Minneapolis sinkhole, circa 1952. Credit: Minnesota Historical Society

FRESHWATER

FINAL REPORT

Hennepin County Bedrock Collapse Project

G. Brick, B.J. Bonin, and C.E. Jennings

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Abstract

"Urban sinkholes are an emerging Anthropocene geohazard" (Dixon et al., 2017) and two of the greatest disasters in Hennepin County are associated with the consequences of bedrock collapse: the 1869 Eastman Tunnel disaster, and 1880 collapse of Chute's Cave creating the largest sinkhole in Minnesota, at 300 feet in diameter (Brick, 2009). Hennepin County Emergency Management contracted Freshwater and Midwest Geological Consultants to identify areas where bedrock collapse could lead to sinkholes.

"Sinkhole" covers a wide range of phenomena, ranging from potholes in the street to meteorite craters. Here it refers to collapse features in limestone or sandstone that result from natural or human undermining. Increased precipitation intensity has the potential to lead to more occurrences of undermining, raising sinkhole risk. In addition to being a direct threat to life, sinkholes can damage property, infrastructure, disrupt water and sewer infrastructure and obstruct roadways.

We prioritized shallow bedrock areas (less than 100 feet) and areas near bedrock valleys, because they are more susceptible to cave- and sinkhole-forming processes. Downtown Minneapolis, Nicollet Island, W. River Parkway, and Minneapolis-St. Paul International Airport were priority areas; additional areas were investigated as a result of community reporting and other data. A "new" source of information—namely, construction records for sanitary sewers and storm drains in Minneapolis—contained valuable geological details that were used to further refine risk areas.

Hennepin County Emergency Management will use results of this investigation to highlight risk to the public, similar to their landslide atlas, allowing stakeholders to take action to mitigate that risk.

DISCLAIMER

The information and maps contained in the Hennepin County Bedrock Collapse Hazard Atlas shall be considered advisory and shall not require the development of any new policy by, or impose any new policy on, any government or private entity. The atlas is made available to inform local governments and the general public regarding the risks of bedrock collapse, karst, or sinkhole hazards in Hennepin County. It is not intended to provide detailed site-specific information or replace on-site geotechnical investigation.

Hennepin County makes no representations or warranties regarding the accuracy of the data or maps contained in this atlas. Neither Hennepin County, its Emergency Management Department, nor any sinkhole study partners shall be liable under any circumstances for any direct, special, incidental, or consequential damages with respect to any claim by any user or third party on account of or arising from the use of these data or maps. Users should cite Hennepin County Emergency Management and this atlas as the original source of the data and also should clearly denote cases where the original data have been updated, modified, or in any way altered from the original condition.

There are no restrictions on distribution of the written information or reproduction of maps created from the graphics files. Broad distribution is encouraged in order to support more effective hazard mitigation. Any modification made should be indicated and attributed.

Introduction

“Urban sinkholes are an emerging Anthropocene geohazard,” according to Dixon and others (2017). Two of the greatest disasters in Hennepin County history are associated with tunnel driving in the St. Peter Sandstone, an extensive unit that is shallowly buried in Minneapolis, viz., the 1869 Eastman Tunnel disaster, and the collapse of Chute’s Cave in 1880, which created the largest sinkhole in Minnesota history, with a diameter of 300 feet (Brick, 2009). Recognizing the potential for significant impact from such events, Hennepin County Emergency Management contracted with Freshwater and Midwest Geological Consultants to use existing records to identify areas where the risk of bedrock collapses leading to sinkholes is higher, thereby avoiding disasters like those that occurred earlier in the region’s history.

The term sinkhole can cover a wide range of phenomena, especially amongst laypersons, ranging from potholes in the street to meteorite craters. In this report, and geology more generally, it refers to collapse features in rock, typically limestone, usually due to undermining. In Hennepin County the cave-forming unit and therefore sinkhole unit is not limestone; it is a weakly cemented silica-sand rock layer. Silica is comparatively insoluble (unlike limestone) so the caves form as a result of the physical removal of the sand by natural or human activities with limited dissolution. Sinkholes occur when the overlying material is thin and collapses into the void, often when it becomes large enough to span joints in the overlying Platteville limestone, if present. This is different from Florida-type sinkholes, which form in the groundwater mixing zone of fresh and saline water with collapse occurring into pre-existing limestone voids that have been drained of supportive groundwater, possibly by the overdraft of nearby water wells. See Figure 1 for a generalized example.

In this paper we introduce a “new” source of information for investigating urban sinkholes, namely, the original engineering records for sanitary sewers and storm drains. In Minneapolis, at least, they show geological details in the profile view, which in many cases, though drafted by non-geologist construction foremen or engineers, can be reliably interpreted. Some of these sketches (see figures below) are quite old, dating to the late 19th century, and were later illustrated with beautiful water colors. These maps have been used by speleologists to study bedrock

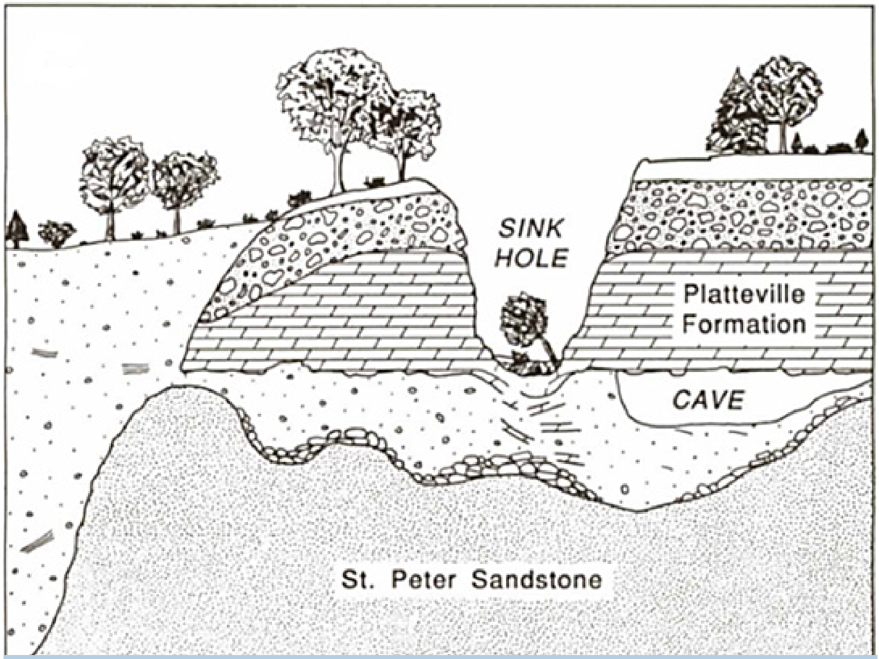

Fig. 1. Sinkhole formation near buried bedrock valley, Twin Cities metropolitan area. Removal of supporting sand to the buried valley when it was a surface valley in pre- or interglacial times, or incomplete filling of the cave leads to collapse of the overlying limestone and soil, forming a sinkhole. Swanson, L.; Meyer, G.N. (1990).

voids in the St. Peter Sandstone below the Minneapolis downtown area (Brick, 2009).

Climate data show a clear trend of increasing intense rainfall events across Minnesota (Metropolitan Council, 2018). More intense rainfall events will test the capacity of stormwater conveyance systems, which may increase the risk of bedrock collapse in areas that may already be at risk. Intense rainfall events can pressurize storm drains and sewers, which forces water out of joints and other weak spots in the piping system into bedrock voids left behind from the tunnelling process. When the water drains back into the storm drain afterward, it usually carries fragments of bedrock (in this case, sand), so the void on the outside of the storm drain grows, which can lead to pipe failure and ground collapse at the point of failure.

