The Great Subterranean Spring of Minneapolis, Minnesota, USA, and the potential impact of subsurface urban heat islands (SUHIs)

Greg Brick, Minnesota Department of Natural Resources, Lands & Minerals Division, 500 Lafayette Road, St. Paul, Minnesota, USA 55155

ABSTRACT

Anthropogenic subsurface urban heat islands (SUHIs) in groundwater under cities are known worldwide. SUHIs are potentially threats to springs because much spring fauna, like trout, amphipods, and rare plants, is cold stenothermal. The city of Minneapolis, Minnesota, USA, has a SUHI documented by the temperature of an underground spring, dubbed "Little Minnehaha Falls," inside Schieks Cave, which is located 23 m below the central core of the city. In 2000 the temperature of that spring was elevated 11°C above regional background groundwater temperatures (8°C) at this latitude (45°N). A thermometric survey of the cave and nearby tunnel seepages in 2007 found that an abandoned drill-hole through the bedrock ceiling of the cave was discharging groundwater with a temperature of 17.9°C. By comparison, groundwater in the deep water-table below the cave was closer to natural background temperatures for the region. The unusually warm groundwater was thereby localized to the strata above the cave. This is the strongest signal of anthropogenic groundwater warming in the state of Minnesota and is attributed to vertical heat conduction from basements and pavements. Minneapolis is unique among SUHIs in that a cave forms a natural collection gallery deep below the

city surface, whereas the literature is almost exclusively based on data from observation wells.

INTRODUCTION

Elevated groundwater temperatures are a potentially important threat to springs because much spring biota is cold stenothermal, examples being trout, amphipods, and rare plants (Brick, 2017b). According to Taniguchi et al. (2007), “The heat island effect due to urbanization on subsurface temperature is an important global groundwater quality issue because it may alter groundwater systems geochemically and microbiologically.” In the “Twin Cities” of Minneapolis-St. Paul, Minnesota, USA (**Fig. 1a**) there are designated trout streams within the metropolitan area, whose springsheds are heavily built over and will be impacted by rising groundwater temperatures (Meersman, 2012).

According to Taylor and Stefan (2008), “Urban development can influence groundwater temperatures in a number of ways: Paved surfaces become much warmer than sod surfaces on clear, sunny days. Heat is conducted from these surfaces into the soil, and can reach shallow groundwater. Taniguchi and Uemura (2005) provide evidence of conduction-based warming of groundwater due to urbanization. Surface water runoff from warm ground surfaces can infiltrate from ponds, channels, or rain gardens. Percolating warm water may carry its heat, not lost in the soil, into an aquifer.”

Elevated groundwater temperatures below cities are well known worldwide. In Asia, Taniguchi et al. (2009) have documented anthropogenic thermal effects on groundwater in Osaka, Japan, and Bangkok, Thailand. In Europe, Epting et al. (2017) confirm the same trends at Basel, Switzerland. According to Hemmerle et al. (2019) "This is demonstrated for the city of Paris, where measurements from as early as 1977 reveal the existence of a substantial subsurface urban heat island (SUHI) with a maximum groundwater temperature anomaly of around 7 K." In North America, Ferguson and Woodbury (2004, 2007) describe the subsurface heat island effect below Winnipeg, Manitoba: "Downward heat flow to depths as great as 130 m has been noted in some areas beneath the city and groundwater temperatures in a regional aquifer have risen by as much as 5°C in some areas." Yalcin and Yetemen (2009), Zhu et al. (2010), Menberg et al. (2013b), and Bayer et al. (2019), among others, go so far as to consider tapping into SUHIs as a source of geothermal energy. In keeping with conventions in the SUHI literature, from this point on C (Celsius) will be used to indicate a measured temperature, whereas K (Kelvin) indicates a temperature difference.

The earliest known record of groundwater temperature in the Platteville Limestone in what became Minneapolis is from Nicollet (1845). At Coldwater Spring (a Platteville spring about 10 km from Schieks Cave and its underground spring) Nicollet reported an average of 7.8°C in July 1836 and 7.5°C in January 1837 (Nicollet, 1845: 69).

Taylor and Stefan (2008, 2009) projected a rise in groundwater temperature for the Twin Cities metropolitan area of 3 K (and even higher in global warming scenarios) in research funded by the Minnesota Pollution Control Agency. However, they were most likely unaware that the first measurement indicating elevated groundwater temperature in Minneapolis had already been reported by an undergraduate geology student years earlier from Chalybeate Springs, a mineral water resort that was popular before the American Civil War. These springs emanate from the Platteville Limestone with a temperature of 14°C, 6 K above the expected 8°C at latitude of 45°N (Brick, 1993).

A time series of temperature measurements at Coldwater Spring, on the outskirts of Minneapolis, lasting nearly two years (2013-2015), recorded fluctuations from 10.7°C to 13.1°C, well above those of Nicollet (1845) already mentioned. Kasahara (2016) attributed this to "an anthropogenic source of heat within the spring-shed or spring discharge area." See also Alexander and Brick (2021: 98).

However, while these elevated temperatures are notable, they are half the temperature changes in a spring and a free-flowing well located inside a cave under downtown Minneapolis at a depth of 23 m below street level, which is the focus of the remainder of this chapter.

BACKGROUND

Cave and Spring

Schieks Cave is the largest cave under downtown Minneapolis, underlying half a city block **(Fig. 1b)**. This maze cave in the St. Peter Sandstone has a ceiling of Platteville Limestone. Its exact origin is rather murky (Brick, 2017a).

Fig. 1a. Location of the Minneapolis-St. Paul metropolitan area (star). Modified from Wikimedia/U.S. Geological Survey.

