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SINKHOLES: THEIR GEOLOGY, ENGINEERING AND ENVIRONMENTAL IMPACT

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Altura Minnesota lagoon collapses*

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ABSTRACT

In April 1976, a series of karst sinkholes opened in the holding lagoon of the Altura, Minnesota Waste Treatment Facility. This major failure was preceded by minor sinkhole formation during the construction of the facility in 1974. Subsequent detailed field mapping of the region around the community revealed at least 23 sinkholes not shown on existing maps. The distribution of the sinkholes as well as post-failure investigations of the lagoon indicate that catastrophic collapse is related to the presence of a thin, poorly indurated, jointed sandstone overlying a thick carbonate unit. The sandstone served to collect solutionally aggressive vadose water and to concentrate that water onto specific areas of the underlying carbonate. The resulting differential solution produced voids into which the overlying materials collapsed.

Introduction

Southeastern Minnesota is an area characterized by productive farms, small community centers, and a few moderate-sized cities. It is also an active karst area with characteristic geomorphic and ground water quality problems. Sinkholes develop over widespread areas. In most of the region drinking water has been shown to nearly exceed maximum acceptable standards for several parameters, and many individual wells exceed the drinking water standards. Growing concern by local and state leaders over increasing ground water problems prompted support for research in hydrogeology throughout the region.

The history of public works development on karst is all too often one of structural failure and/or ground water contamination caused by underestimating the design limitations inherent to karst regions. Yevjevich (1981) reviews many such problems on a national and international scale. Design experience from non-karst areas has proven to be an inadequate preparator for construction in karst regions. Evaluation of the past failures and their causes from a hydrogeologic standpoint helps to unravel the complexities inherent in karst regions and can help to avoid future problems. This paper documents the hydrogeologic environment and the consequences of one karst-related failure.

Background

Altura is a small town (population 354 in the 1980 census) in southeastern Minnesota. The major local industry, a turkey processing plant, increases the load on Altura's waste treatment facility by a factor of 10 during the 6 months of the year when the plant operates. The town's 1954-vintage filtration plant was seriously overloaded by the processing plant's wastes. During the late 1960s the Minnesota Department of Health received numerous complaints about the malodorous red effluent discharged from the old plant. That effluent sank into carbonate bedrock a short distance from its discharge point.

During the period 1971 through 1974, consulting engineers for the city of Altura designed and built an aerated pond system to treat the community's waste water. The system consists of two 1.1 ha primary aeration ponds, a 5.0 ha effluent storage pond, a chlorination and dechlorination system, and associated pumping system (Ellison, 1977). In the spring of 1974 precipitation waters, accumulated in the nearly completed effluent storage pond, drained suddenly into two sinkholes which developed in the pond bottom (Beaton, 1974). The estimated locations of these two collapse pits (Liesch, personal communication 1984) is shown on Figure 1 (Alexander, 1980). The sinkholes were excavated, backfilled with clay, and the clay liner in the pond upgraded. A hydrogeologic investigation was initiated and the ponds went into operation in the fall of 1974 (Beaton and Meyer, 1980).

The consulting hydrologist, investigating the potential for additional sinkhole development, conducted hammer seismic and electrical resistivity studies of the site. This study