Intense rainfall can also overwhelm the capacity of a local drainage system, which includes both surface flow and storm drain conveyance, which may cause erosion and flooding. In addition to pipe failure and flooding, excess water also accelerates the natural processes that cause sinkholes that result from geologic processes to form. This underlying level of risk is understandably overlooked by public works officials and emergency planners, as maintaining these systems is a public safety priority.

Identifying these areas of risk, and quantifying them to some degree, is the goal of this report. Bedrock collapse and related sinkhole formation can cause loss of life and property as well as serving as conduits for contaminants to enter into groundwater and surface waters. Providing Emergency Managers with a framework to identify geologic hazards is a necessary first step in planning how to respond when a bedrock collapse event happens.

Background

Bedrock collapse and the resulting collapse of the overlying sediment is a natural hazard in Hennepin County. There are historical examples of this occurring in the county, as well as documented pre-settlement sinkholes within the county borders. Although bedrock collapse is a natural phenomenon, the risk of new collapses is increased by human activity and increased intense precipitation events related to climate disruption. As the formation of a geologic sinkhole due to bedrock collapse puts lives at risk, disrupts infrastructure and would result in destroyed property, these hazards must be understood and addressed in order for response and mitigation efforts to be enacted.

Until this assessment, there were no comprehensive surveys of the bedrock collapse hazard in Hennepin County. Detailed, countywide, geologic-sinkhole data have not been available to assist public officials, businesses, and residents in making decisions that could prevent or reduce their risk.

PREVIOUS MINNESOTA SINKHOLE STUDIES

Gao and Alexander (2008, and additional publications by them) have investigated sinkhole distribution in the karst counties of southeastern Minnesota. The Twin Cities is at the far northern tip of their area of consideration. A summary of the history of sinkhole investigations in Minnesota is given by Alexander and Brick (2020).

Gao established three karst groups based on Paleozoic stratigraphy. Hennepin County falls into the third, lowermost, karst group, which includes Lower Ordovician units, including the Platteville and St. Peter formations with the intervening Glenwood Shale. Paradoxically, while the Ordovician Decorah Platteville Group falls into Gao's "Low Probability" category, the shallow depth to bedrock is almost everywhere below Gao's own 50-feet-of-cover criterion, which thus restores it as high probability. But while more avowedly karstic counties have thousands of sinkholes, Hennepin County does not have enough to conduct a Nearest Neighbor Analysis that yields reliable predictive results. Another method of predicting sinkhole locations is to conduct an analysis of linear surface features that may relate to joint sets in the shallowly buried bedrock (lineaments). Steenberg and others (2011) mapped vertical fracture traces on a small scale at several Twin Cities outcrops, but did not project them as lineaments. There are insufficient Platteville lineaments to make viable interpretations of preferred orientations.

THE CAVE UNIT

As early as Frizell (1883) it was noted, in the wake of the catastrophic Eastman Tunnel debacle, that "The softest stratum at the [St. Anthony] falls is 16 to 22 feet below the bottom of the [Platteville] limestone. The attempt to excavate in this stratum and to keep excavations clear by pumping, has resulted in extensive and dangerous cavities." This was formalized more than a century later by Mazzullo and Ehrlich (1987) as the "Cave Unit." We investigated and extended the model of Mazzullo and Erhlich (1987) from Ramsey to Hennepin County (Bonin et al., 2020) which correlates the formation of voids in the St. Peter Sandstone bedrock underlying Minneapolis with tunnel driving in the so-called "Cave Unit" in the middle of the sandstone. This actually suggests a predictive model for bedrock collapse (e.g., Galve et al., 2009; Khomenko, 2008). Our investigation identified that cross-bedded layers of St. Peter Sandstone displayed more erosion features and excavations, whether by human activity or by other wildlife such as birds, than the massive sections of sandstone outcrop. Further, we observed that seepage within the St. Peter Sandstone occurred at the top of the massive sections, indicating a greater degree of cementation. However, we found that geophysical log data were not sufficient to identify the Cave Unit away from outcrops.

Cave unit in the St. Peter Sandstone

KNOWN INSTANCES OF BEDROCK COLLAPSE

Sinkholes form low-lying areas that fill up with sediment over time. Often these topographic depressions will be filled to facilitate construction or development. Historical sinkholes from bedrock collapse may not take the form of the classic sinkhole (e.g., the Seven Oaks Oval Park in Minneapolis). Construction records are an important resource—and in an urban area often the only resource—to identifying collapse features. Filled sinkholes can cause both differential compaction and corrosion issues, as the fill is often of a different geological material than the surrounding area.

Sinkholes from bedrock collapse or subsurface erosion can form in unconsolidated sediment that overlies the bedrock. One example is located in Minneapolis, south of Minnehaha creek near Nicollet, Blaisdell, and Wentworth avenues south. Two substantial topographic depressions overlying a buried bedrock valley are located in this area and are used locally for drainage. The easternmost one is filled, but the boundary between the fill and the native sediment appears to focus drainage and causes small (1–3 meter) sinkholes to form along this boundary (investigated by the authors as part of this study). The western depression is not filled, and the land was developed around the depression, which does not hold water. The bedrock underlying this area is Ordovician St. Peter Sandstone at a depth between 15 and 30 meters (50 and 100 feet).

Identifying other areas like this one with follow-up investigations to determine the need for collapse mitigation was one goal of this study. What makes this area significant is that it is located far from an area of active bedrock erosion such as the Mississippi River gorge and is instead related to buried eroded bedrock that presents a hidden risk. A (geologically) small collapse of the sandstone at this depth would cause the washout collapse of the overlying sediment of a wider area but roughly equal volume to the bedrock collapse. For example, the vertical fractures in sandstone that opened up at Dancing Waters in Washington County, Minnesota, in 2005, caused a large-footprint sinkhole due to sediment that was washed into the fracture by rapid surface water flow (Barr and Alexander, 2009).

Man getting out of his car after driving into a sinkhole, 1942. Credit: Minnesota Historical Society

WATER MAIN LEAKAGE

A different cause of collapse relates to leakage from water mains (Clark, 1960). In neighboring St. Paul, there's a history of void formation in the St. Peter Sandstone bedrock by leaking water mains installed in bedrock tunnels and left untended for long periods of time. If a leak begins, the water can begin eroding a void which, upon attaining sufficient size, will intersect the land surface above and collapse, causing a crown hole (Waltham, 1993). In Minneapolis, these conditions apply mostly to Nicollet Island, where pressurized pipes are laid in sandstone tunnels, rather than being buried per se, as in the downtown area. The sandstone remains competent as long as it is dry, but when it becomes a conduit for groundwater in the vicinity of a cliff edge or void, it disintegrates (Dobereiner and Freitas, 1986; Waltham, 2016).

However, water mains are of interest for void formation even when they are not immediately in contact with bedrock, because they are one end of the "source and sink" necessary for voids to be scoured out, being the source of concentrated flow that could find outlet in a sink or incipient void, perhaps initially almost invisible, that will grow and later collapse. The sink includes both water and sediment, as unaccounted-for sediment from a water main or sewer break has to go somewhere. Where sediment seems to have disappeared after a pipe failure, this should be considered a warning sign that a bedrock collapse is possible in the area. In any case, it has been established elsewhere (e.g., Goluter and Kazemi, 1988; Wengstrom, 1993) that once a leak has appeared in a certain location, the very act of fixing the leak predisposes that location to further leaks and collapse, owing to ground disturbance and the subsidence of fill materials, as well as possible galvanic reactions between the new and old pipe materials.