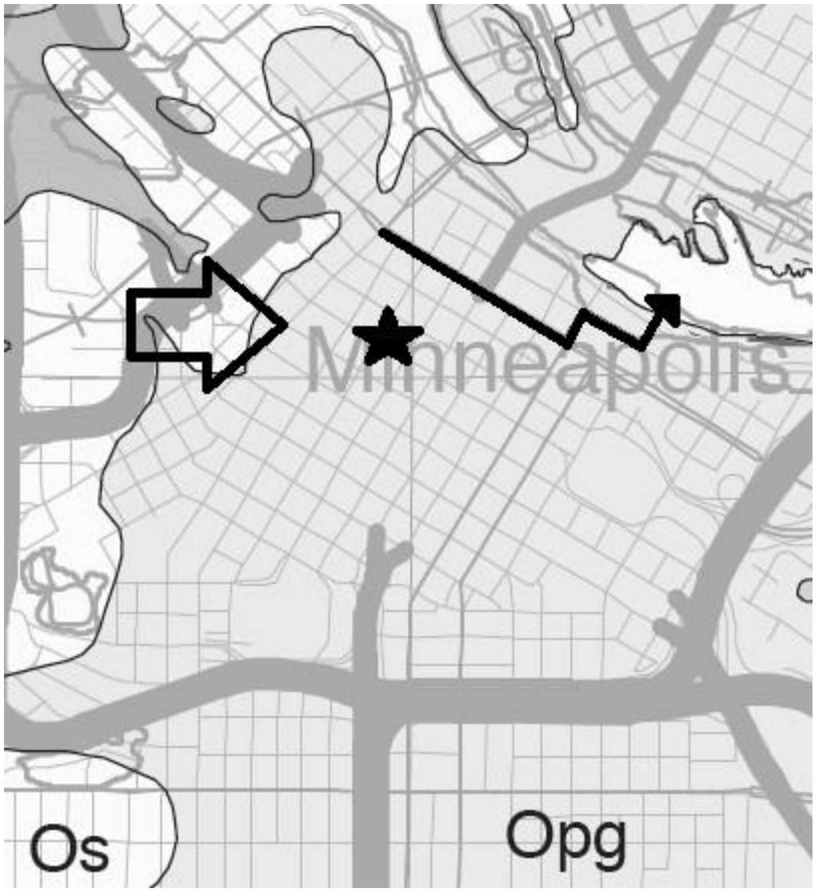

Fig. 1b. Location of Schieks Cave (star) on Hennepin County bedrock map, north at top (Retzler, 2018). Opg=Ordovician Platteville-Glenwood Formation, Os=Ordovician St. Peter Sandstone. Big arrow indicates general direction of groundwater flow in the shallow Quaternary aquifer based on Kanivetsky (1989). Thin arrow represents the Washington Avenue tunnel, where temperature measurements were taken in 2007, and its flow direction to Mississippi River (see Table 1).

The first document regarding Schieks Cave (or its spring) is the 1904 Nic. Lund map. Although rather crude and incomplete, the map is rich in hydrologic details such as "creeks" and "lakes." At the location of the ceiling spring the map notes "WIDE CRACK IN LEDGE, LARGE BODY OF WATER COMING THROUGH." Upon first entering the cave, Carl J. Illstrup, city sewer engineer, reported that "Dripping from the ceiling at one place there was a regular curtain of water 30 feet [10 m] in width. The water in the middle [of a pool at the bottom of the curtain] was 20 feet [6 m] deep at one point and tapered down to inches at the shore line. It was a beautiful sight but we had to drain it to remedy the troubles in the Fourth Street tunnel" (Fitzsimmons, 1931).

A second map, by J.E. Lawton in 1929, based on a detailed survey, depicts Schieks Cave extensively modified by the construction of piers, walls, and artificial drainage systems, the latter to prevent further erosion of the soft sandstone. The ceiling spring was shown as "WATER FALLS," but this time enclosed in a separate concrete chamber provided with floor drains. Both cave maps are reproduced as Plate 3 in Kress and Alexander (1980).

Longnecker (1907) described the spring and well in print for the first time and Brick (2021) gives an extended analysis of his narrative from a geological perspective. Longnecker included a photo captioned "The Subterranean Falls," showing how "the crystal-pure spring water gushes forth between the ledges of limestone and falls into a concrete basin built by the city engineer's staff." Dornberg (1939) was the first to refer to the ceiling spring as "Little Minnehaha Falls" (LMF) and label it as such on his map **(Fig. 2)**. This was a jocular reference to Minnehaha Falls, a well-known Minneapolis landmark. Zalusky (1953a) described LMF as "a falls which I estimated in the darkness to be about 10 feet [3 m] wide and a drop of 5 feet [1.5 m]." So Illstrup's 10-m curtain of water had apparently dwindled to a third of its former length. Kress and Alexander (1980) state that "In view of the almost complete cover of the surface by buildings or pavement and the inevitable disruption of the near-surface groundwater flow by the excavation of building foundations, it is not surprising that 'Little Minnehaha Falls' is drying up."

