters the large, 6.5 m diameter upper entrance to the River des Peres tunnel, which was constructed during 1927–1940 (ASCE, 1988). The basin above the upper tunnel entrance has an area of 25.7 km^2, is more than 43% impervious area (Southard, 2010), and features a topographic drop from about 220 to142 m above sea level.

The River des Peres tunnel runs generally southeastward for 5.5 km, picking up additional tributaries and storm sewers along the way, while increasing to two tubes that each are 9 m in diameter. The large tunnels debouch into the open, rock-lined channel of the lower River des Peres, a small tributary to the Mississippi River. Criss and Nelson (2022) provided a DEM that showed the entire River des Peres watershed and these various features.

2 EVENT SYNOPSIS

On July 26, 2022 a series of training thunderstorm cells delivered intense rainfall in a 15-hour period along a narrow, ~10 km-wide, 400 km-long ESE belt that extended across Northeast Missouri and Southwest Illinois (NWS, 2022a). More than 23 cm of rainfall were reported for this period by the official St. Louis weather station operated by NWS (2022b); the three rain gauges operated by University City reported totals of 24.5, 24.4, and 24.1 cm (UCFWS, 2022). The latter gauges received an average of 11.76 cm during the most intense, 2.5-hr interval of this storm, when rainfall delivery was nearly steady. Widely reported statistics are that this was a "1000-year" storm based on the 6-hour rainfall delivery, or a "500-year" storm based on the 12-hour delivery (cf. NOAA, 2017). While appropriate for the storm, these extreme metrics are inappropriate descriptors of the widespread flash flooding that accompanied this event (see below).

3 METHODS

A comprehensive network of hydrologic monitoring stations was in place in University City on July 26, 2022. First, the city has established a flood warning system based on rainfall received in 5 minute intervals at three, 20.3 cm diameter rain gauges in the basin (UCFWS, 2022). A forthcoming report will describe this system and its remarkable performance during the July event.

Second, nine submersible level loggers were deployed by

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UCFWS in March 2022 along the uRdP channel that record water temperature and total pressure at 5 minute intervals. All units operated as designed during the July event, and an additional unit recorded local atmospheric pressure. Thus, water depths can be easily determined from the pressures measured by the in-stream sensors, by making standard corrections for barometric pressure and for temperature-dependent water density. Stream gauge 07010022 on the uRdP also recorded water levels at 5 minute intervals and is calibrated for discharge; additional gauges 07010030 and 0710035 provide data for two downstream tributaries (USGS, 2022; Criss and Nelson, 2020).

Third, the Missouri Department of Transportation established an extensive system of topographic benchmarks in St. Louis County (MODOT, 2020). MODOT also maintains a network of stationary GNSS transmitters that, along with the GPS satellites, allow the rapid determination of site elevations to ±2 cm by a standard GNSS receiver. The elevation of peak flood levels at 80 sites within the uRdP basin were established by survey of seed lines and leaf lines using a GNSS receiver and a total station, by the level loggers and gauging stations, and in a few cases by strand lines, event photographs and interviews. Accuracy for most of these peak flood elevations is estimated to be better than ±5 cm, but those based on photographs, strand lines, and interviews are considered to be less reliable.

Finally, an accurate digital elevation map (DEM) with 1-m resolution (0.03 arcsecond) is available for most of St. Louis County, including all of the River des Peres basin and its tributaries (MSDIS, 2021). Comparison of this DEM with benchmark elevations and our own GNSS data suggest that the vertical accuracy of this DEM is typically better than ±25 cm, so basin topography is very well known. Criss and Nelson (2022) provided details about this DEM, which they annotated to show the boundary of the River des Peres and several important features. They also described their new QGIS method, used below, to prepare detailed inundation maps using a DEM and flood mark elevations.

4 THE JULY 26, 2022 FLASH FLOOD IN THE UPPER RIVER DES PERES

4.1 Hydrologic Response

The stage hydrographs in Fig. 1a show how the water level along the upper River des Peres varied during the flash flood, as recorded by multiple sensors along the channel. Sensors 5, 6 and 10 are affected by proximal, undersized bridges and are not shown. The stream was nearly dry before the storm, being no more than a few cm deep at the gauged sites, but quickly rose by as much as 5 m to the record peak at about 5:10 A local time (GMT 10:10 A). The sharpest hourly rise at sensor 8 was 3.39 m, recorded between 1:20 to 2:20 A, but during the next 3 hours the stream rose another 1.3 m.