In addition to "source and sink" interest as described above, differences in geology along the length of a pipeline can contribute to pipe failure. There are two general ways that this can happen: 1) change in geological materials and 2) change in compaction. Geological materials (clay, sand, limestone) have different chemical characteristics that especially affect metal pipes. Sand and sandstone have little impact on metal pipes, but clay and organic materials tend to corrode pipes and fittings, often rapidly, leading to pipe system failures. In addition, differences in compaction of geological materials can lead to shear stress along boundaries that can fracture pipes. As sinkholes are an extreme example of a difference in compaction that can shear pipes, noting where water and sewer repair clusters are located may be an indication that the underlying bedrock is at risk of collapse.

Methods

Bedrock collapse and related sinkhole formation is a natural process, or more accurately is a category that includes several distinct natural processes that act alone or in concert to produce sinkholes that affect the built environment. Human activity and climate disruption can accelerate the processes of collapse and sinkhole formation. Sinkholes may appear at the ground surface in response to changes in the volume of material below a particular point on the ground. This can be the result of rotting tree roots that leave a void once the rotten wood is consumed, compaction of fill that reduces volume by increasing the density of the material present, or by removal of material through erosion, which then creates a void.

As examples of bedrock collapse in the Hennepin County historical record are not particularly abundant, and the processes that cause collapse are both out of sight (i.e., underground) and ongoing, geological study was necessary to identify areas where collapses had occurred in the past as well as the geological conditions that lead to collapses.

The authors of this study examined historical records (e.g., newspapers, technical reports, etc.) that documented collapses in and around Hennepin County, as well as construction records for buried utilities were examined for collapse features.

In addition, Minnesota Public Radio interviewed the study's authors, which resulted in 29 sinkhole reports from the public—28 of these were investigated in the field (one that was not investigated was located in Rice County and was outside the scope of this project.)

To expand the search for collapses, the authors examined the Minnesota Well Index and the Minnesota Geological Survey's Borehole Geophysical Database, conducting searches to identify features in sandstone that could be useful in predicting collapses, such collapse-prone sandstone and large voids in carbonate rock. The authors also examined bedrock outcrop to identify specific portions of geological formations, most notably in the St. Peter Sandstone, that are especially prone to collapse and erosion.

GEOLOGIC ASSESSMENT

The key to this work was to search for records of caves and sinkholes using historical archives and field work where possible. We prioritized by depth to bedrock (0–50 feet first then 51–100 feet) because shallowly buried bedrock is more vulnerable to collapse than bedrock that is buried beneath a thick blanket of sediment. Examples of historical caves and sinkholes include Chute's Cave, Schieks Cave, the Nicollet Mall cave, the collapses of the mill run in 1869 near Nicollet Island and St. Anthony Falls, as well as the 34th Street Cavern along West River Parkway (Fig. 2). Related to this, the authors searched for indications of additional, isolated features along buried valleys. Sinkholes can open up on the slopes of valleys that were once at the surface but are now filled. Where bedrock valleys had formed in the past and filled with glacial sediment, the caves and voids along the edges of these valleys may have been incompletely filled. The buried caves and voids can still collapse, or act as a conduit to convey water and sediment from the surface, and form sinkholes.

Fig. 2. Locations of historical and natural sinkholes and voids: (1) Nicollet Mall Cave, (2) Schieks Cave, (3) Eastman Tunnel, (4) Chute's Cave, (5) 34th Street Caverns and Seven Oaks Oval Park. Base map from gisgeography.com

WELL RECORDS

We searched both the Minnesota Well Index and the Borehole Geophysics Database for records of wells open to the St. Peter Sandstone within a one-county buffer of Hennepin County. Wells open to the St. Peter Sandstone are rare in the metro area. The well index search produced only 508 wells that are open to this unit, most of which are located in the east metro area. Of the 508 wells, 125 of them have portions (at least four feet) of the St. Peter cased off, even though it is the source aquifer for those wells. This means that the sandstone, usually the uppermost part of the formation, was determined to be unstable in some way while the well was being constructed and the well casing extended to ensure the stability of the well. This observation concurs with the field work undertaken by this study.

Only 27 wells open to the St. Peter Sandstone within the search area had records in the Borehole Geophysical Database, and these wells were all located in the eastern metro area. We obtained no relevant information from these records; however, this does not mean that these records are not useful. The bottom portion of the St. Peter Sandstone stands out in most of these logs as one or two distinct areas of higher natural gamma counts (the only borehole log routinely conducted in Minnesota that measures through well casing), which indicates some potassium-rich clay in the lower part of the formation. The field studies conducted as part of this report did not observe the St. Peter "cave unit" in the base of the formation, which implies that this particular part of the St. Peter has a lower risk of collapse. Future geophysical records, including caliper and borehole video, may prove useful in locating and confirming collapse-prone bedrock.

MINNEAPOLIS
SEWER RECORDS

The city of Minneapolis has sewer records documenting the geological conditions encountered during construction of each sewer. These records are surveyed for location and elevation to the nearest one-tenth of a foot. The cross sections are illustrated in color and have brief written descriptions of the geological materials.

Sinkhole in a downtown Minneapolis street caused by a spring storm. Minneapolis Star and Tribune Company June 16, 1937, from the Minnesota Historical Society.

Using utility records as a basis for geological interpretation comes with conditions. First, the people recording the information, both in the field and on the records, may or may not have geological training. However, this should not diminish the value or usefulness of the geological information, especially when field verification is possible using other sources. Second, utilities are essentially linear features. Distinguishing between a filled sinkhole and a filled gully requires mapping multiple blocks of linear utilities to determine if there is a larger trend that may explain the existence of the feature. For example, over the course of examining Minneapolis' records, an area of very shallow bedrock was shown extending on an axis along 40th Avenue North from the Mississippi River west to Robbinsdale. The Minnesota Geological Survey's depth to bedrock map shows a broad area of shallow bedrock in north Minneapolis, but the MGS' definition of "shallow" is 0–50 feet. The sewer records show surveyed elevations along the sewer trench, and maps this bedrock feature to the nearest foot (or less). By combining dozens of utility records, this bedrock ridge, which is covered by less than 15 feet of sediment and fill along most of its length, can be mapped in considerable detail, identifying where solid bedrock can impact construction and public works in addition to being of interest to geologists.

Comparing the depressions shown on the sewer plats with depth-to-bedrock maps allows for many of the depressions to be classified as filled wetlands or streams, and not potential sinkholes. The depressions that occur in areas where bedrock is not near the surface (deeper than 30 meters or 100 feet) are unlikely to be related to bedrock

A gas tanker that hit a sinkhole in Minneapolis, 1946. Credit: Minnesota Historical Society.

collapse or drainage. Depressions observed in areas with shallow bedrock, especially along the edges of buried bedrock valleys that may have been weathered prior to being buried by glacial sediments, may possibly be related to bedrock failure or drainage even if naturally filled. Since this study focuses on the risk of bedrock collapse, whether or not these features can be confirmed as collapse features is outside the scope of this study. In terms of risk assessment, that they could be related to bedrock collapse in an area susceptible to bedrock collapse makes these features important. Future work will be necessary by geologists to explore these features to determine which, if any, are of geological origin and pose a risk to life and property.