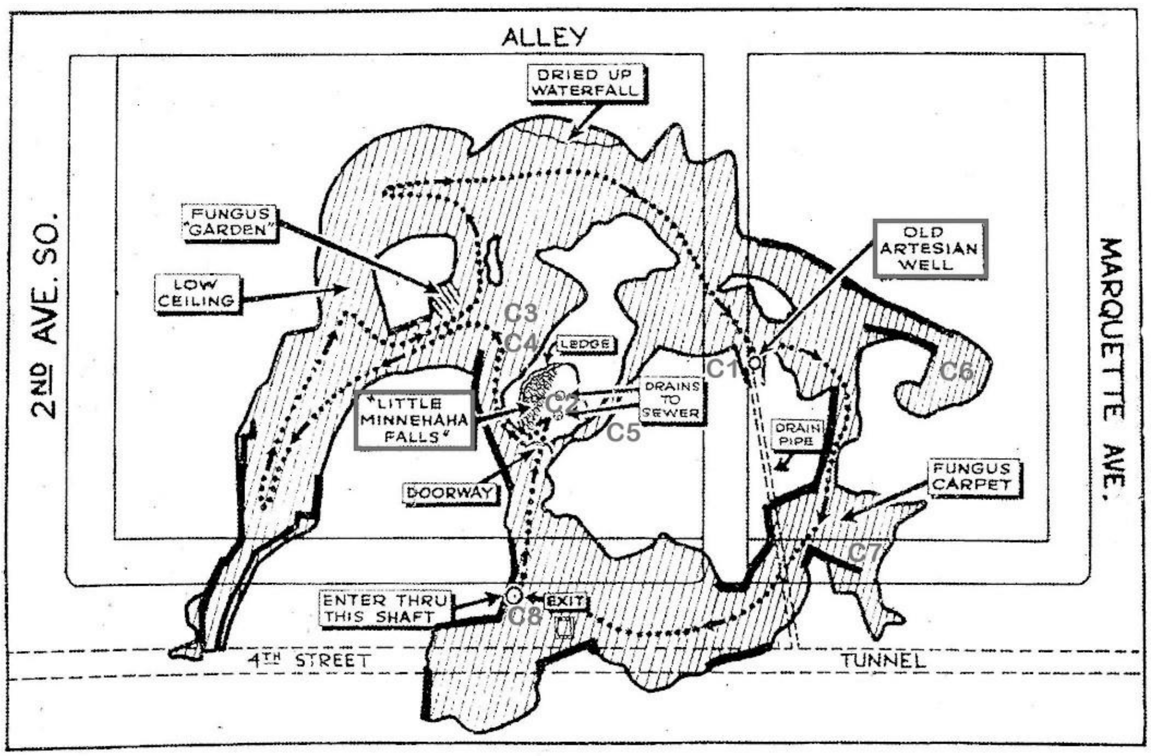

Fig. 2. Dornberg's 1939 map of Schieks Cave, a maze cave in the St. Peter Sandstone, showing the ceiling spring, dubbed "Little Minnehaha Falls" and the "Old Artesian Well," a drill-hole through the Platteville Limestone forming the ceiling of the cave. C1 to C8 are temperature measurement points (see Table 1).

Discovery of Thermal Anomaly

No substantive new information about the spring was forthcoming until my own visit of 28 May 2000. An extended account of the trip is found in Brick (2009: 191-203). Schieks Cave is normally accessed by a 23-m shaft from Fourth Street and traffic must be diverted to open the manhole, which is why the Minneapolis Sewer Department rarely visits the cave, so it's difficult to acquire additional data.

Spring water pours from a bedding plane in the Platteville Limestone, depositing vertically striped flowstone on the walls of the concrete chamber built to contain the spring **(Fig. 3a)**. Judging from Dornberg's 1939 photos, the discharge did not appear to have diminished much since then, contrary to other reports. The water fell as an extended sheet about 3 m long (matching Zalusky's dimensions of half a century earlier) and the flow rate was visually estimated at 5 gallons per minute (GPM) (=19 liters per minute). Floor drains convey the water to the North Minneapolis Tunnel, a deep-level sanitary sewer.

Fig. 3a. A concrete chamber inside Schieks Cave hosts the anthropogenically warmed ceiling spring "Little Minnehaha Falls," which issues from a bedding plane in the Platteville Limestone, depositing "zebra" flowstone on the walls. Photo by author, 2000.

Fig. 3b. Spring issuing from fissure in the Washington Avenue tunnel. Seepage entrains whitish St. Peter sand grains from outside the tunnel lining. Photo by author.

Upon equilibrating a calibrated SPER Scientific® mercury thermometer (±1%) in the spring orifice for several minutes, I was surprised to note that the groundwater temperature was 19°C, higher than the expected 8°C at this latitude (Brick, 2014).

I also examined a drill-hole in the limestone ceiling of the cave, which discharged an estimated 50 GPM (=190 liters per minute), falling into a shallow concrete basin **(Fig. 4)**. However, I mistakenly thought this was stormwater at the time, only later recognizing it as a water well, so I did not measure its temperature during the first trip. There's no manifestation of this abandoned well at street level, the site being entirely covered with buildings and a car park. Dornberg (1939) refers to it as the "Old Artesian Well" (OAW).

