Altura, MN Waste Treatment Lagoon Failures:

A Hydrogeologic Study

by

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ABSTRACT

In April 1976, a series of karst sinkholes opened in the holding lagoon of the Altura MN Waste Treatment Facility. Subsequent detailed field mapping of the region around the community revealed at least 22 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.

The disabled facility has been diverting partially treated effluent into a nearby dry run since the lagoon collapsed. A dye trace documented that the effluent after sinking underground reemerges from three local springs and then flows into a river which is a regional trout fishery. However, a second dye trace from the sinkhole in the lagoon failed to establish a connection to any local well or spring.

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 facilities 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 2.7-acre (1.1 ha) primary aeration ponds, a 12.4-acre (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 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 10 ft (3.0 m). The subsequent events are described in Ellison (1976). On April 27, 1976, the planned discharge of the effluent pond's contents, 3.73×10^7 gal (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 12 ft (3.6 m) in diameter and approximately 23 ft (7.0 m) deep as measured to the top of the bedrock rubble.

Ellison (1976) calculated that just under 2×10^7 gal (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 $5.2x10^4$ gal/day ($2.0x10^5$ l/day) and rose to about $3.33x10^5$ gal/day ($1.26x10^6$ 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 60 to 100 ft (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 2 in (5 cm) to 3.5 ft (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.

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.

Bedrock Geology

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 300 ft (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 60 ft (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 shown in Figure 2 emerge from the St. Lawrence. In the study area, the Crystal Springs State Fish Hatchery receives in excess of 1600 gal/min (6000 l/min) from two St. Lawrence springs.

The uppermost Cambrian unit is the Jordan sandstone. The Jordan averages 100 ft (30 m) in thickness and crops out extensively in the study area. Directly above the St. Lawrence contact, the Jordan is a massive, upwardgrading, 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 200 ft (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 very 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 Member 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 20 ft (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 0.38 miles (0.61 km) from the treatment facility. Well No. 2 is on the east side of Altura about 0.66 miles (1.07 km) from the lagoons. Well No. 1 is cased to only 46 ft (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). A primary goal of this study was, therefore, to determine where the partially treated effluent went after it sank underground. The most direct, unambiguous technique available was water tracing using a fluorescent dye.

DYE TRACING

Rhodamine WT, a fluorescent red organic dye, is the most effective dye for studies in carbonate aquifers. It is stable in most ground water environments with good resistance to photochemical and biological degradation. Rhodamine WT is fairly inexpensive, has a low toxicity and adsorption by sediments, and the background fluorescence in the red part of the spectrum in most natural waters is very low (Smart and Laidlaw, 1977). The dye can be detected with a field fluorometer at concentrations as low as a few parts per trillion (10^{-12} g/g).

There are two basic options for detecting the dye: quantitative direct water samples and qualitative integrating charcoal samplers (the latter are commonly referred to as charcoal 'bugs'). The potential flow paths of the effluent included the fractured, karst Oneota aquifer, the porous and highly jointed Jordan aquifer, and surficial aquifers in the valley alluvium. We planned for an extended study and opted for the qualitative charcoal bug detectors. The use of bugs has the advantage of allowing for weekly or longer collection of samples thus conserving time and money. The disadvantages are that bugs are occasionally lost or damaged, and the data are qualitative.

Fluorescent dyes are also used to determine the flow of surface streams. The dye is injected at a known rate, allowed to mix with the stream, the resulting diluted concentration downstream is measured, and the flow is calculated. This technique works very well on small, high gradient streams where conventional flow measurements are difficult if not impossible.

On October 18, 1980 a sampling network of springs, wells, and surface-stream stations was established (Fig. 3 and Table 1). Bugs were placed at these stations and were changed periodically throughout the study. On October 25, 1980 the dye dilution technique was employed to measure the flow in the effluent stream at four locations between the terminal sink and the treatment plant outfall. The goal was to establish where in the section the effluent was sinking.

On October 26, 1980 the first dye trace was initiated. A twenty-five pound

(11.3 kg) slug of 20 percent Rhodamine WT was poured into the effluent stream at the outflow pipe shown on Figure 3. The dye traveled down the effluent stream, over exposed Oneota and Jordan bedrock and valley alluvium. The dye reached the terminal sink of the effluent stream, 1.8 miles (2.9 km) downstream from the outflow pipe, during the night of October 26-27, 1980.