The discharge hydrographs in Fig. 1b compare the estimated flow at sensor 8 during the flash flood, as calibrated by USGS (2022), with the flows predicted by a theoretical model whose constants are fully constrained (Criss, 2022; Criss and Winston, 2008). The discrepancy between the USGS calibration and the theoretical model is significant, with the latter predicting a higher, earlier flow peak. Much of the discrepancy may be due to the limited capacity of the uRdP tunnel and the undersized Pennsylvania Ave. bridge to convey the high flows that arrived, causing the stream to back up, and high water levels to persist for a longer period. The channel at the tunnel entrance was overwhelmed for the first time since it was constructed in 1940. This caused water to deeply inundate the area immediately upstream, and forced the flow to continue above ground far to the east of the tunnel entrance, causing a fatality and much damage to homes, businesses, and the Metrolink train.

4.2 Flood Statistics

Hypothetical flood profiles calculated by HUD (1977) and FEMA (2015) are basically identical and suggest that the 2022 flood was a 50 to 100-year event along most uRdP reaches, except close to the tunnel entrance where flooding was much worse. Moreover, water levels have been measured at the USGS stream gage on the upper River des Peres since 1997, and the series of annual peaks can be used to independently estimate the probabilistic return period of the 2022 flood. Assuming a normal distribution of the peak annual levels and standard equations (Chow 1964), the 2022 flood was less than a “100-year” event. Statistical calculations that incorporate historical trends (method of Criss 2016) suggest that the return period is closer to 50 years. Given that the period of record is shorter than these statistical return periods, more detailed estimates are not justified. Nevertheless, these estimates are congruent with those tabulated by Southard (2010), and with those calculated with his empirical “urban regression equations” based on basin area and impervious coverage, which likewise suggest that this flood was approximately a 50-year event.

So, why the disconnect between the widely-reported, 500 and 1000-year return period for the July rainfall event, and the ~50 year return period for the associated flash flood? The reason is that the 2022 flood peak occurred before 6 hours of rainfall had occurred, so the statistical metrics for rainfall received in intervals of 6 hours or more have nothing to do with the record flood peak. Moreover, because of the hydrological lag times, peak flood flows invariably arrive significantly later than the causal rainfall, so the rain that caused the 2022 flood peak occurred during an even shorter period.

In the particular case of the upper River des Peres, the hydrologic time constant is close to one hour (Criss, 2022), and correlations show that this stream responds most strongly to intense rainfall delivered in a 75 minute interval. Thus, the statistical return periods of the rainfall received in 1 or 2-hr intervals, and not for rainfall delivered in 6 or 12 hour intervals, provide the appropriate metrics for the associated flooding. During the most intense parts of the July 26 storm, 6.07 cm were received in one hour and 10.0 cm were received in 2 hr. The NOAA (2017) tables indicate rainfall return periods close to 20 and 85 years for these intensities, respectively, and these periods are congruent with the independent estimates based on stream gauging. In short, this was a ~50 year flash flood.

4.3 Flood Wave

Given precise knowledge of their *xyz* positions, the level loggers deployed along the uRdP channel provide information about water depths and water surface elevations (WSEL), channel and floodwater slopes, and the dynamic propagation of the