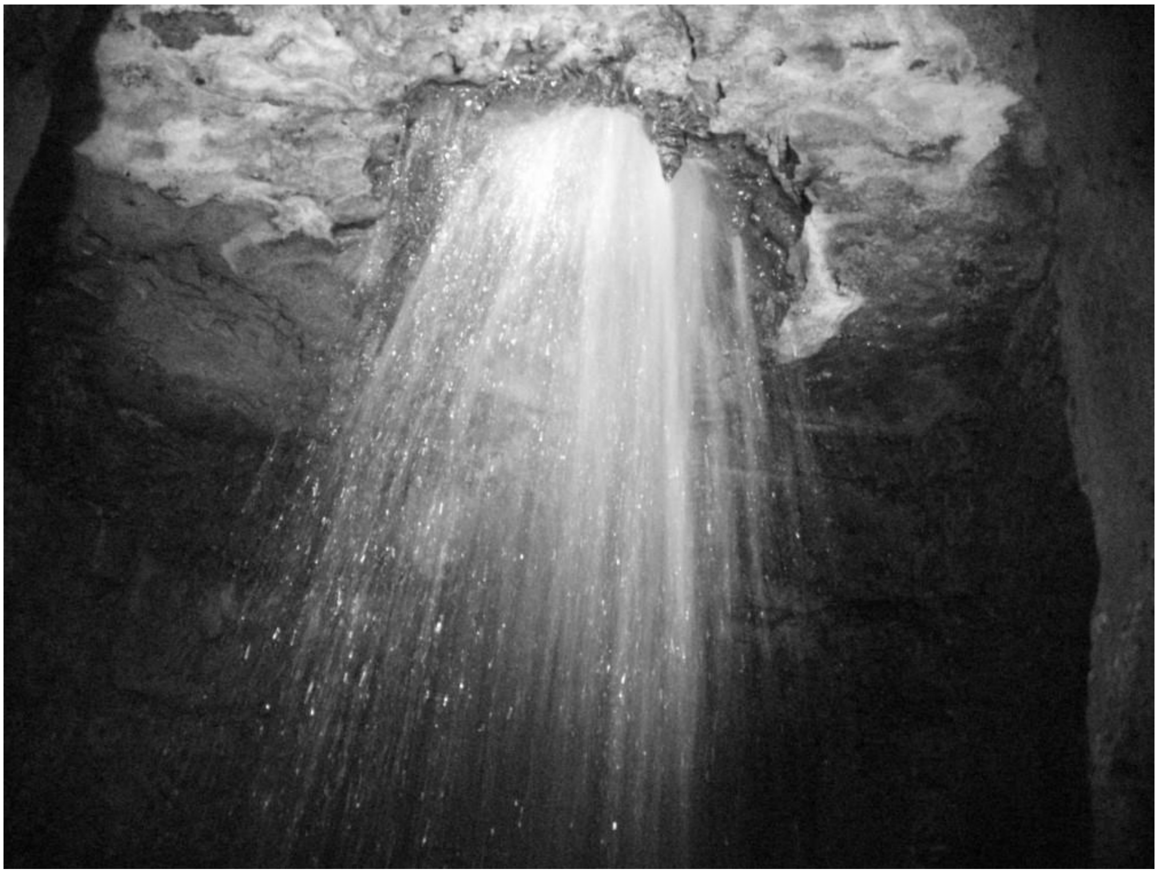

Fig. 4. The Old Artesian Well flowing in the "wrong" direction, showing bottom of drill-hole in the Platteville ceiling of Schieks Cave. Photo by author.

Geology

The bedrock layers are Ordovician units making up the Twin Cities basin, overlain by unconsolidated Quaternary glacial sediments (Retzler, 2018). A diagrammatic cross-section of the geology at Schieks Cave is shown as **Fig. 5**. Relative thickness of the layers above the cave are depicted in accordance with Zalusky (1953b), who apparently had access to the driller's fieldnotes from the construction of the Fourth Street entrance shaft.

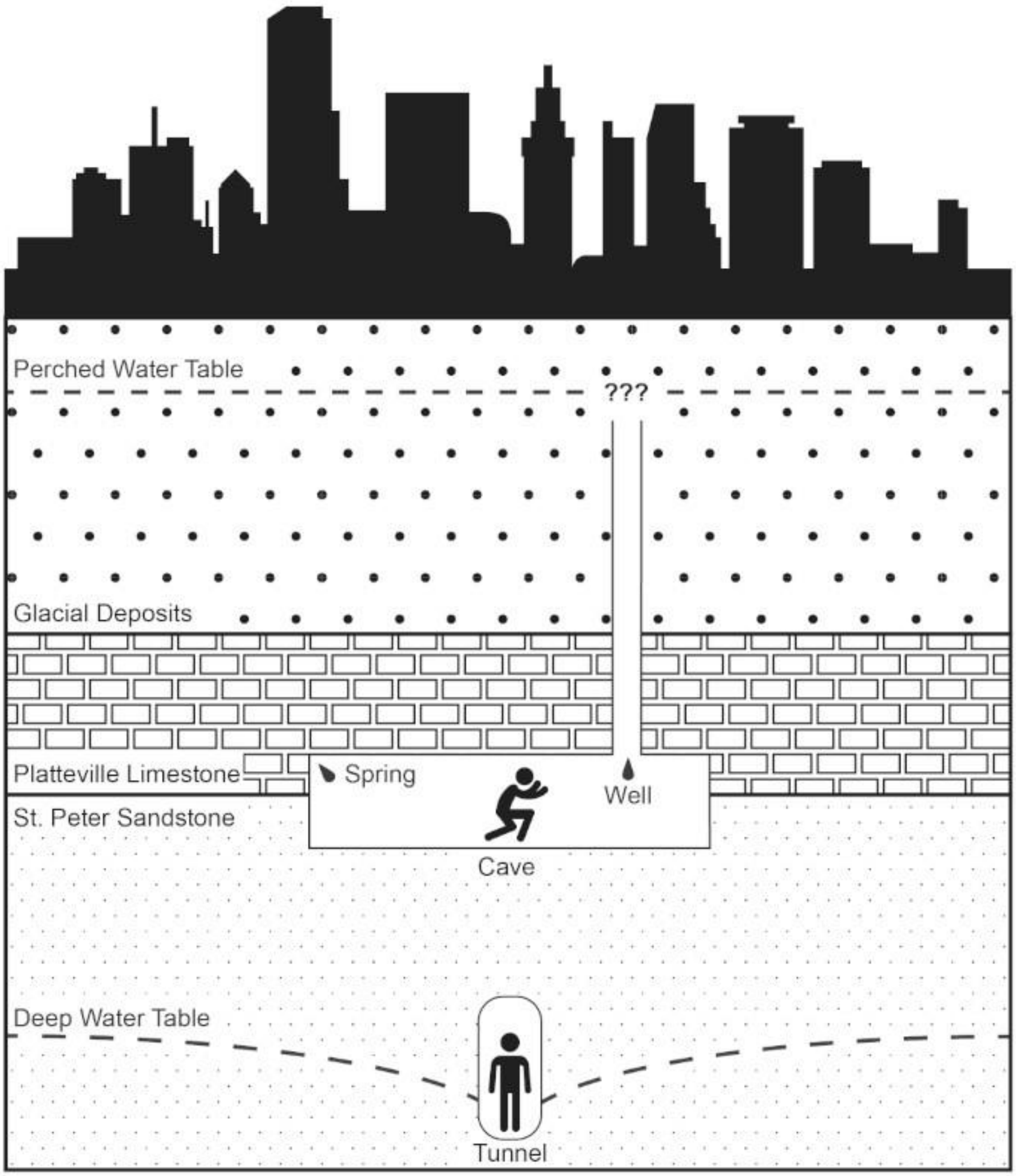

Fig. 5. Geological cross-section of Minneapolis at Schieks Cave (not to scale). LMF (spring) and OAW (well) are shown inside cave. A one-meter layer of Glenwood Shale between the Platteville and St. Peter has been omitted for clarity. Tunnel is 30 m below ground surface. Artwork by Jessica Rogge.

The Platteville Limestone is karstified, acting as aquifer or aquitard depending on the setting (Steenberg et al., 2011). The largest and most abundant springs in Minneapolis emanate from this layer (Brick, 1997). While a meter thick layer of Glenwood Shale, intercalated between the Platteville and St. Peter, has been omitted for clarity, this layer acts as an aquitard within the Twin Cities basin. Inside Schieks Cave, however, LMF issues from a bedding plane separating the two lowermost members of the Platteville Limestone: the thin Pecatonica (which usually falls away in open voids) and the thicker Mifflin (which remains to form flat ceilings) members. The shale does not appear to play a role here.