During February 1981 an opportunity developed to run a dye trace from the largest sinkhole in the storage lagoon. Melting snow, accumulating in the storage pond, produced a small stream which drained into the large sinkhole. Conditions for a dye trace were far from optimum. Dye from the primary trace was still emerging from several springs eliminating Rhodamine WT as a tracer. The ground was still frozen and ground water recharge and flow were assumed to be at the low ebb for the year. The turkey processing plant was not in operation and the pumping rate of the city wells was much lower than during the summer and fall. Nevertheless, in cooperation with the Altura town council, a trace was initiated from the failed effluent storage pond. On February 27, 1981, 4.5 kg (9.9 pounds) of 86 percent Fluorescene (disodium fluorescene) were injected into a stream which was disappearing into the large sinkhole in the bottom of the storage pond.

The sampling of the stations in Figure 3 was continued through July 20, 1981. Two of the spring stations were resampled in August and September of 1981.

Results

Results of the Rhodamine WT dye dilution stream flow measurements of October 25, 1980 are shown in Figure 4. The flow rates were determined by using the formula:

$$Q = q\ (C_o/c)$$

where: Q is the effluent flow rate (l/sec)

q is the injection rate of the dye (l/sec)

C_o is the concentration of the injected dye

c is the concentration of dye in the effluent stream after it is well-mixed*.

*c was measured in the field on direct samples of the effluent flow using a Model 10-005 Turner Designs field fluorometer.

The flow in the effluent creek was measured at four locations between the terminal sink and the outflow pipe. At the outflow pipe discharge was measured at 14.7 l/sec. As the effluent descended across the upper portion of the Oneota, 0.6 l/sec of the flow was lost. There was no measurable loss of flow across the middle portion of the Oneota. 1.8 l/sec of the effluent was lost to the lowest portion of the Oneota, the exposed section of the upper Jordan and to the initial part of the valley alluvium. The bulk of the flow, 12.3 l/sec, sank into the sands and gravels of the valley fill.

The results of the Rhodamine WT analyses from the bugs of the first dye trace are listed in Table 2. Field stations are shown in Figure 3. The dye was chemically stripped from charcoal using the techniques described in Aley and Fletcher (1975), and the Rhodamine WT was then measured in the stripping solvent. The data are reported as equivalent concentration of Rhodamine WT because at low concentrations, the signal reported by the fluorometer may be due solely to naturally occurring fluorescent compounds. Dye trapped on the bugs is a function of its concentration in the water. However, the exact relationship between dye in the water and dye extracted from the bug has not been determined. The values reported in Table 2 are therefore only a qualitative record of the change in concentration as the dye flows past the bug.

The consecutive occurrence of two equivalent Rhodamine WT values equalling or exceeding 0.5 ppb was chosen as a positive indication of the injected dye. This value is based on inspection of the accumulated data presented in Table 2, and is believed to exceed any fluctuations of natural fluorescence occurring as seasonal change in this ground water system.

The Rhodamine WT data in the bugs from Stations 4, 6, 8, and in two surface water stations which drain these springs; Stations 2, and 5, indicate well-defined pulses of dye moving in the system. We did not detect Rhodamine WT in any other sampling locations. In Figure 5 we have presented plots of Stations 2, 4, 6 and 8 as well as background data from Stations 3 and 9 for comparison.

One very anomalous data point appears in the data set -- the Oct. 25 to Nov. 1 datum of 51.0 ppb from Station 4. The datum is over three times higher than the next highest value and occurs immediately after the dye was injected into the losing stream; i.e., faster than the expected subsurface flow in this geologic environment. A rumor has reached the authors recently that an individual or individuals removed a quantity of Rhodamine WT dye before it sank underground and poured it in this spring. As the rumor cannot be substantiated, the datum is included in both Table 2 and Figure 5, but is suspect.

All of the well stations yielded low values of equivalent Rhodamine WT concentrations. The average of 41 analyses from seven wells gave a value of 0.03 ± 0.02 ppb. The equivalent Rhodamine WT concentrations in the three springs in which we detected no pulses above our 0.5 ppb cutoff value, yield an average background value of 0.11 ± 0.12. The factor of 3.8 increase in the spring background relative to the well background is presumably due to a larger component of biologically derived fluorescence in the springs.

The Fluorescene data set proved to be more ambiguous than that of the Rhodamine WT. Table 3 reveals no well-defined pulses of fluorescent dye moving through the system. Well stations all yielded consistent equivalent Fluorescene values presumably in the background range. A mean of 1.02 ± 0.69 ppb was calculated for the wells. Background fluorescence in the Fluorescene spectrum was 34 times that of Rhodamine WT in the wells.