What is not known from these construction records is whether the sewer foreman documented the conditions in the trench as he found it or as he left it. It is reasonable to assume that a sewer crew would excavate any hole, especially in the bedrock, to ensure that workers would not be at risk of injury or death by falling rock, sand, or other similar materials. It is also reasonable to assume that the goal of the foreman's records is to show materials present after backfilling the trench, as that would be relevant to future excavation work. Author Bonin's experience with excavation projects in Minneapolis for sewer and water pipe work has found that both of these kinds of records were kept without a discernable pattern attributable to time or location. Therefore, it appears that the records were not part of a standard operating procedure, rather general guidance that left it up to each foreman to decide what was relevant, and how much detail to include for each excavation.

CITIZEN SINKHOLE RESPONSE

This project benefitted from a well-timed Minnesota Public Radio story and the article's subsequent appearance in online searches conducted by residents who were concerned about apparent sinkholes (www.mprnews.org/story/2019/09/27/hennepin-county-begins-project-to-assess-sinkhole-risk). We responded promptly to calls and reports of "sinkholes" from residents of Hennepin County whenever we have received them, bringing steel probes and downhole visualization cameras to the site. The preponderance of these residential calls, especially in areas of thick glacial mantle, seem to belong to the class of root-rot sinkholes as described by Newton (1987, pp. 24-25), i.e., there was a tree in the location years ago, which, unbeknownst to current owners, has rotted away, leaving macropores that preferentially channel surface water, imitating true karst sinkholes. Our first recommendation to landowners is to dig the hole out, if possible, to expose any tell-tale rotten wooden roots.

On the other hand, when we have been called in (by residents) for so-called sinkholes in Minneapolis streets, the cause often seems to be soil flux into drainage pipes, leaving a void that collapses, or to settling into what might be Quaternary scour holes filled with compressible clays or peats (Banks et al., 2015; Berry, 1979). These geologic features are often sketched on sewer profiles.

Results

The Hennepin County Geological Atlas depth-to-bedrock map was used to identify shallow bedrock, and that coverage was subdivided into 0–50 foot and 50–100 foot depths. Rock at these depths is at highest risk of collapse that could cause a sinkhole at the land surface. Depth to bedrock was further subdivided to account for rock units most prone to collapse—the carbonates of the Platteville Formation and the sandstones of the St. Peter Sandstone, Jordan Sandstone, and the Mazomanie Formation of the Tunnel City Group. Some of these units only appear in the subsurface in the north and west parts of the county, notably near Rogers. The three sandstone units are variably cemented and can readily erode when exposed to moving water. The carbonate rock forms classic karst and can collapse into voids formed in the uppermost St. Peter Sandstone. The sewer records were used as a proof of concept, showing that filled depressions can be located nearly anywhere with regards to depth to bedrock, however the probable sinkholes are all located in the shallow bedrock risk that we had mapped.

AREAS OF SPECIAL CONCERN IN HENNEPIN COUNTY

There are three main areas of concern that are described in more detail below:

1. Channel Rock Disturbed Area—West River Road from Lake Street to Minnehaha Park. The largest cave in Minneapolis, Channel Rock Caverns, together with the Seven Oaks Oval Park, exist in this area, suggesting that it is prone to bedrock collapse;

2. Northeast—in the vicinity of Dickman Park, a sinkhole cluster was observed on the sewer strip maps;

3. Minneapolis-St. Paul International Airport (MSP)—the thinned edge of the Platteville Limestone near river valleys has a propensity to sinkholes. A classic example from St. Paul is Fountain Cave. The cave developed where it did, near the outcrop, where Glacial River Warren had eroded and thinned it in post-glacial times, leaving it to invasion by a surface stream named Fountain Creek (Brick, 1995). Likewise, MSP is near a buried Platteville edge, its geologic setting explained by Hamilton (2002).

In the case of MSP, it was the Light Rail Project that induced sinkhole formation. According to (Wascoe, 2002), “Contractors digging light-rail tunnels beneath Minneapolis-St. Paul International Airport have crossed a buried river valley for the second time, creating smaller sinkholes near the surface than they did during their first pass. Patrick Mosites, project manager for the Metropolitan Airports Commission (MAC), said two sinkholes measuring 60 and 40 cubic yards recently were filled with grout to solidify the area. In February, excavation of the first tunnel created a large sinkhole that closed a Northwest Airlines gate for a week and required 350 yards of fill. The sinkholes developed above the area where concrete rings are being fitted together to form the tunnel. The holes were below an area where planes taxi and park, but pavement over the construction area prevented the sinkholes from being visible at the surface."

We contacted Pat Mosites and he replied (June 7, 2021 email) that "All [sinkhole] occurrences were in the alluvial valley. Exception was when an old bore hole (near the parking management building) created a[n] underground pool of water that when the machine passed under it collapsed the saturated sandstone and flooded the machine for a moment. However even in this case the bedrock did not collapse." Because the sinkholes were in alluvial material rather than bedrock, they are of no further concern here.

REPORTS FROM THE PUBLIC

Following media reports on this project, the public contacted the authors with 29 reports of possible sinkholes. While most of the 29 reports could be attributed to rotting tree roots or issues with pipes, four of the reports could not be readily explained, and five others were determined to have geological origins. As previously stated, one was in Rice County and not investigated for this work, although it appears to be a St. Peter Sandstone setting.

Four of the reports did not identify the probable cause of the "sinkhole." One of these was in Burnsville near the Minnesota River in Dakota County and close enough to Hennepin to be relevant and in an area with documented sinkholes. However, the engineering records were inconclusive. Three were in areas of shallow bedrock, two with Minneapolis engineering records showing filled holes under the street and one with active pavement failure occurring at the time of investigation. In these cases, further work is necessary to determine the cause of the complaints. Determining both the cause of the holes and accounting for the missing volume would determine if these areas are in fact sinkholes or not.

One of the reports was a true sinkhole. Between Wentworth and Nicollet Avenues in south Minneapolis, on the blocks south of Diamond Lake Road, a pair of depressions adding up to approximately one acre in area are evident in the USGS topographic map data. The eastern of the two probable sinkholes in the area, mostly located under the United States Postal Service (USPS) parking lot, is filled. Several smaller holes have opened along what appears to be the margin of this sinkhole between the fill and the native material, most recently in 2019. The authors investigated this at the time and determined that it is a true sinkhole, probably related to drainage into the filled sinkhole. The area residents have provided anecdotes of various neighbors using holes in the ground to dispose of stormwater. Minneapolis Sewer records show a funnel-shaped depression in the sand under Blaisdell Avenue South that was filled with black dirt and clay when the block was developed in approximately 1930. This filled area is centered on the USPS driveway.

Two other reports were geological in origin but not as dramatic as the south Minneapolis sinkholes. Both of these are located within one block of the Mississippi River gorge. One, on the east side of the Mississippi River, was from a resident who reported using a hole in the ground to drain their swimming pool each fall. This residence is located just east of and nearly directly above a large spring which issues from the Platteville Formation limestone in the wall of the gorge. Further investigation is necessary to determine if the hole in the yard and the spring are linked, but this clearly demonstrates sinkhole risk. The second, on the west side of the Mississippi River gorge, is a straight line of sunken pavement, offset retaining walls and garage foundations, and multiple storm drain repairs. The geology at this location is fine sand over Platteville Formation limestone. While additional testing should be undertaken, it appears that surface water is infiltrating the sand and then flowing through a fracture in the bedrock with enough velocity to erode the sand into the fracture. Removal of the sand along this fracture is probably causing the problems reported by the resident and those observed by the authors.

One of the reports is also of geological origin, but it couldn't be determined if the topographic depression was a sinkhole or a gully that had been filled on the downstream side. This site is located at the edge of the Mississippi River gorge on the west side of the river, and the river road was constructed between this depression and the edge of the gorge. The bottom of the depression appears to be the same elevation as the top of bedrock, however we did not find any bedrock in the hole. Further investigation of this site is necessary to determine its origin.