Two water tables are depicted in Fig. 5: a perched water-table in the shallow Quaternary aquifer and Ordovician limestone above the cave, and a deep water-table in the St. Peter Sandstone below the cave. The uppermost sandstone has a separate unsaturated zone. Groundwater infiltrates the tunnels through breaks in the concrete lining.

METHODS

Disclaimer: This project reports ad hoc data sets from a site that is difficult to access. The data sets were not obtained in a formally designed academic research project.

A search for existing well water temperature data was conducted. Two drilled wells penetrate Schieks Cave, one of which is the “Old Artesian Well” described above. The second is the M.L. & T. Co well, with an intact steel casing that passes entirely through the cave to an unknown depth below, about which no further information exists and which will not be further considered here. These wells are not listed in the online Minnesota Well Index (MWI) database, maintained by the Minnesota Department of Health, apparently because they predate the index, which began in 1974. A query of MWI for all wells within a 1.6 km radius of Schieks Cave found no temperature data for wells terminating in the glacial drift, Platteville Limestone, or St. Peter Sandstone (A.J. Retzler, pers. comm., 2021).

On 15 April 2007, I made another trip to Schieks Cave during which I conducted an extended thermometric survey of groundwater in the cave and underlying tunnel system, using the same thermometer as before.

LMF was measured in the same spot as before and the groundwater showering from OAW was measured in a concrete basin built into the floor of the cave. The water in this shallow basin undergoes rapid turnover. The same day, seepages in the Washington

Avenue tunnel, as well as flowing non-wet weather stormwater where tributary tunnels entered the main tunnel (for comparison purposes) were measured. The tunnel forms a 1.4-km transect from northwest to southeast at an average depth of 30 m (**Fig. 1b**). The deep-water table in the St. Peter Sandstone was accessed where it seeped through breaks in the concrete tunnel lining, usually leaving reddish staining on the walls (**Fig. 3b**).

RESULTS

The water temperatures from the 2000 and 2007 visits are listed in Table 1 along with descriptions of sampling points. The data include temperature measurements from: 1) Platteville Limestone groundwater in Schieks Cave (C1 – C8), which ranged from 16 to 17.9°C; 2) St. Peter Sandstone seepage in the Washington Avenue tunnel (T1 - T3), from 12.5 to 14°C; and 3) stormwater flow in the same tunnel (T4 – T10), from 13 to 18°C. Employing the terminology of Benz et al. (2017) the anthropogenic heat intensity (AHI) was 9.9 K for this SUHI at the time of the 2007 survey. The AHI reports the difference between the local value and the average rural groundwater background temperature.

The Schieks Cave features and their temperature sampling points are shown in **Fig. 2**. LMF was 19°C in 2000 and 17.1°C in 2007, while groundwater captured in the OAW concrete basin was 17.9°C. The cave air temperature was 18°C, measured inside the concrete chamber containing LMF. The average surface air temperature for the month of April, 2007, recorded at the Minneapolis-St. Paul International Airport, was 8.44°C (NOAA, 2021).

Much of the non-wet weather baseflow of the Washington Avenue tunnel is derived from groundwater infiltration and each tributary tunnel (T4 – T8) contributes its own separate temperature. The farthest downstream measuring point, the Chicago Avenue Outfall (T10) was 13.5°C, which presumably represents the mean temperature of all contributing flows in the storm drains mixed together. This temperature falls within the St. Peter seepage range, suggesting its ultimate origin as infiltration water.

DISCUSSION

The flows from LMF and OAW are documented inside Schieks Cave from the earliest map (1904) until today, more than a century, indicating that the water does not originate from leaking pipes or water mains (cf. Lerner, 1986).

Other possible sources of heat to groundwater can be excluded. Tissen et al. (2019) considered potential natural causes of elevated temperatures for SUHIs, especially hot springs, which are not present in Minnesota. Tissen et al. (2019) also considered Acid Mine Drainage (AMD). While the Platteville Limestone contains pyrites, subject to oxidation—an exothermic reaction—monitoring of Platteville springs has never detected elevated pH among them (Minnesota Department of Natural Resources, 2021).

Groundwater entering Schieks Cave was elevated above background by 11 K in 2000, larger than the 3 K predicted by Taylor and Stefan (2008, 2009) for the Minneapolis latitude. As a conceptual model, basements and pavements are warming the shallow Quaternary aquifer by vertical conduction **(Fig. 6)** and this water finds its way via OAW and fissures down through the Platteville Limestone, into the cave.