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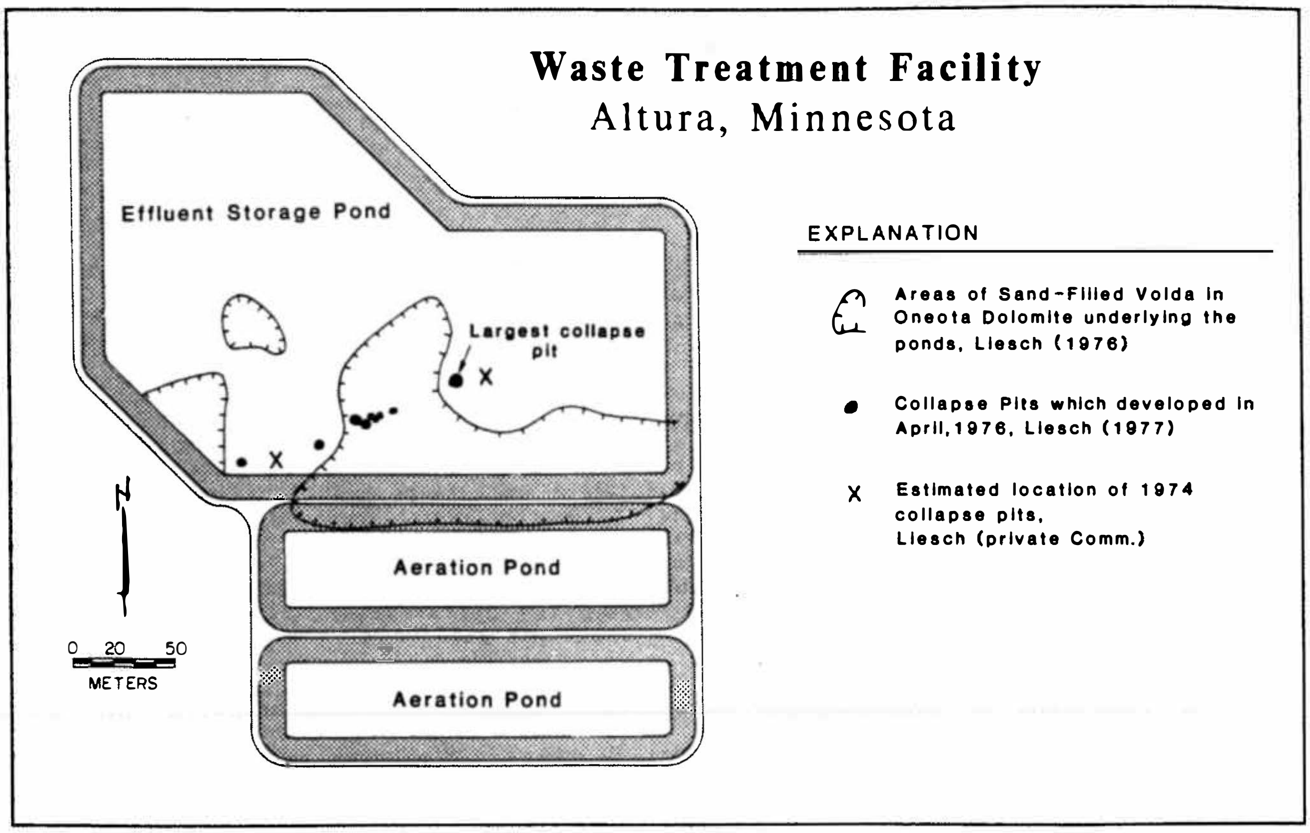

Figure 1: Plan view of the disabled Altura, Minnesota, Waste Treatment Facility showing the locations of the collapse sinkholes in the effluent storage pond.

revealed extensive areas of sand-filled voids in the underlying Oneota Dolomite (Liesch, 1974, 1976). Liesch recommended that three deep monitor wells be installed around the site and that an ongoing monitoring program be initiated. He concluded that any undetected voids would not be of sufficient size to cause a substantial collapse and a hazardous loss of water from the storage ponds or lagoon (Liesch, 1976). The monitor wells were never installed.

The treatment facility processed the waste stream from Altura for a year and a half before the effluent storage pond filled to its design depth of 3.0 m. The subsequent events are described in Ellison (1976). On April 27, 1976, the planned discharge of the effluent pond's contents, 1.41×10^8 l, into a nearby dry ravine was initiated. As soon as the discharge was underway it appeared to the operator that the pond level was dropping faster than could be accounted for by the discharge. The discharge gate was closed at 4:00 PM on April 28, but the level in the pond continued to drop. At 8:00 AM on April 29 discharge was resumed in an effort to minimize the loss through the unknown leaks.