The fifth report was related to well drilling near the river. The driller encountered a large void while constructing a well in the buried limestone. The authors have frequently experienced drilling into voids while supervising well

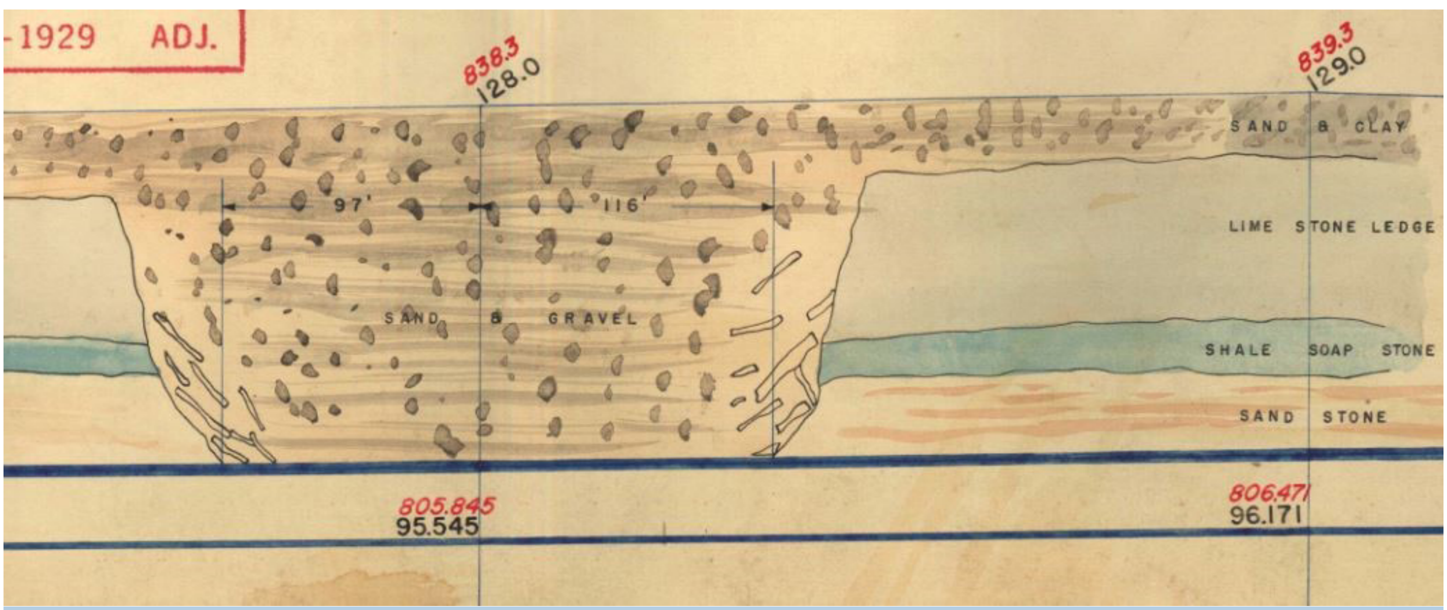

Fig 3. A "classic" sinkhole as depicted on sewer linens, 2nd Street NE and 5th Avenue NE.

construction around the metropolitan area. While this doesn't necessarily indicate a risk of bedrock failure, it does attest to the existence of voids in buried bedrock around Hennepin County and Minnesota in general. Under the right (or wrong, depending on one's perspective) conditions, these voids could collapse and form a sinkhole.

SEWER RECORDS

Minneapolis sewer records show geological details along the length of each sewer. We found 16 "new" probable sinkholes that we discovered through examining these records. It's been recognized that there are far more sinkholes that have been filled by natural processes than there are currently visible sinkholes (Alexander et al., 2005). In contrast to traditional methods of merely mapping existing sinkholes, however, using these sewer records is like running transects across the landscape, which although impractical in rural areas, provides finer detail than excavating or drilling test holes in urban settings. Here we will discuss specific examples with figures.

Northeast Minneapolis

At Second Street NE and Fifth Avenue NE there appears to be a classic sinkhole (Fig. 3). This feature is 213 feet long, but the sewer records only show the geology along the length of the sewer, i.e., in two dimensions, length and depth. There is what appears to be a second sinkhole at Second Street NE and Seventh Avenue NE, two blocks away, which is 198 feet long. Both of these are formed in shallowly buried Platteville Formation limestone.

A few blocks away on Fourth Street NE at approximately 13th Avenue NE, six shafts, each wider than 40 feet, are shown in the Platteville Formation bedrock. These show up as shafts in limestone, which makes it likely that these features were cleaned up by the construction crews. The cross streets' sewer records show less dramatic geology. The intersection of 13th Avenue NE and Fourth Street does not show bedrock topography, which could rule out a feature such as a westerly trending branched valley. The sewer along 14th Avenue NE does not extend to Fourth Street, however the bedrock profile is penciled in on the cross section, showing a craggy depression in the limestone bedrock with "black dirt" fill. This could be the edge of a bedrock valley or a sinkhole. As 14th Avenue NE ends at this intersection, this raises a flag; were the geological conditions too difficult to extend the road and utilities any farther west of Fourth Street NE? One block away at Third Street NE and 13th Avenue NE, a 50-foot-wide vertical gap in the shallow bedrock filled with "black dirt" is shown on the cross section. This gap extends through the limestone (Platteville Formation), the underlying soapstone and clay (Glenwood Shale), and into the (St. Peter) sandstone. More research is needed to determine if these features can be linked to each other as one buried or filled drainage network or if they are individual sinkholes.

At Polk Street NE, the sewer is set a few feet into the limestone bedrock, there is a boulder-filled area of missing limestone roughly 115-ft long just north of 20th Avenue NE. The 20th Avenue NE profile shows an uneven bedrock surface, but no areas where the bedrock is missing. The sewer is only seven feet deep where it crosses this gap in the bedrock, which makes assessing the nature of this feature challenging.

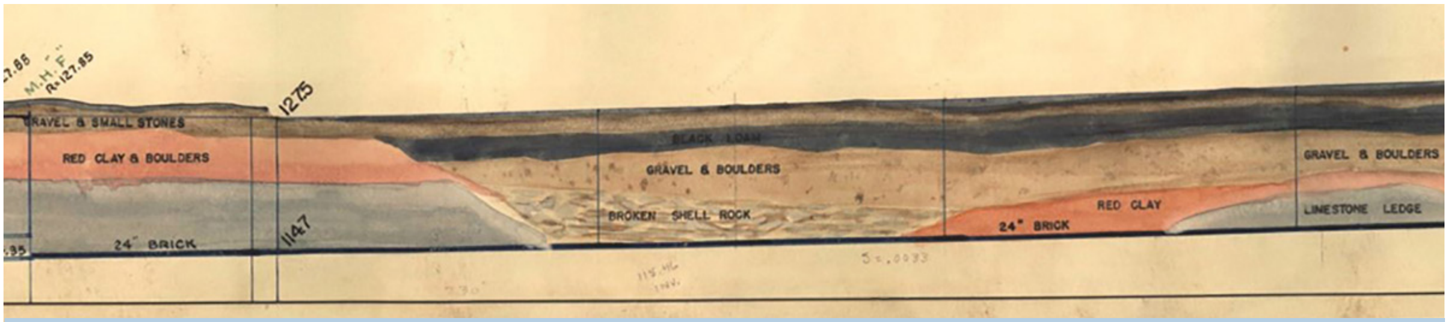

Fig 4. The giant "broken shell rock" sinkhole at Adams Street NE north of Spring Street NE.