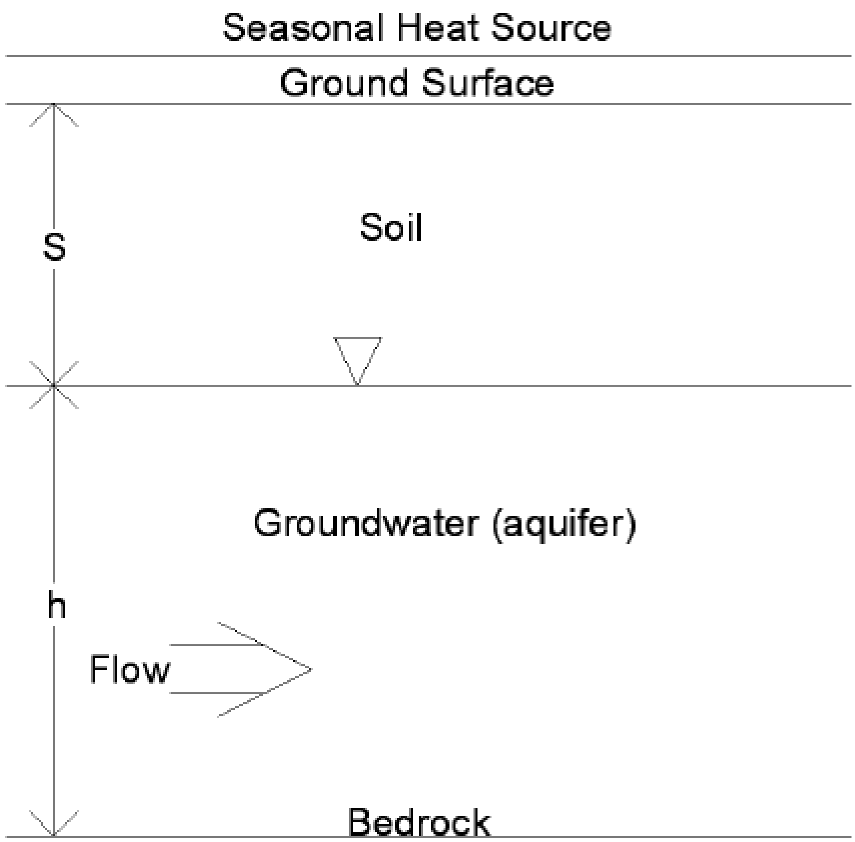

Fig. 6. "Schematic of aquifer of thickness h at depth S below the ground surface (from Taylor & Stefan, 2008, p. 21). At Schieks Cave, S=10.7 m and h=5.5 m. The soil compartment represents the unsaturated zone.

LMF was 19°C in May 2000 and 17.1°C in April 2007, a 1.9 K decrease during this seven-year interval. According to Taylor and Stefan (2008), seasonal temperature fluctuations penetrate the ground to depths of 10 to 15 m, within the depth range of the shallow Quaternary aquifer at this location. Continuous, multi-year temperature monitoring would be necessary to determine the magnitude of fluctuations at LMF. Kasahara (2016) documented a systematic, seasonal fluctuation in the water temperature in Coldwater Spring of 2.3 K (10.8 to 13.1°C) which lagged the surface air temperature by about four months. The change in temperature at LMF is within the range of documented seasonal fluctuation in the Platteville aquifer in Minneapolis.

Located within 23 m of the surface, LMF and OAW reveal elevated groundwater temperatures that are also within the range of depth for thermal anomalies measured by Taniguchi et al. (2007) in boreholes in four Asian cities: "The depth of deviation from the regional geothermal gradient was deepest in Tokyo (140 m), followed by Osaka (80 m), Seoul (50 m), and Bangkok (50 m)."

LMF and OAW, located 27 m apart inside Schieks Cave, had temperatures within 1 K of each other during the only event in which they were simultaneously measured, which would be expected if they are derived from the same aquifer.

At OAW, the temperature went from feeling "icy" (Longnecker, 1907), and thus presumably normal groundwater temperature of 8°C, to 17.9°C, in the 100 years from 1907 to 2007. While the first observation is qualitative and the second is quantitative, the century-long trend is unambiguous. This is strongest signal of anthropogenic groundwater warming in the state of Minnesota.

Where seepage waters were encountered in the St. Peter Sandstone below the Platteville Limestone, they were several degrees cooler, yet still about 5 K above background groundwater temperatures. The tunnel seepages (T1 – T3) cannot be easily revisited because the Central City Tunnel System project (2020-2023) plans to eliminate infiltration and the proposed construction of relief sewers will have likely disturbed the hydrology of the setting (CDM Smith Inc., 2018).

The warm groundwater "pool" of the SUHI thus appears to be perched in the strata above Schieks Cave, most likely (given vertical heat conduction considerations) in the shallow Quaternary aquifer but also the Platteville Limestone.

Attard et al. (2016) defined a thermally affected zone (TAZ) around urban structures as where the groundwater temperature is elevated 0.5 K above expected values. Menberg et al. (2013a) found hotspots below German cities elevated as much as 20 K. Menberg et al. (2013c) concluded that: "By modeling the anthropogenic heat flux into the subsurface of the city of Karlsruhe, Germany, in 1977 and 2011, we evaluate long-term trends in the heat flux processes. It revealed that elevated GST [ground surface temperature] and heat loss from basements are dominant factors in the heat anomalies."

In the case of Schieks Cave, the groundwater direction in the shallow Quaternary aquifer indicates flow from the west, through the heavily commercialized Nicollet Mall and the densest skyscraper cluster, towards the cave (Kanivetsky, 1989). The source of the heat is likely due to heated buildings as was shown by Krcmar et al. (2020), who reported groundwater temperatures had risen 3.2 K by flowing past a building in Bratislava, Slovakia.

Minneapolis is rare among SUHIs in that while the literature is almost exclusively based on data from observation wells, this example involves a cave functioning as a collection gallery for groundwater deep below the city surface. Schieks Cave thus affords a parallel with the historic cellar of the Paris Observatory, which lies at a comparable depth (28 m) and has been used for temperature measurements for centuries (Dettwiller, 1970).

Scott Alexander (pers. comm., 2021), hydrogeologist at the Earth Sciences Department at the University of Minnesota, stated that several shallow campus wells in the Platteville Limestone (used for teaching purposes) have had a long-term temperature of about 25°C. His opinion is that these elevated temperatures are due to the campus steam tunnel system, which is carved in the underlying St. Peter Sandstone. If true, this campus SUHI would be the inverse of the Schieks thermal anomaly in that the greater heat source is from below, rather than above.

The “twin” city of Minneapolis is the neighboring city of St. Paul, capital of the state of Minnesota. Unlike its twin, however, St. Paul features a multilevel utility tunnel system carved within the St. Peter Sandstone, on a larger scale than the university campus (Brick, 2009: 179-188). One of the levels contains a district heating system employing hot water. The conjectural St. Paul SUHI would likely involve both the shallow (perched) and deep water-tables. This SUHI could be more intense than that of Minneapolis, even though St. Paul has a smaller population, challenging some fundamental assumptions about urban heat islands based on population modeling (e.g., Oke, 1973).

CONCLUSIONS

Anthropogenic subsurface urban heat islands (SUHIs) in groundwater under cities are known worldwide. A subsurface urban heat island (SUHI) under the center of the built-up area of Minneapolis, Minnesota, USA, was first detected at a spring inside Schieks Cave located 23 m below street level. SUHIs are potentially threats to springs because much spring fauna, like trout, amphipods, and rare plants, is cold stenothermal.