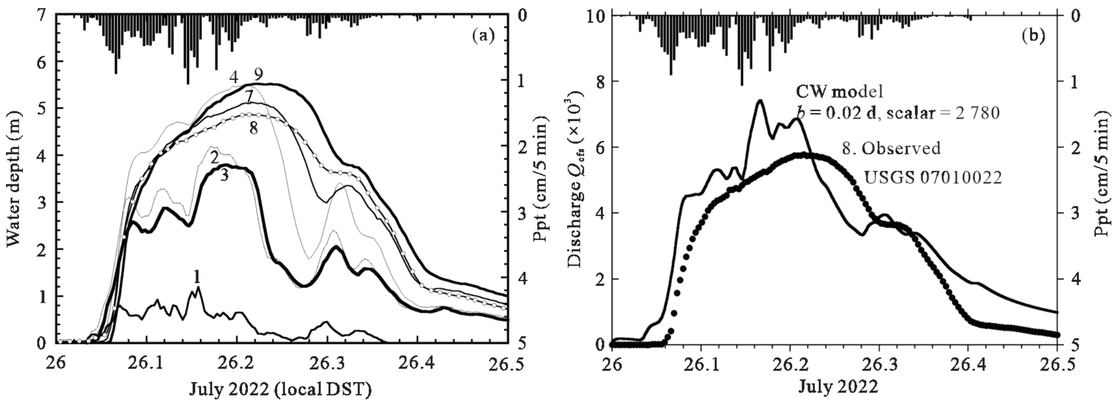

Figure 1. (a) Stage hydrographs from midnight to noon for the July 26 flood event, as recorded by multiple sensors identified by number (see Table 1). Also shown is the average rainfall recorded in 5-minute intervals by the three rainfall sensors in the basin (black bars, right inverted scale; UCFWS, 2022). (b) Graph of discharge vs. time for the July 26 flood event, as estimated in cfs by USGS, compared to a theoretical rainfall-runoff model (Criss and Winston, 2008) whose constants are fully constrained (left scale).

Table 1 Peak water levels and arrival times at ten monitored sites

Proximal bridge	Thalweg distance (m)	2022 WSEL, m MSL	#Peak Time, 7/26/22 AM	*Easting (m)	*Northing (m)	†Channel bottom (m)
1. Dielman	1 825.2	177.12	3:45	728 230	4 284 797	175.92
2. Kempland	3 986.1	167.53	4:05	730 026	4 284 711	163.34
3. Grant	4 805.8	164.63	4:30	730 555	4 284 313	160.83
4. Olive	5 976.9	162.14	5:05	731 235	4 283 818	156.65
5. Groby us	6 251.7	161.53	5:00	731 359	4 283 595	156.00
6. Groby ds	6 287.4	161.21	5:05	731 380	4 283 568	155.78
7. Chamberlain	7 589.2	158.01	5:10	732 348	4 283 208	152.89
8. Purdue	8 473.4	155.85	5:13	732 840	4 283 365	150.97
9. Vernon	9 412.6	154.27	5:15	733 436	4 282 814	148.75
10. Pennsylvania	9 578.1	153.39	5:40	733 562	4 282 736	148.52

#Local time of flood peak arrival, equal to GMT-5; *UTM Zone 15; †Surveyed sensor elevation, which closely approximates the channel bottom.

flood wave. Table 1 provides the information recorded by these nine sensors during the July 26 event. Also included in the table is data for the USGS stream gauge #07010022 at the Purdue Avenue footbridge (#8; USGS 2022).

The propagation of the flood peak down the uRdP channel was recorded by the peak arrival times at the ten measuring stations (Fig. 2a, Table 1). The slope of the regression line indicates an average propagation speed of 3.9 km/h, but the flood peak progressed faster along much of the lower channel. Note that heavy rainfall began after 1: 00 AM, that the flood peak reached all stations after only a few hours of intense rainfall, and that rain continued to fall long after those peaks had passed.

Figure 2b shows how the elevation of the channel bottom and the 2022 flood water surface vary along the upper River des Peres. Although the trends have a small upward curvature, along much of the channel the peak water surface decreased nearly linearly, with a dimensionless slope of 0.002 4 m/m. Water depth, represented by the vertical difference between the curves, tends to increase downstream. Closely spaced sensors were deployed to study the effects of undersized bridges, which can back up water and impede propagation.

4.4 Inundation Map

An inundation map of the 2022 flood was prepared by applying the method of Criss and Nelson (2022) to the data recorded by our in-channel sensors, plus the surveyed levels at > 70 additional points (Fig. 3). Most of the latter represent seed lines and leaf lines, but where data were few, swash lines, photographs, or interviews were used, and reliability is lower. Note that this map of peak water levels does not depict an instantaneous surface, due to the rapid propagation of the flood wave and the short duration of the flood event (Fig. 2a). For that reason, no single satellite or aerial image can accurately capture the area inundated by an urban flash flood.