The Fluorescene values from the springs were both higher and more erratic than the well data. Fluorescence from natural organics is near or within the Fluorescene spectrum, making the detection of this dye difficult. The 47 values measured from the springs ranged from 0.43 ppb to 17.0 ppb with a mean value of 4.8 ± 3.6 ppb. Using a value of 12.0 ppb, two standard deviations from the mean, as a detection limit for the dye, Station 9 showed possible Fluorescene presence. These values measured during the May 23-July 20 and July 20-September 11 periods, are anomalous for two reasons. Duplicate measurements made for these two periods did not replicate well and the integration period exceeded by weeks that of the previous data. This suggested the possibility that the high data points were due to the accumulation of natural background during the longer integration period of these two data intervals.

A plot of equivalent concentration of dye (ppb) vs. ΔT (days of integration) was constructed to help evaluate the accumulation possibility. A plot of the data from Station 9 (Fig. 6) shows a strong correlation ($r = 0.918$) between the measured dye concentration and ΔT. This suggests that accumulation of fluorescing material was responsible for the elevated equivalent Fluorescene values and that none of the data in Table 3 represent detection of the Fluorescene injected into the sinkhole in the lagoon bottom.

In contrast, the Rhodamine WT data discussed above are not consistent with an accumulation of background fluorescence. Figure 7, which plots the Rhodamine WT data from station 8 in the same format as Figure 6, illustrates the difference in behavior of the Rhodamine WT and Fluorescene data. The Rhodamine WT data show a poor correlation with integration time ($r = 0.506$) and are therefore not consistent with a progressive accumulation of background model.

DISCUSSION

The goals of this study were to evaluate the hydrogeologic environment connected with the collapses of the storage lagoon at Altura and to determine the subsurface flow paths of the disabled treatment facility's effluent. The first 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.

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.

The study's second goal was accomplished through two dye traces. The first trace documented the migration paths of partially treated sewage effluent into the surface and subsurface waters of the Kieffer Valley. Hydrologic connection was confirmed to three springs, and final discharge of the effluent into the Whitewater River was documented.

The second dye trace produced no verifiable contaminant paths. Ghikas and others (1983) listed four possible causes for failure to detect a dye trace:

1. The tracer passed the observation points undetected between two samplings.
2. The tracer was diluted below the detection level.
3. The tracer passed after the end of the monitoring period.
4. The tracer passed an unknown and therefore unmonitored discharge point.

Given the integrating nature of the charcoal bugs, 1) can be ruled out. The second cause is certainly possible, particularly given the higher background fluorescene in the Fluorescene region of the spectrum. Cause 3) is always a possibility and the Fluorescene may be discharging at this moment. The end of the monitoring was dictated by economics, not by hydrogeology. We tried to avoid cause 4) by design of the sampling network, but in the absence of monitoring wells near the lagoon we were constrained to use springs and a few wells as our sampling points. Our network was thinnest to the north and east. We did not, however, detect any Fluorescene in the Altura municipal well which is roughly east of the collapsed sinkhole.

Dye trace experiments yield definitive positive results, but do not yield definitive negative results. Our inability to find the Fluorescene pulse cannot be used to argue that connections do not exist to any given well or spring. Water did go into the sinkhole in the lagoon bottom and that water goes somewhere. On the basis of available data we are unable to specify where the water goes. An attempt to trace the flow from the lagoon failure in West Plains, Missouri, also failed to document a connection to local wells even though the users of the wells had been made ill (Camin, 1978). People can be more sensitive 'detectors' of pathogen contamination than are dye traces.

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. 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.

The Rhodamine WT dye trace of the partially treated effluent from the disabled facility documented the effluent's subsurface flow paths. Three springs through which the effluent returns to the surface flow were identified. The effluent resides underground for a few weeks to months and then empties into the South Fork of the White Water River.

The Fluorescene dye trace from the sinkhole in the failed lagoon did not yield positive results.

Neither of the dye traces documented connections to any municipal or private water supply wells which we monitored. This does not prove that such connections may not exist, it only indicates that under the conditions of these traces we did not document a connection.

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REFERENCES

Alexander, E.C. Jr., 1980. Geology Field Trip. In E.C. Alexander, Jr. (ed.), An Introduction to Caves of Minnesota, Iowa and Wisconsin, National Speleological Society Convention Guidebook No. 21, 180 pp.

Alexander, C., 1981. Minor caves near the Altura Waste Treatment Lagoon. Minnesota Speleological Monthly, v. 13, no. 1, p. 3-4.