Minneapolis is rare among SUHIs in that while the literature is almost exclusively based on data from observation wells, this case involves a cave functioning as a collection gallery for groundwater deep below the city surface.

A thermometric survey of the cave and tunnel seepages in 2007 revealed a temperature trend extending from 1907 to 2007, showing rising temperature from normal groundwater temperatures for this latitude (8°C) to 17.9°C in one century. This is strongest signal of anthropogenic groundwater warming in the state of Minnesota and is attributed to vertical heat conduction from basements and pavements.

Future studies of the spring and well in Schieks Cave should involve multilevel sampling, data loggers, lengthy time series spanning several years to detect possible seasonal trends, and MODFLOW visualization of data. Any future trip should take water samples as well as additional temperature readings of this feverish spring.

LITERATURE CITED

Alexander, E.C., Jr., & Brick, G.A. (2021). Minnesota Caves and Karst. IN: Brick, G.A. & Alexander Jr., E.C. (2021) *Caves and Karst of the Upper Midwest, USA*. Springer International Publishing Switzerland, 319 p https://doi.org/10.1007/978-3-030-54633-5

Attard, G., Rossier, Y., Winiarski, T., & Eisenlohr, L. (2016). Deterministic modeling of the impact of underground structures on urban groundwater temperature. *Science of the Total Environment* 572: 986-994

Bayer, P., Attard, G., Blum, P., & Menberg, K. (2019). The geothermal potential of cities. *Renewable and Sustainable Energy Reviews* 106: 17-30

Benz, S.A., Bayer, P., & Blum, P. (2017). Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany. *Science of The Total Environment* 584-585: 145-153

Brick, G.A. (1993). *The Platteville Springs of Minneapolis*. Term Paper, GEO 5613, Fall Quarter 1993. Minneapolis: University of Minnesota, 22p.

Brick, G.A. (1997). Along the Great Wall: Mapping the Springs of the Twin Cities. *Minnesota Ground Water Association Newsletter* 16(1): 1-7 https://www.mgwa.org/newsletter/mgwa1997-1.pdf

Brick, G.A. (2009). *Subterranean Twin Cities.* Minneapolis: University of Minnesota Press, 226p

Brick, G.A. (2014). Thermal pollution of groundwater under Minneapolis. MGWA Spring Conference. https://www.mgwa.org/meetings/2014_spring/2014_spring_abstracts.pdf

Brick, G.A. (2017a). A third kind of cave in the world: Anthropogenic. *Proceedings of the 17th International Congress of Speleology, Sydney, Australia*, II: 248

Brick, G.A. (2017b). *Minnesota Spring Inventory Guidance Document.* Minnesota Department of Natural Resources, Ecological and Water Resources, County Geologic Atlas Project, St. Paul, 32p https://files.dnr.state.mn.us/waters/groundwater_section/mapping/msi/MSI_GuideDoc.pdf

Brick, G.A. (2021). "This Strange Voyage": Significance of the 1907 Longnecker Narrative for Underground Minneapolis. *Minnesota Speleology Monthly* 52(1): 3-11

CDM Smith Inc. (2018). Preliminary Design Report, Central City Tunnel System, City of Minneapolis https://www.minneapolismn.gov/media/-www-content-assets/documents/wcmsp-214802.pdf

Dettwiller, J. (1970). Deep soil temperature trends and urban effects at Paris. *Journal of Applied Meteorology* 9(1): 178-180

Dornberg, D. (1939). Camera Safari Explores ‘Lost World’ Under Loop. *Minneapolis Journal*, April 16, pp 1, 8

Epting, J., Scheidler, S., Affolter, A., Borer, P., Mueller, M.H., Egli, L., García-Gil, A., & Huggenberger, P. (2017). The thermal impact of subsurface building structures on urban groundwater resources–a paradigmatic example. *Science of the Total Environment* 596-597: 87-96

Ferguson, G., & Woodbury, A.D. (2004). Subsurface heat flow in an urban environment. *Journal of Geophysical Research* 109: B02402

Ferguson, G., & Woodbury, A.D. (2007). Urban heat island in the subsurface. *Geophysical Research Letters* 34: L23713-L23713

Fitzsimmons, R.J. (1931). Burrowing workers risk lives for public’s health. *Minneapolis Tribune*, August 23, p 1

Hemmerle, H., Hale, S., Dressel, I., Benz, S,A., Attard, G., Blum, P., & Bayer, P. (2019). Estimation of groundwater temperatures in Paris, France. *Geofluids* Article ID 5246307 https://doi.org/10.1155/2019/5246307

Kanivetsky, R. (1989). Quaternary Hydrogeology. IN Balaban, N.H. (ed), *Geologic Atlas of Hennepin County, Minnesota*. County Atlas C-4. St. Paul: Minnesota Geological Survey, Plate 5. https://hdl.handle.net/11299/58491

Kasahara, S. (2016). *A hydrogeological study of Coldwater Spring, Minneapolis, MN*. Honors Thesis, University of Minnesota, 59p https://hdl.handle.net/11299/182336

Krcmar, D., Flakova, R., Ondrejkova, I., Hodasova, K., Rusnakova, D., Zenisova, Z., & Zatlakovic, M. (2020). Assessing the impact of a heated basement on groundwater temperatures in Bratislava, Slovakia. *Groundwater* 58(3): 406-412

Kress, A., & Alexander, Jr., E.C. (1980). Farmers and Mechanics Bank Cave. IN: EC Alexander, Jr (ed) *An Introduction to Caves of Minnesota, Iowa, and Wisconsin. Guidebook for the 1980 National Speleological Society Convention*, Huntsville, AL, pp. 59-67

Lerner, D. N. (1986). Leaking pipes recharge ground water. *Groundwater* 24(5): 654-662

Longnecker, J. (1907). In Caverns of Eternal Night. *Minneapolis Tribune*, July 7