Water depths were greater than those documented for prior floods at all sites along the channel where we have information (cf. Criss and Nelson, 2022; Hauth and Spencer, 1971). Relative to the 2008 flood, the 2022 flood was deeper by about 25 cm in the Olive to Chamberlain reach, by nearly 60 cm at the USGS gauge, and by >100 cm near the tunnel entrance. Much of this effect, and the inundation to the east of the tunnel entrance (Fig. 3), resulted because the RdP tunnel was overwhelmed for the first time during the 2022 event. The uRdP

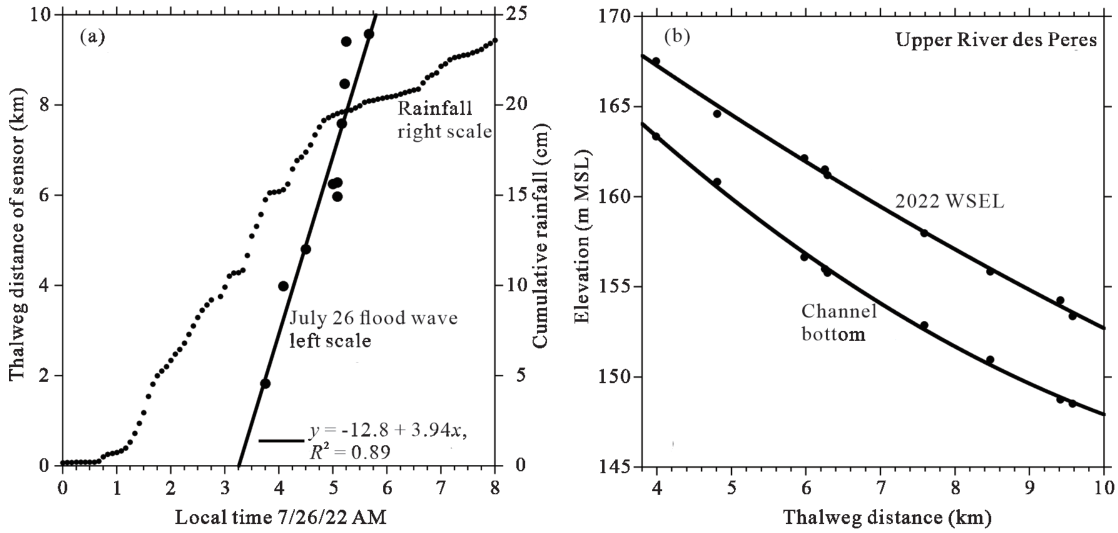

Figure 2. (a) Propagation of the 2022 flood wave as recorded by in-stream sensors, at an average indicated rate of 3.9 km/h (large dots and regression line, left scale). Small dots (right scale) show cumulative rainfall, represented by the average of the three rain gauges in the basin (UCFWS, 2022). (b) Elevation of the channel bottom, as closely represented by the sensor locations, compared to the peak water levels (WSEL) recorded by those same sensors. The uppermost site at Dielman is not shown. Curved lines are simple quadratic fits to the depicted points.