At Adams Street NE north of Spring Street NE, there is a 150-foot gap in the shallow limestone filled with "broken shell rock," with the depiction of thinned sediments along the edges of the gap. This appears to be an old sinkhole (Fig. 4). More recent sediments overlie the gap and appear to be horizontally layered.

The profile of the 16th Avenue NE sewer shows a gap in the bedrock between Fillmore Avenue NE and Lincoln Ave NE, of approximately three blocks. The profile in this area appears to show the pre-development conditions. Bedrock ends at Fillmore and is missing until Lincoln. In between, there is "crushed stone screenings" fill approximately 12–16 feet thick. This does not appear to be an erosional feature. It could be the site of a former quarry, or a large sinkhole. The street at this location was vacated and turned into a school and park, which often means that the land was unsuited for development. Was this the case? This area should be investigated both historically and geologically to determine if it is a sinkhole.

South Minneapolis

A large-diameter, deep sewer was installed on top of or near the buried bedrock surface from the Minnehaha Falls vicinity to west past Lakes Hiawatha and Nokomis. Top of bedrock measurements appear to have been taken regularly along the route of the sewer. At the southeast end of Lake Hiawatha, the bedrock drops off and was apparently not measurable by the work crew. This is the eastern edge of the deep bedrock valley that cuts through south Minneapolis, into which lie the Nokomis chain of lakes; Hiawatha, Nokomis, Taft, Mother, etc. We would expect to see the edge of this filled valley to have sinkholes. However, this review of engineering records did not reveal any such features.

In the Powderhorn Terrace sewer plan, between 12th and 14th avenues south, there is large (300 foot), relatively steep and deep filled depression that appears out of place from the rest of the area. If the depression is related to bedrock collapse, it is an old feature; the soil horizon appears to be deposited conformably along the slopes of the depression. Only a portion of this feature is shown in cross section, so additional exploration is recommended.

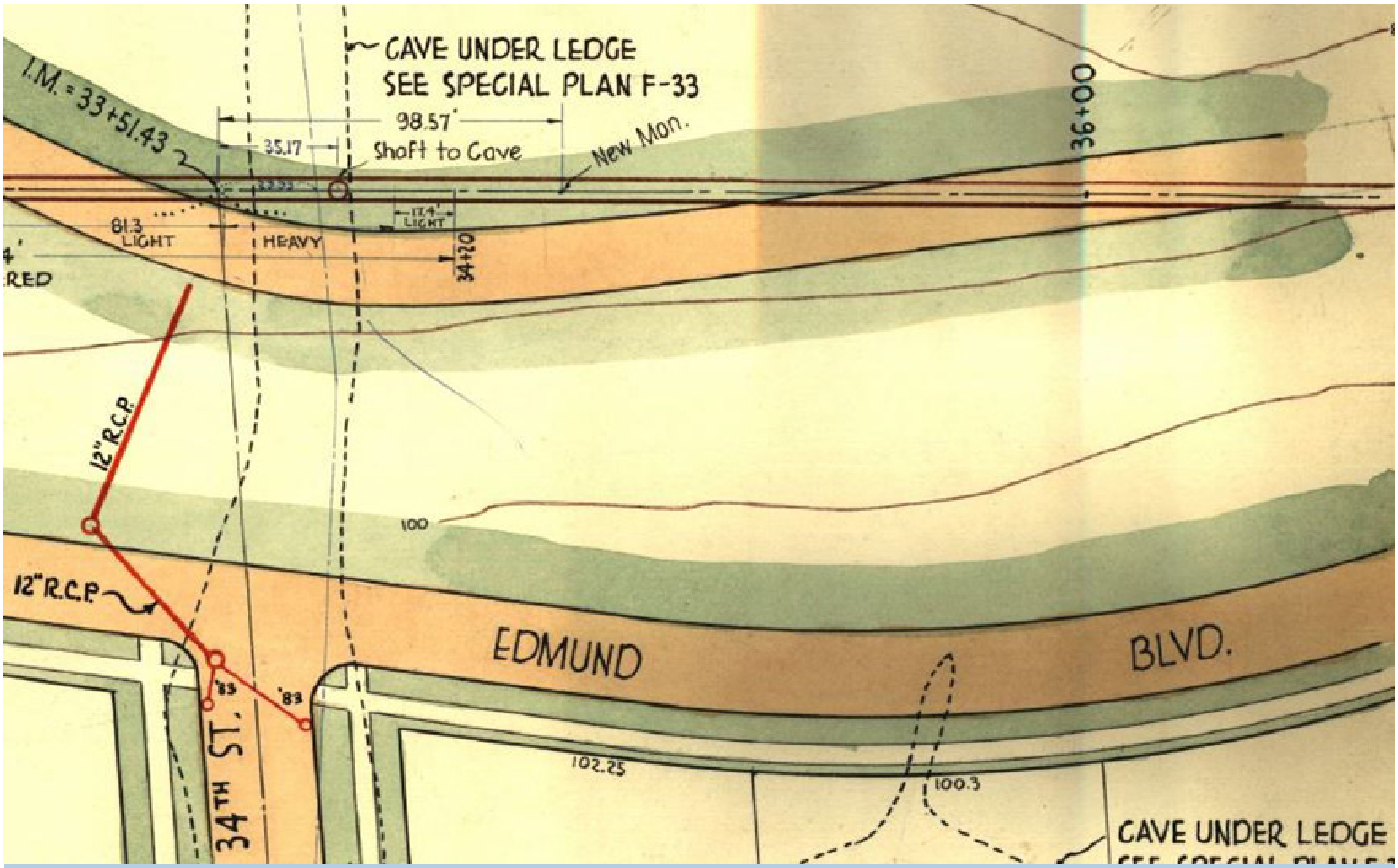

Fig 5. Storm drain rerouted to avoid 34th Street Cavern (dashed lines).

On Park Terrace and 34th Street South on the north side of the Seven Oaks Oval Park, the storm and sanitary sewers are routed around the sinkhole. The storm drain on 34th Street and Edmund Blvd. in particular is routed diagonally through the intersection to avoid the cavern northeast of the sinkhole (Fig. 5). This shows how sewers are routed around caverns where they are known to exist before being constructed.

North Minneapolis

Where Sixth Street North tangentially intersects Interstate 94, the sewer is set six–7 feet into limestone, and shows a 70-foot long area where the "ledge" (a layman's term for hard, layered rock such as limestone) is missing and is instead shown as "broken ledge fill." The site is located tens of feet west of the retaining wall that marks the edge of the roadcut for Interstate 94. The fill cuts across the "gravel clay & boulders" strata (probably glacial sediment) that overlies the bedrock. The origin of the fill is unclear. North of this feature, at Sixth Street North and 40th Avenue North, is another depression in the limestone approximately 150 feet long, which is mostly filled with "broken ledge fill." At this location the limestone is at the ground surface, as is the fill, which may mean that the fill is not placed by the construction crew. The depression had additional fill added on top of the "broken ledge fill," which was most likely added by the sewer or paving crew. The storm drain profile for 40th Avenue North also shows a depression in the limestone that contains "broken limestone & fill" that extends an unknown distance east. A common engineering practice makes this feature interesting; there is a deep shaft manhole set into this depression. Since constructing into solid limestone is difficult, manholes are often constructed into the weakest parts of the rock where possible. In this case, freeway construction in 1981 made lowering the storm drain necessary at this location or somewhere to the west. This makes it unclear as to whether or not bedrock competence had any influence on where to locate the shaft manhole on this drain. The construction notebooks for this project might be useful for this site. Still, understanding how geology influences design and construction of deep structures is an important consideration in interpreting construction records.