Meersman, T. (2012). The comeback of urban trout. Brook trout dart in Ike's Creek in Bloomington, a rehabilitated sliver of nature not far from mall parking ramps and jets flying low overhead. *Minneapolis Star Tribune,* June 5, B1, B5

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., & Blum, P. (2013a). Subsurface urban heat islands in German cities. *Science of the Total Environment* 442: 123-133

Menberg, K., Bayer, P., & Blum, P. (2013b). Elevated temperatures beneath cities: an enhanced geothermal resource. IN: *Proceedings of the European Geothermal Congress*, Pisa, Italy

Menberg, K., Blum, P., Schaffitel, A., & Bayer, P. (2013c). Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island. *Environmental Science & Technology* 47(17): 9747-9755

Minnesota Department of Natural Resources (2021). Minnesota Spring Inventory, https://www.dnr.state.mn.us/waters/groundwater_section/springs/msi.html

Nicollet, J.N. (1845). Report intended to illustrate a map of the hydrographical basin of the Upper Mississippi River. Document of the US House of Representatives, 28th Congress, 2nd Session, No. 52. Washington (DC): Blair and Rives, 170p.

http://www.worldcat.org/title/report-intended-to-illustrate-amap-of-the-hydrographical-basin-of-the-upper-mississippiriver/oclc/166586906?referer=di&ht=edition

NOAA National Centers for Environmental Information (2021). April 2007, Local Climatological Data, Minneapolis, MN. https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:14922/detail. Accessed 26 July 2021.

Oke, T.R. (1973). City size and the urban heat island. *Atmospheric Environment* 7(8): 769-779

Retzler, A.J. (2018). Bedrock Geology, Plate 2. IN: Steenberg, J.R., Bauer, E.J., Chandler, V.W., Retzler, A.J., Berthold, A.J., & Lively, R.S. (2018) *Geologic Atlas of Hennepin County, Minnesota, County Atlas Series C-45, Part A*. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/200919

Steenberg, J., Runkel, A., & Tipping, R. (2011). Hydrostratigraphy of a fractured, urban aquitard: The Platteville Formation in the Twin Cities Metropolitan Area. *MGWA Newsletter* 30(4): 23-26

Taniguchi, M., Shimada, J., Fukuda, Y., Yamano, M., Onodera, S.I., Kaneko, S., & Yoshikoshi, A. (2009). Anthropogenic effects on the subsurface thermal and groundwater environments in Osaka, Japan and Bangkok, Thailand. *Science of the Total Environment* 407(9): 3153-3164

Taniguchi, M., Takeshi, U., & Karen, J. (2007). Combined effects of urbanization and global warming on subsurface temperature in four Asian cities. *Vadose Zone Journal* 6(3): 591-596

Taniguchi, M., & Uemura, T. (2005). Effects of urbanization and groundwater flow on the subsurface temperature in Osaka, Japan. *Physics of the Earth and Planetary Interiors* 152(4): 305-313

Taylor, C.A., & Stefan, H.G. (2008). Shallow groundwater temperature response to urbanization and climate change in the Twin Cities Metropolitan Area: Analysis of vertical heat convection effects from the ground surface. SAFL Report No. 504 http://home.safl.umn.edu/bmackay/pub/pr/pr504.pdf

Taylor, C.A., & Stefan, H.G. (2009). Shallow groundwater temperature response to climate change and urbanization. *Journal of Hydrology* 375(3-4): 601-612 https://doi.org/10.1016/j.jhydrol.2009.07.009

Tissen, C., Benz, S.A., Menberg, K., Bayer, P., & Blum, P. (2019). Groundwater temperature anomalies in central Europe. *Environmental Research Letters* 14(10): 104012

Yalcin, T., & Yetemen, O. (2009). Local warming of groundwaters caused by the urban heat island effect in Istanbul, Turkey. *Hydrogeology Journal* 17(5): 1247-1255

Zalusky, J.W. (1953a). What about the Loop Cave? *Hennepin County History* 13(1) (January): 5-6

Zalusky, J.W. (1953b). The Loop Cave continued. *Hennepin County History* 13(2) (April): 2-3, 5

Zhu, K., Blum, P., Ferguson, G., Balke, K.D., & Bayer, P. (2010). The geothermal potential of urban heat islands. *Environmental Research Letters* 5(4): 044002

Table 1. Thermometric Survey of Cave and Tunnels, 15 April 2007*

Origin	Description/location of temperature readings	Temp °C
Platteville Limestone groundwater in Schieks Cave.	C1: Old Artesian Well (OAW) concrete basin (rapid turnover)	17.9
	C2: Little Minnehaha Falls (LMF) ceiling spring at bedding plane*	17.1
	C3: Galvanized drip basin (south)	17.0
	C4: Galvanized drip basin (north)	16.9
	C5: Black Medusa formation, flowing like faucet	16.9
	C6: ML&T Co well hole, from still pool around steel casing	16.5
	C7: Seepage on flowstone in concrete drain	16.5
	C8: Black drip pool at base of ladder, seeping around steel shaft lining	16.0
St. Peter Sandstone seeps in storm drains via gaps in concrete lining.	T1: Red springs near floor, Washington Ave S, half way between 3rd & 4th Ave S	14.0
	T2: Red spring in floor of side passage, Washington Ave S/3rd Ave S	12.5
	T3: Leakage jetting from tunnel lining with red staining, Washington Ave S/Hennepin Ave	13.0

Non-wet weather flows in storm drains measured in tributary just before it joins flow in Washington Avenue tunnel.	**T4: Hennepin Ave at Washington Ave S**	**13.0**
	T5: Nicollet Mall at Washington Ave S	**15.5**
	T6: Marquette Ave at Washington Ave S	**14.5**
	T7: Side-passage half way between Marquette Ave & 2nd Ave S at Washington Ave S	**13.0**
	T8: 2nd Ave S at Washington Ave S	**18.0**
	T9: Iron Gate pool, Portland Ave/Washington Ave S	**15.5**
	T10: Chicago Ave Outfall at Mississippi River	**13.5**

***On 28 May 2000, the temperature of LMF was measured at 19°C. This was the only temperature measurement prior to the thermometric survey of 15 April 2007.**