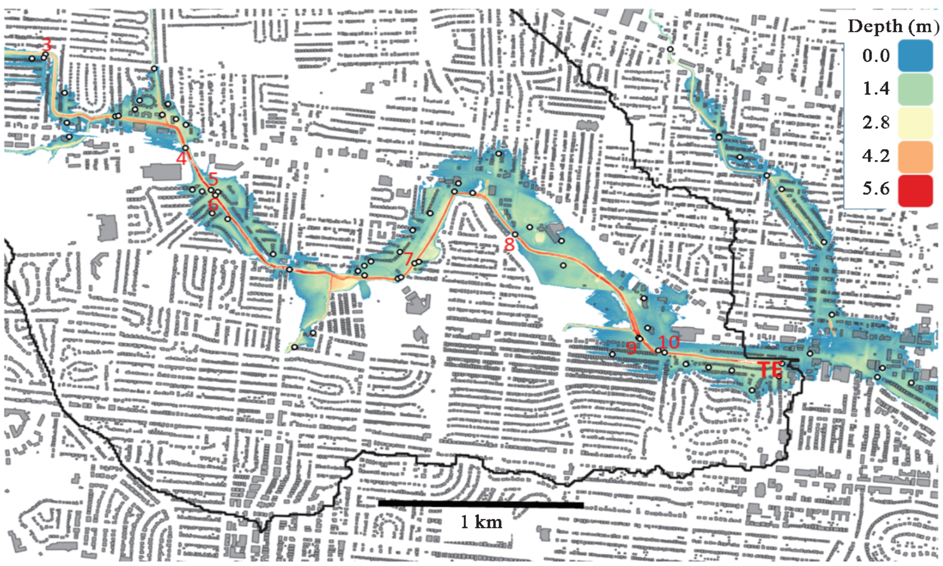

Figure 3. Inundation map for the July 26, 2022 event showing color-coded water depth (shading) along the uRdP thalweg (red line) in University City. Black line is the watershed boundary above the tunnel entrance (red TE); note the deep inundation of the area to the east. Gray rectangles are buildings. White dots are locations where water levels were measured; those numbered in red from 3 to 10 refer to the monitored sites in Table 1. Upstream sensors 1 and 2, as well as 10 surveyed points, are offscale. See text.

channel was also overtopped for the first time to the south of sensor #3, causing water to flow south and downhill along Grant Ave. (Fig. 3).

5 DISCUSSION

Urban flash flooding is a growing international problem. Urban flash floods differ and in many ways are more serious than regional floods of large rivers because of their sudden, unexpected development, and because their rapid increases in water levels occur proximal to large populations and valuable infrastructure. Intense storms of short duration are becoming more frequent, aggravating problems caused by urban development that include high impervious cover, channelized and narrowed streams, reduced natural storage, destroyed riparian borders, and extensive storm sewer networks, all of which accelerate the delivery of floodwater to streams. Efforts to compensate for these problems are being made at a slower pace than new construction projects aggravate them.

The sensor network installed before the July 2022 flash flood may have measured the most detailed record yet available for the progress of an urban flash flood. The detailed inundation map provided by this network and by our subsequent, intensive survey effort should help define effective response strategies. Though expensive, we advocate the buyout of repeatedly flooded, low-lying properties, and the floodproofing of buildings subject to basement flooding, as being the most effective strategies. Construction of large detention basins will also help. Stronger realty disclosure laws are also needed. At the very least, building codes must be strengthened so that urban flash flooding is not further and unnecessarily aggravated.

In short, flooding is becoming worse, and minimizing the problem will require serious effort and cooperation between homeowners, businesses, developers, scientists, engineers, and government. Homeowners need to become more aware of flooding problems, and to learn about strategies they can use to protect themselves from flash floods, and in appropriate cases, to floodproof their homes. Citizens must also understand that most flood fatalities in Missouri are related to vehicle use, particularly with the countless attempts of motorists to drive across inundated bridges and low areas, only to discover how quickly they can be trapped in an inundated, powerless car. Scientists and engineers need to conduct expert, data-driven studies of flooding, and then provide appropriate advice to public citizens and governments. Developers, businesses, and realtors need to learn about the dangers of continued floodplain development. Governments must listen to experts, maintain appropriate zoning of low-lying lands, assist with buyouts and floodproofing of low-lying properties, and modify construction codes in ways that minimize flood aggravation. The establishment of a Stormwater Commission by University City, and its assistance in establishing the monitoring network described here, is a fine example of a first step, but a great deal more needs to be done.

6 CONCLUSIONS

The flood of July 26, 2022 along the upper River des Peres in University City, Missouri provides a startling example of a highly destructive urban flash flood. The dynamics of this flood were recorded by a concentrated network of rain gauges and in-stream level loggers, whose data were augmented by intensive post-event surveying of marks indicting peak water levels. Though the causal storm featured the extraordinary, >500-year delivery of 24 cm of rainfall in 15 hours, the stream responded most strongly to the 10 cm of rain delivered in about 2 hours. The latter amount, and the historical record of flood levels at the gauging station (USGS, 2022), suggest instead that this was closer to a 50-year event. Exaggerated return periods are commonly used to describe flood events, which misleads the public as to their actual frequency and the growing danger.