At Lyndale Avenue North, the sewer crosses a 120-foot wide gap in the shallow limestone bedrock south of 40th Street North that is filled with "broken ledge, stones, clay, and boulders fill," with the profile depicting a dramatic

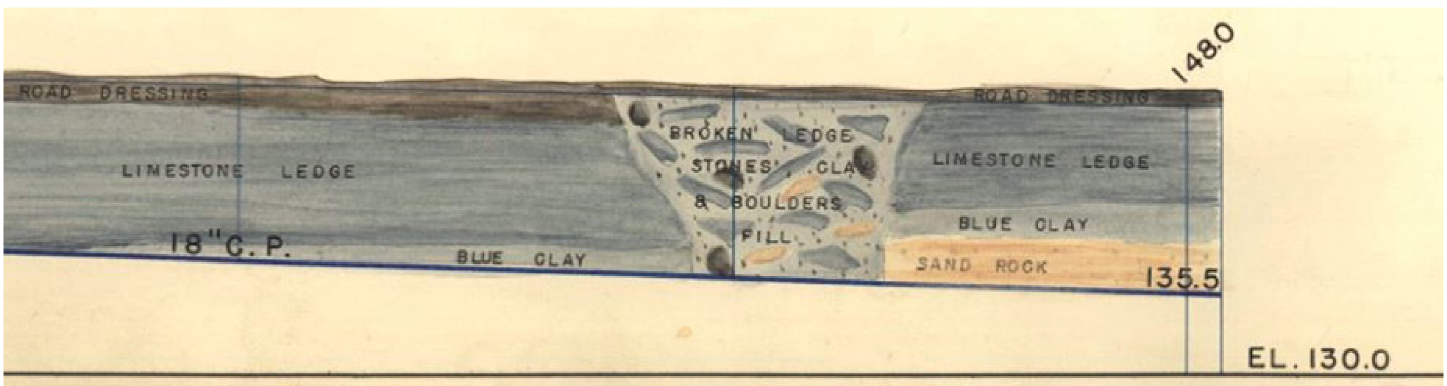

Fig. 6. The Lyndale Sinkhole likely formed along the offset between rock layers.

sketch of a pipe-shape filled with randomly oriented blocks (Fig. 6). The top of the Glenwood Shale is measured (the drawings being to scale in three dimensions, as the sewers were surveyed in three dimensions to the nearest one-tenth of a foot) as being three feet higher on the north side of the hole compared to the south side. Sandstone is shown on the north side of the hole and not on the south side. This appears to be an old sinkhole caused by drainage through a small fault or offset joint between the limestone and the sandstone.

The Lyndale Avenue North sewer crosses a 70-foot wide, 9–10-foot deep filled hole in the 5200 block of Lyndale Avenue North. Neither bedrock nor the bottom of the hole are shown in the profile. As bedrock appears to be shallow in this area, and the hole cuts through the clay and sand strata in the area, this does not appear to be some sort of buried topographic feature and should be considered a sinkhole until investigated.

At Bryant and 41st avenues north there is a 475-foot gap in the bedrock at the surface that is filled with red clay and boulders (probably Cromwell Formation till) to a depth of at least 12 feet. This is clearly an old feature, being filled with glacial material, which should be monitored for future subsidence. Based on these records, it is unclear if this is an erosion feature or a large collapse feature, and until it is examined by a geologist it should be assumed to be a collapse feature for purposes of risk management. Areas of shallow, eroded, and weathered bedrock have a higher risk of sinkhole formation than competent rock, so even if this is an old erosional feature it presents a substantial risk of sinkhole formation in the future.

Hazard Assessment and Risk Analysis

Sinkholes and collapses related to utility pipe or tunnel failure may indicate bedrock collapse or geologic sinkhole formation, although failures related to geology are rare. Ponds and lagoons constructed on shallow bedrock may create enough hydraulic head to induce vertical failure of fractured or jointed bedrock and catastrophically drain.

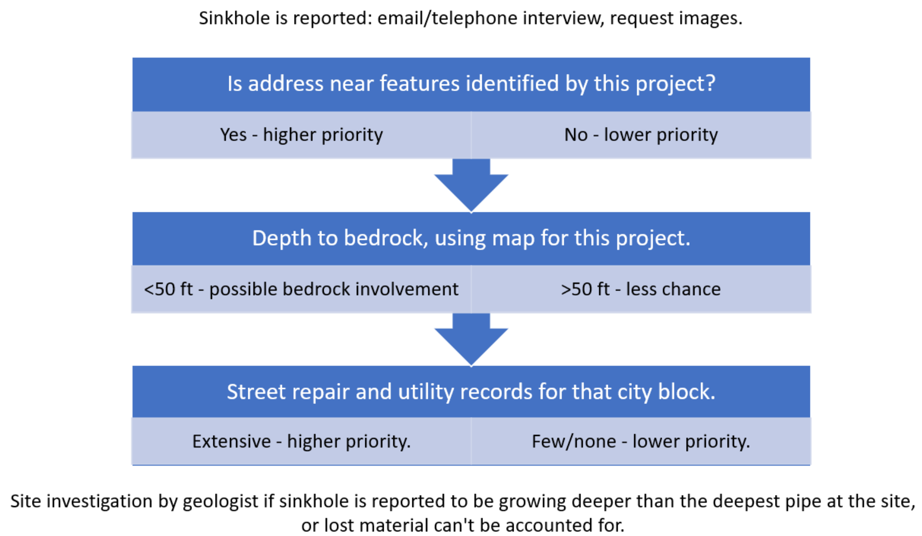

Fig. 7. Detailed construction records can be of immeasurable value to identifying historical collapses of bedrock in urban areas.

Even where utilities have no history of failures, persistent creep slumping of structures such as roadbeds and retaining walls, especially when this occurs on areas with little or no topographic grade, may indicate a potential problem. If such failures occur and the liberated liquids and washed-out sediments cannot be accounted for downstream of the failure, utility managers must be aware that that material had to go somewhere and look for signs of bedrock collapse or actual sinkholes. These should be investigated by a geologist in addition to a geotechnical engineer.

Springs should be monitored for unexplained discharges of sewage or sediment, as this may indicate bedrock collapse in that springshed which could endanger life and property.

A general order of investigation to rule out less hazardous instances can be conducted by a lay person up to a point. The steps involved are listed here (Fig. 7). Protocol for a professional geologist is provided in the appendix.

Pipe-failure-related washouts where the majority of the washed-out material cannot be found may indicate a significant bedrock collapse risk even if the cause of the failure is not related to geology. This indicates that the fluids, along with sediment or debris, are going somewhere, and that may be into a significant void in the underlying bedrock. Further, the volume and chemistry of the escaped materials may cause the void(s) in the bedrock to enlarge, sometimes rapidly, somewhere downstream of the failure. These events should be investigated by a competent geologist to identify environmental risk, of both bedrock collapse and environmental contamination, who should then work with engineers to devise plans to mitigate future problems at that site.