By the morning of May 7, the effluent storage pond was completely drained. The cause of the leaks was clearly visible. A line of nine sinkholes had opened across the bottom of the pond. At 2:37 PM on May 7, 1976 the tenth and largest sinkhole was observed to develop by sudden collapse. The location in the storage pond of these sinkholes is shown in Figure 1. The largest sinkhole was approximately 3.6 m in diameter and approximately 7.0 m deep as measured to the top of the bedrock rubble.

Ellison (1976) calculated that just under 7.6×10^7 l were lost through the sinkholes. The remaining effluent, discharged into the dry ravine, reportedly disappeared underground within a few hundred feet. Whichever route was taken, the effect was the same -- the entire content of the effluent storage pond had entered into the area's ground water system in about 9 days. No adverse health effects were reported. A makeshift monitoring of Altura's municipal wells and nearby private wells, initiated after the pond was drained, detected no evidence of the effluent.

With the effluent storage pond out of operation the immediate problem became what to do with the effluent from the two remaining aeration ponds. It was decided to bypass the storage pond and to discharge, on a semi-continuous basis, the partially treated effluent from the primary aeration pond into the dry run. The effluent averaged about $2.0x10^5$ l/day and rose to about $1.26x10^6$ l/day when the turkey plant was in operation (Ellison, 1976). This effluent sinks underground before reaching the South Fork of the Whitewater River. The original NPDES permit for the site specified BOD_5 and TSS limits of 5 mg/l each for the effluent discharged into the dry run. The partially treated effluent from the two primary aeration ponds was several times the original limits. The Minnesota Pollution Control Agency (MPCA) then raised the BOD_5 and TSS effluent limits to 25 and 30 mg/l respectively (Breimhurst, 1977). This decision was based on the observation that the effluent sank underground and therefore would not have a significant effect on the Whitewater River (Anderl, 1977).

During December 1976 and January 1977 a series of ten exploration holes were bored in the bottom of the effluent storage pond (Liesch, 1977). These borings ranged from 18 to 30 m and extended through the New Richmond Sandstone into the top of the Oneota Dolomite. All 10 holes penetrated 'voids', which ranged from 5 cm to 1.1 m thick, in the Oneota Dolomite. Liesch (1977) concluded that an apparently integrated system of voids, penetrated at various depths by most of the bore holes, caused a continuous loss of circulation (drilling fluid) during the coring operations in the lower levels of the dolomite. The drilling confirmed the location of the sand-filled voids identified in the 1974 geophysical survey.

Liesch (1977) and Ellison (1977) outlined a number of alternative solutions to the problem caused by the failed storage pond. Beaton and Meyer (1980) and Beaton (1980) outlined the subsequent considerations which resulted, in June 1980, in an agreement to rehabilitate the storage pond by 1) sealing the existing sinkholes, 2) by building a new dike to isolate the northwestern portion of the pond, 3) to line the northwestern portion of the pond with a 20 mil polyvinyl chloride membrane, and 4) to use the resulting smaller, sealed pond for effluent storage as per the original design. To date no action has been taken.

It was in the preceding context that we undertook, in the fall of 1980, a hydrogeologic study of the Altura area. Our study had two primary goals: 1) to document the karst hydrogeologic conditions which led to the double failure of the effluent storage pond, and 2) to determine the subsurface flow path of the partially treated effluent flowing from the facility. The first goal involved detailed mapping of the area's geology, hydrology and karst features and a dye trace from the sinkhole in the pond. The second goal was accomplished by the dye trace of the sinking effluent. The results of the dye traces will be reported elsewhere.

Hydrogeology

The most detailed published bedrock geologic mapping of the area around Altura is Sloan and Austin's (1966) 1:250,000 scale St. Paul sheet. The region's hydrogeology and Paleozoic lithostratigraphy have been mapped at 1:500,000 scale by Broussard and others (1975) and by Mossler (1983). We have mapped the bedrock geology of the Altura 7.5-minute USGS topographic quadrangle at 1:24,000 scale (Book, 1983). Figure 2 is adapted from a portion of Book's (1983) map.