Water depths during the July flood increased as rapidly as 3.3 m/h. In-stream sensor data show that the flood pulse moved at an average rate of 3.9 km/h down the channel. An area greater than 1.5 km^2 was inundated in University City alone, resulting in the condemnation of >300 homes. The River des Peres tunnel was overwhelmed for the first time, causing inundation downstream of its entrance that resulted in a fatality and in the serious interruption of the urban transit rail system. The inundation map provided here may be the most accurate yet available for an urban flash flood, and should be a valuable asset in future planning.

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REFERENCES CITED

ASCE, 1988. The River des Peres... A St. Louis Landmark. [2022-10-19]. http://sections. asce. org/stlouis/History/files/River% 20des% 20Peres%20%20A%20St.%20Louis%20Landmark.pdf

Chow, V. T., 1964. Handbook of Applied Hydrology. McGraw-Hill, New York

Criss, R. E., Winston, W. E., 2008. Discharge Predictions of a Rainfall-Driven Theoretical Hydrograph Compared to Common Models and Observed Data. *Water Resources Research*, 44(10): W10407. https://doi.org/10.1029/2007wr006415

Criss, R. E., 2016. Statistics of Evolving Populations and Their Relevance to Flood Risk. *Journal of Earth Science*, 27(1): 2–8. https://doi. org/10.1007/s12583-015-0641-9

Criss, R. E., 2022. Hydrologic Time Scale: A Fundamental Stream Characteristic. *Journal of Earth Science*, 33(5): 1291–1297. https://doi.org/10.1007/s12583-022-1655-8

Criss, R. E., Nelson, D. L., 2020. Discharge-Stage Relationship on Urban Streams Evaluated at USGS Gauging Stations, St. Louis, Missouri. *Journal of Earth Science*, 31(6): 1133–1141. https://doi. org/10.1007/s12583-020-1089-0

Criss, R. E., Nelson, D. L., 2022. Stage-Based Flood Inundation Mapping. *Natural Hazards*, 112(3): 2385–2401. https://doi. org/10.1007/s11069-022-05270-6

FEMA, 2015. Flood Insurance Study, St. Louis County, Missouri. Volumes 1–4. Study number 29889CV001A.

Hauth, L. D., Spencer, D. W., 1971. Floods in Coldwater Creek, Watkins Creek, and River des Peres Basins, St. Louis County, Missouri. U. S. Geological Survey Open File Report 71-106. [2022-10-19]. https://pubs.er.usgs.gov/publication/ofr71146

HUD, 1977. Flood Insurance Study, City of University City, St. Louis County, Missouri. U. S. Dept. of Housing and Urban Development, Washington D.C. 21

MODOT, 2020. St. Louis County Benchmark System. [2022-10-19]. https://stlouiscountymo.gov/st-louis-county-departments/transportation-and-public-works/roadway-publications-and-manuals/dot-survey-bench marks-current/survey-benchmark-manual/

MSDIS, 2021. Missouri Spatial Data Information Service. [2022-10-19]. https://data-msdis.opendata.arcgis.com

NWS, 2022a. July 26th, 2022 Historic Flash Flooding in the St. Louis Metro Area. [2022-10-19]. https://www. weather. gov/lsx/July262022 Flooding

NWS. 2022b. NWS Forecast Office St. Louis, MO. [2022-10-19]. https://www.weather.gov/lsx

NOAA, 2017. Atlas 14 Point Precipitation Frequency Estimates: Missouri. [2022-10-19]. https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html

Southard, R. E., 2010. Estimation of the Magnitude and Frequency of Floods in Urban Basins in Missouri. USGS Scientific Investigations Report, SIR 2010-573, Rolla, MO. 27

UCFWS, 2022. University City Flood Warning System. [2022-10-19]. https://www.wqdatalive.com/public/147

USGS, 2022. Real Time Data for Missouri. [2022-10-19]. https://waterdata.usgs.gov/mo/nwis/rt