CORRELATION TO CLIMATE

Climate data show a clear trend of increasing intense rainfall events across Minnesota (Metropolitan Council, 2018). More intense rainfall events will test the capacity of stormwater conveyance systems, which may increase the risk of bedrock collapse in areas that may already be at risk. Storm drains are not generally designed to be under pressure. Large-volume precipitation events can cause runoff that exceeds the capacity of the storm drain system, which pressurizes the pipes. This will blow out the pipe where there are weak spots. The sediment from these blowouts will generally be carried away down the sewer, which causes maintenance problems downstream in addition to the blowout itself. However, in areas prone to sinkhole formation, water from intense precipitation events can exacerbate the natural processes of bedrock collapse and sinkhole formation. Where these processes are occurring, the water and sediment released as a result of a broken pipe may flow into voids in the ground instead of the pipe. Any material in that pipe or the surrounding fill that poses a health hazard will be conveyed into the groundwater system where it could pose a hazard to the public—in addition to increasing the risk of bedrock collapse. The city of Minneapolis is currently addressing this risk by adding storm drain relief tunnels to what already exists, effectively doubling the capacity of the system (CDM Smith Inc., 2018).

Appendix: Site Protocol for Geologists

Most of the time, the prospective sinkhole will turn out to be a quite minor feature unrelated to bedrock collapse, but there's always the exception, so you must remain vigilant. Determine whether the prospective sinkhole is in the yard or in the street.

If it's in the yard, it's often a root-rot sinkhole of the kind described by Newton (1987), where the roots of a former tree have rotted away underground, leaving macropores that drain surface water and enlarge themselves slightly. Digging out the feature with a shovel will often reveal this wood, confirming the diagnosis. Or perhaps the tree can be seen on old aerial photos. This kind can be remedied by merely filling in the hole with compacted soil. However, in cases where bedrock is very shallow to surface, these same innocuous features can create real bedrock voids, again, as explained by Newton (1987). Go to the Slug Test.

For the Slug Test, fill the hole using the garden hose. If it fills readily and stays filled, this suggests minimal leakage and a confined feature of minor concern. But if the water drains endlessly, it must be going into a void somewhere.

As a caveat to the Slug Test, its value is lessened if it's near a large structure. Often houses have subfloor spaces that could conceivably tap off large amounts of water, giving a false positive.

A simple tool for probing and defining voids is the steel lance, about 2 meters long. Thrust it into the ground in a pattern around the feature, "feeling" for voids, you may be able to map them out.

In some cases, you can get an image of what's in the hole by using a "Lizard Cam" on a six-foot cord. Practically speaking, it's of most value where a recognizable object appears on the screen, e.g., a broken tile drain comes into view, which would diagnose the problem at once. In the majority of cases, however, you'll merely see an inverted image of disturbed soil with no way of judging scale, and no determination can be made.

If the property is on the crest of a river bluff, there's another possibility. It may be that the water is draining to an outcrop, where there's a good chance it would leave staining on the rock face, tufa deposits, or altered vegetation growth. The steep hydraulic gradient thus afforded could lead to on-going sinkhole enlargement so the landowner is recommended to seek some means of abatement, such as diverting the drainage.

If it's in the street, it's often due to voids created by soil washing away into storm drains or sanitary sewers. A street that is heavily patched and has extensive repair records at the city usually indicates troubled ground, which could be related to sinkhole formation but usually is not. Check the risk map and see if the location is in one of the more elevated risk areas. In any case, apart from reporting it to city maintenance, there's nothing more you can do about it. Have the city staff look into it before doing anything else.

Regardless of whether the prospective sinkhole is in the yard or the street, it's good practice to walk around the immediate neighborhood, in the streets and alleys, and look for anything else that seems out of place or "odd." Examples include dips in the curb and gutter that align with sunken areas of yard or buckles in structures such as foundations or retaining walls. If you meet neighbors, ask them if they have had any problems, as corroboration from others usually means there's a real problem afflicting a wider area, that should be addressed.

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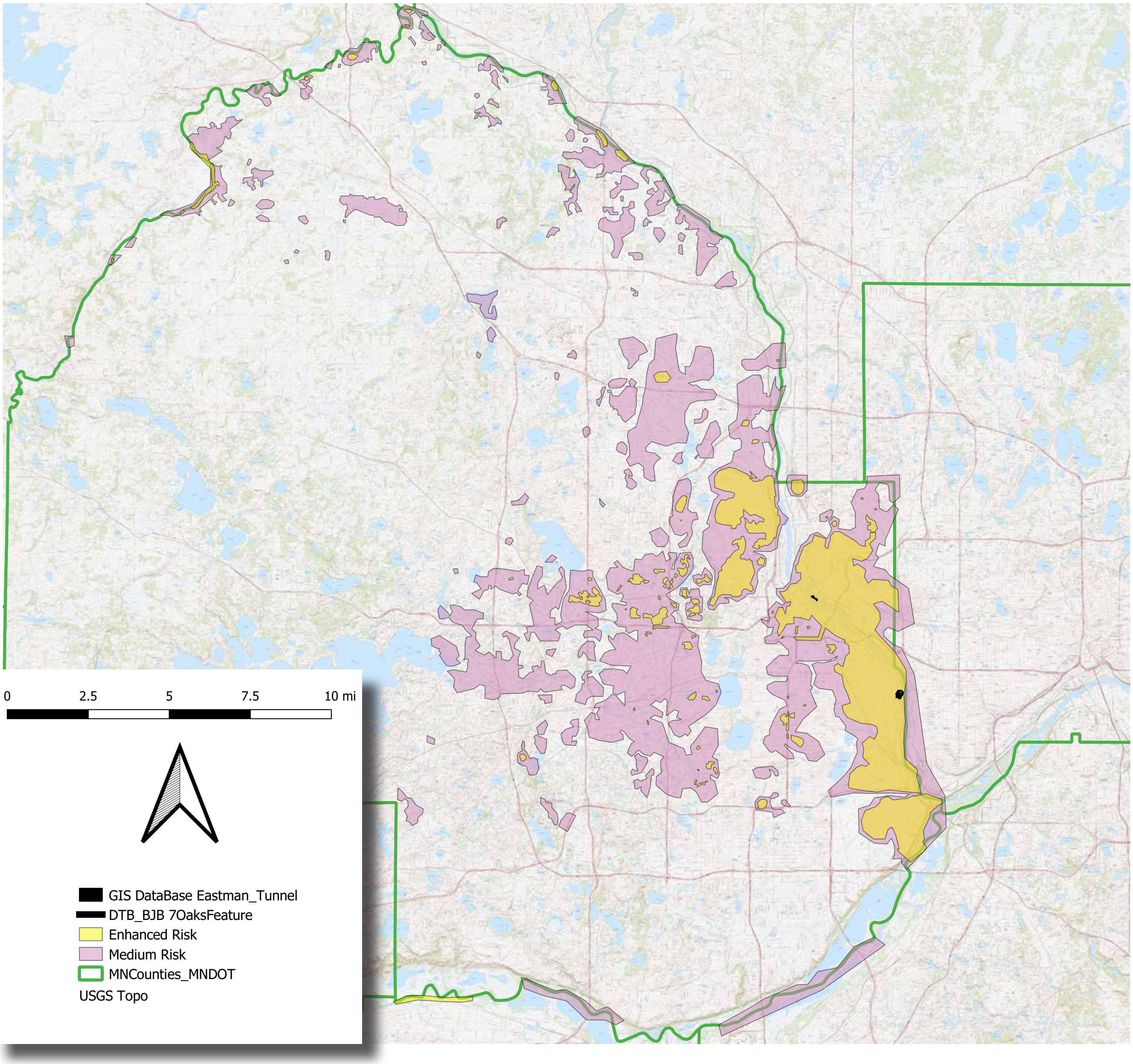
Maps

HENNEPIN COUNTY BEDROCK COLLAPSE RISK



POSSIBLE BEDROCK COLLAPSE FEATURES
FROM MINNEAPOLIS SEWER RECORDS