Altura is underlain by a series of lower Ordovician and Cambrian sandstone and carbonate strata which regionally dip very gently to the southwest. The town is situated on an elevated rolling ridge which is more than 100 m above deeply incised stream valleys to the northwest, east and west. The lowest stratum of concern to this study is the Cambrian Franconia Formation. Although the Franconia sandstone is not exposed in the region shown in Figure 2, it is not far below the surface of the deeper valleys and is an important aquifer in the area.

The Franconia is overlain by the St. Lawrence Formation, which is about 18 m thick in the study area and is exposed in the lowest portions of the valleys. The St. Lawrence is a silty to sandy carbonate unit with sporadic thin layers of interbedded shale. Outcrops are highly jointed. Outside the study area, the joints can be seen extending into the underlying Franconia Formation. In the study area the joints visibly extend upwards into the overlying Jordan sandstone. Although the St. Lawrence is mapped as a regional confining bed in Minnesota (Kanivetsky and Walton, 1979), it is leaky at best in Winona County. Book and others (1983) have recently shown, in a dye trace a few miles from Altura, that dye injected into the Oneota Formation emerges from Franconia springs. Several of the springs

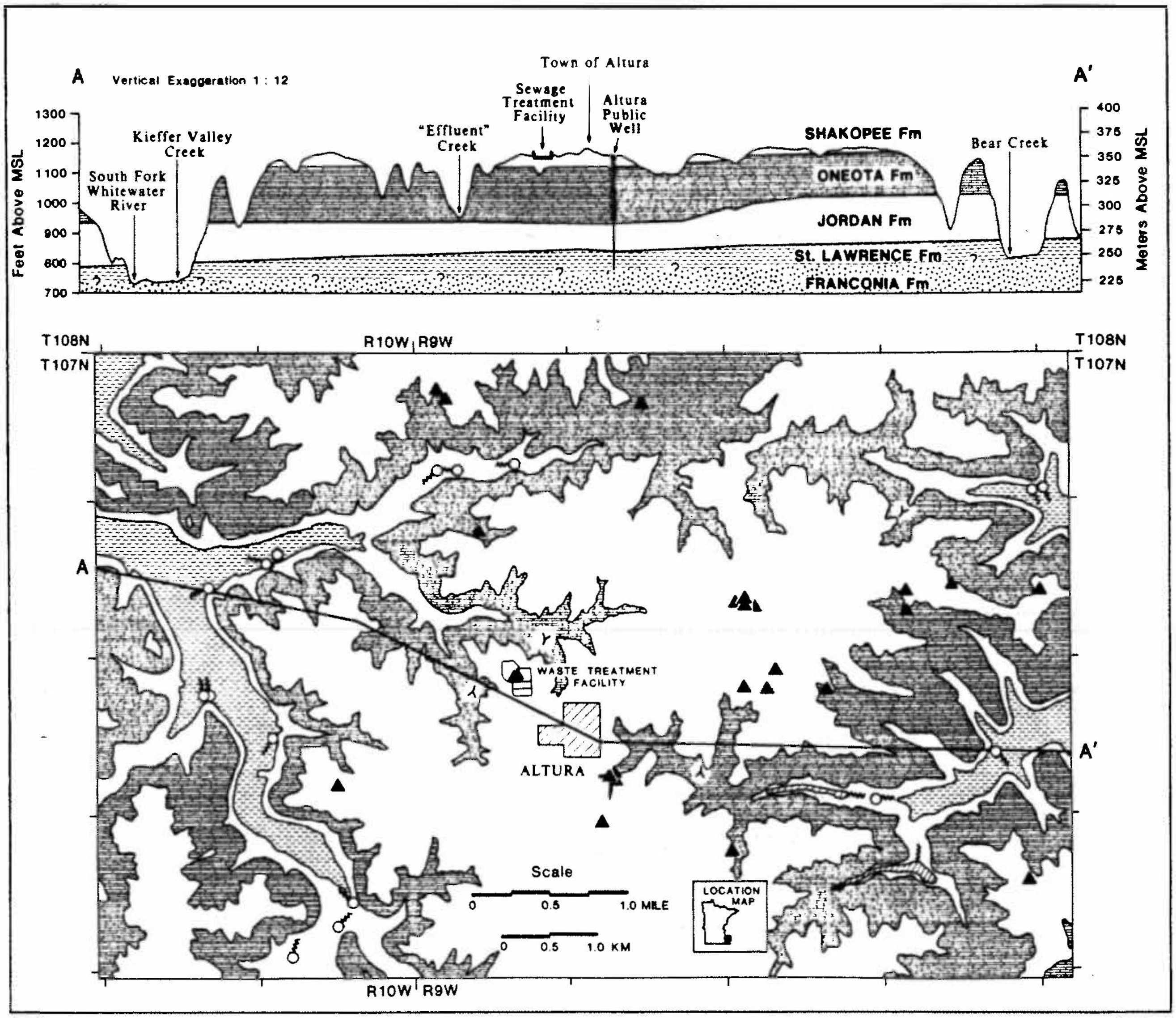

Figure 2: Bedrock geology of the area around Altura, Minnesota. Solid triangles are sinkholes. Open circles and crosshatched areas with squiggly tails are springs and seeps respectively. 'Ys' are caves.

shown in Figure 2 emerge from the St. Lawrence. In the study area, the Crystal Springs State Fish Hatchery receives in excess of 6000 l/min from two St. Lawrence springs.

The uppermost Cambrian unit is the Jordan Sandstone. The Jordan averages 30 m in thickness and crops out extensively in the study area. Directly above the St. Lawrence contact, the Jordan is a massive, upward-grading, fine- to coarse-grained friable sandstone. Upward in the unit, it becomes progressively more indurated with carbonate and siliceous cements, first forming lenses and concretions and then well-bedded, highly lithified strata. Joints are common throughout the Jordan and springs in the well-lithified portions tend to discharge directly from joints. In the more friable lower part, springs are often a combination of discrete flow from joints and diffuse flow from numerous seeps. The Jordan is the major source of water for upland wells in the study area.

The Ordovician Prairie du Chien Group conformably overlies the Jordan. The Prairie du Chien is composed of the lower Oneota Dolomite and upper Shakopee Formation. The Oneota is nearly 61 m thick in the study area and is a fine- to medium-grained, thick- to thin-bedded dolomite. The Oneota is a prominent cliff-former and the break in slope from the rolling uplands to the steep valley walls is usually at or just below the top of the Oneota. Both drill cores and outcrops reveal that the dolomite is highly jointed and has undergone extensive solution. The dolomite is vuggy to cavernous particularly in the upper portion. Only a few springs, confined to discharge from well-developed joints, have been mapped in the Oneota. No wells in the study area have been found which are finished in or rely solely on the Oneota as a water supply. Many older wells are open holes through the Oneota, however.

The Shakopee Formation is subdivided into the lower New Richmond Sandstone member and the upper Willow River Dolomite member. The latter is present only at the highest elevations of the study area and does not enter into the following discussions. The New Richmond Sandstone of the Shakopee Formation is a fine- to medium-grained quartzose sandstone with infrequent interbedded medium-grained arenaceous carbonate beds. This sandstone unit is friable, easily eroded, and does not form many outcrops. It does, however, form the first bedrock unit on much of the uplands in Figure 2. The New Richmond rarely exceeds a thickness of 6.1 m. It is extensively jointed and a few high springs emerge from the New Richmond/Oneota contact. The New Richmond is not a significant aquifer in the study area but is used to a minor extent south of the study area.

The entire region was glaciated at least once by a pre-Wisconsinan advance and scattered patches of drift can be found throughout the region. A blanket of Wisconsinan loess was deposited on the area, and varying thicknesses of recent alluvium and colluvium have collected on the valley floors and in karst solution cavities.

Karst Features

We have located and mapped four caves in the region shown on Figure 2. All four caves are small, phreatic maze caves in the Oneota (Alexander, 1981, 1983a, 1983b). The locations of these caves are shown on Figure 2. Sediment-filled solution cavities are common features in outcrops and quarry walls which expose the Oneota. The karstification of the Oneota probably began during the Ordovician and has continued intermittently until the present. U/Th disequilibrium dating of a speleothem in Skunk Hollow Cave (Alexander, 1983a), one of the caves shown on Figure 2, indicates that the cave is older than $(116 \pm 4) \times 10^3$ yr (R. Lively, pers. comm., 1983).

We have located 23 sinkholes (in addition to the ten in the bottom of the effluent storage pond) in the area covered by Figure 2. Eight of these sinkholes are currently open, while the others have been filled to return the land to agricultural use. The filled holes were identified through interviews with the local landowners. At least five of the sinkholes developed catastropically in the spring of the year in response to unusually wet conditions. It appears that the sinkholes tend to develop through the New Richmond Sandstone into the underlying Oneota. The New Richmond appears to be an integral part of the sinkhole development phenomena in this area.

Water-Quality Considerations

The deeply incised stream valleys northwest, west and east of Altura serve to isolate the hydrologic system beneath the town. The Kieffer Valley, northwest of Altura, is an intermittent stream system into which the effluent discharge flows. It is used primarily for livestock grazing, but two residences near the mouth of the valley draw domestic water from shallow sandpoint wells in the valley alluvium. Kieffer Valley is a tributary to the South Fork of the Whitewater River whose valley forms the west side of the ridge on which Altura is built. The Whitewater River is a major trout fishery and recreational stream. To the east is Bear Creek Valley, a residential/agricultural area. Several local homesteads draw water from shallow wells in the valley.

The waste treatment facility is on the crest of a knoll immediately northwest of Altura (Fig. 2). The town has three municipal wells, each of which produces water primarily from the Jordan Sandstone. Wells No. 1 and No. 3 are on the west side of town 0.61 km from the treatment facility. Well No. 2 is on the east side of Altura about 1.07 km from the lagoons. Well No. 1 is cased to only 14 m. It is evidently in direct hydraulic connection with the surface, shows evidence of surface contamination, and is used only in emergencies. Public health investigations (see for example Mierau, 1975) indicate that although Well No. 2 is cased and grouted through the Oneota into the Jordan, the well exhausts and draws large volumes of air as the static water level fluctuates. Well No. 2 exhibits seasonal fluctuations in nitrates and coliform bacteria, indicating surface connections and potential contamination. Well No. 2 is shown diagramatically in the cross section of Figure 2. Well No. 3, though cased and grouted into the Jordan, hydraulically intersects with Well No. 1

and therefore with the surface. This connection was determined when an attempt to seal Well No. 1 was undertaken. Four yards of clay were dumped into Well No. 1 and within an hour the previously sediment-free Well No. 3 turned muddy (Mierau, 1977).

Liesch (1976) reported that the municipal wells of Altura produce a cone of depression in the Jordan large enough to intercept any downward leakage from the treatment facility. The partially treated effluent from the treatment facility and any leakage from the site, enters the local ground water system. That effluent must be reaching: 1) the municipal wells, 2) the local private wells, 3) local springs and seeps discharging to the Whitewater River or Bear Creek, or 4) some combination of 1), 2), and/or 3).

Discussion

The goal of this study was to evaluate the hydrogeologic environment connected with the collapses of the storage lagoon at Altura. The goal was accomplished by detailed geologic mapping and by an inventory of karst features. Interviews with local landowners revealed information on the 23 sinkholes shown in Figure 2, and that catastrophic sinkhole formation is a common occurrence around Altura. The sinkholes range in size from meters to tens of meters across and deep. Most are small and are immediately filled to return the land to its original use. They are also too small and/or too transient to be shown on regional scale geologic or topographic maps. Anecdotal information indicates that the sinkholes most often form in the spring, particularly after heavy rains. As can be seen in Figure 2, most of the sinkholes develop through the New Richmond Sandstone into the underlying Oneota Dolomite.

Our detailed mapping therefore substantiates Liesch's (1974) interpretation that development of sinkholes in the Altura lagoon was dependent on the presence of the New Richmond Sandstone. Expanding on Liesch's (1974) explanation of this phenomenon the following model emerges: 1) Surface water percolating through the soil layer becomes charged with CO_2 and thereby can dissolve carbonates. 2) The sandstone unit serves to collect the carbonate-undersaturated soil water and concentrates its downward migration along joints and fissures. 3) The solutionally agressive waters are concentrated into specific areas of the carbonate beneath the joints in the sandstone. 4) Selective dissolution and widening of interconnecting Oneota joints creates voids in the dolomite. 5) The growing Oneota voids are bridged by increasingly unsupported and incompetent sandstone beds. 6) Loading of the sandstone, naturally by precipitation or artificially by construction, ultimately leads to collapse. 7) Surface runoff or impounded water was then concentrated into the collapse depression and mechanical erosion moves sediments through the underlying karst openings further enlarging the surface collapse.

Note: The installation of bentonite clay liners may actually aggravate this phenomenon, despite the low permeability of the clay. Ion exchange reactions in the bentonite will tend to reduce the calcium and magnesium ion activities as water passes through the liner. Thus waters seeping from a bentonite-lined structure will probably be considerably more solutionally aggressive to carbonates than was the soil percolation.

Williams and Vineyard (1976) compiled data on 97 recorded catastrophic collapse features in Missouri karst since 1930. Twenty-four of the collapses were attributed to artificially altered surface drainage and ten were caused by impoundment structures. The Altura collapse fits Williams and Vineyard's pattern. The hydrogeology of the Altura site is particularly susceptible to such collapses. There is good reason to believe that the collapses could eventually expand to the two remaining primary treatment ponds as the conditions which led to the original collapses continue to exist.

Camin (1978) discusses the history of the West Plains, Missouri, sewage treatment lagoons. Sinkhole collapse began during the construction of the facility in 1964. Additional collapses occurred in 1966 and 1974 at various locations in the lagoons. A major collapse in May of 1978 contaminated the local aquifer and resulted in 800 cases of flu-like illnesses among people who drank contaminated ground water. The most damaging collapse did not occur, therefore, until the facility had been in operation for 14 years. The sequence of events at West Plains and Altura has been strikingly similar so far.

Summary

The waste treatment lagoon failures at Altura, Minnesota, are not unique. The failures are only one of many cases in which water retention structures have collapsed in karst hydrogeologic regimes. Although sinkholes were not visible at the site prior to construction and are not shown on available topographic and geologic maps of the surrounding area, sinkholes were present a short distance in any direction from the site. These sinkholes, had they been identified, could have provided an indication that the region was an active karst. A clear indication of the site's instability was given by the initial collapses in 1974 during the construction phase of the lagoons and Liesch's (1974, 1976) subsequent geophysical investigations. These warnings were not heeded and the disabling 1976 collapses occurred. The presence of a thin, jointed, poorly indurated sandstone overlying a thick carbonate unit is particularly prone to catastrophic collapse. There is a substantial risk of future collapses under the existing aeration ponds.

Final Note

The 1980 plan to rehabilitate the effluent storage pond has been changed. The current plan (S. Higuchi, pers. comm., 1984) is to: 1) abandon use of the effluent storage pond, 2) fill the sinkholes in the pond bottom, and 3) construct a building to house a waste water clarifying device within the abandoned pond. The turkey processing plant is now pretreating its effluent to decrease the seasonal loading on the entire facility. Altura's waste treatment facility will ultimately cycle waste water through the two existing aeration ponds, the new clarifying device, a chlorination/dechlorination system and then continuously discharge the final effluent into the dry run west of the facility.

Acknowledgments

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