Alexander, C., 1983a. Skunk Hollow Cave, Winona County. Minnesota Speleological Monthly, v. 15, no. 2, p. 30-31.

Alexander, C., 1983b. Hog Hollow Cave, Winona County. Minneosta Speleological Monthly, v. 15, no. 7, p. 81-82.

Aley, T. and M.W. Fletcher, 1976. The water tracer's cookbook. Missouri Speleology, v. 16, no. 6, p. 1-32.

Anderl, W.H., 1977. Field investigation on Altura Minnesota, July 12, 1977. Minnesota Pollution Control Agency Office Memorandum to J.F. McGuire, dated August 16, 1977, 1 p.

Beaton, P.T., 1974. Altura, Minnesota pond collapse. Minnesota Pollution Control Agency Office Memorandum to L.C. Barbie, dated June 18, 1974, 3 pp.

Beaton, P.T., 1980. Letter to E.C. Alexander, Jr., dated August 25, 1980, 5 pp.

Beaton, P.T. and G.W. Meyer, 1980. Summary of the events leading to the current rehabilitation proposal for the Altura pond system. Minnesota Pollution Control Agency Memorandum to T. Hoffman, dated July 18, 1980, 3 pp.

Book, P.R., 1983. Bedrock geology of the Altura 7.5' quadrangle. Unpublished manuscript map.

Book, P.R., J.B. Dalgleish, and E.C. Alexander, Jr., 1983. Semiquantitative tracing of groundwater flow through fractured karst and jointed sandstone aquifers (abstract). EOS, Trans. Amer. Geophys. Union, v. 64, no. 18, p. 229.

Breimhurst, L.J., 1977. Letter to R.J. Ellison, dated August 26, 1977, 2 pp.

Broussard, W.L., D.F. Farrell, H.W. Anderson, Jr., and P.E. Felsheim, 1975. Water resources of the Root River watershed, southeastern Minnesota. U.S. Geol. Survey Hydrologic Investigations Atlas HA-548, 3 plates.

Camin, K.Q., 1978. Report of West Plains, Mo. Lagoon Incident, May 5 - June 22, 1979. U.S. Environmental Protection Agency, Region 7, Kansas City, Mo. Report dated June 30, 1978, 45 pp.

Ellison, R.J., 1976. Report on sinkholes and leakage at Altura, Minnesota waste treatment facility. Letter to P.T. Beaton, Minnesota Pollution Control Agency, dated July 19, 1976, 80 pp.

Ellison, R.J., 1977. Report on proposed rehabilitation of the Altura waste water treatment facilities. Ellison-Pihlstrom Report dated Oct. 18, 1977, 29 pp.

Ghikas, I.Ch., G.P. Kruseman, I.L. Leoniadis, and D.H. Wozab, 1983. Flow pattern of a karst aquifer in the Molai area, Greece. Ground Water, v. 21, no. 4, p. 445-455.

Kanivetsky, R. and M. Walton, 1979. Hydrogeologic map of Minnesota bedrock hydrogeology: A discussion to accompany State Map Series S-2. Minnesota Geol. Survey, 11 pp.

Liesch, B.A., 1974. Hydrogeologic investigation of the Altura area for Altura, Minnesota. Report dated November 1974, 18 pp.

Liesch, B.A., 1976. Evaluating polution-prone strata beneath sewage lagoons.

Public Works, v. 107, no. 8, pp. 70-71.

Liesch, B.A., 1977. Test drilling investigations at Altura, Minnesota waste treatment facility. Report dated April 7, 1977, 10 pp. plus maps.

Mierau, L.W., 1975. Report on investigation of municipal water supply, Altura, Minnesota. Minnesota Department of Health Report dated April 8, 1975, 7 pp.

Mierau, L.W., 1977. Notes from a 21 June, 1977 telephone conference with J. Winkelman. Minnesota Department of Health Files, Rochester, Minnesota, 2 pp.

Mossler, J.H., 1983. Paleozoic lithostratigraphy of southeastern Minnesota. Minnesota Geol. Survey Miscellaneous Map Series M-51, 8 plates.

Sloan, R.E. and G.S. Austin, 1966. Geologic map of Minnesota: St. Paul Sheet. Minnesota Geol. Survey.

Smart, P.L. and I.M.S. Laidlaw, 1977. An evaluation of some fluorescent dyes for water tracing. Water Resources Res., v. 13, no. 1, pp. 15-30.

Williams, J.H. and J.D. Vineyard, 1976. Geologic indicators of catastrophic collapse in karst terrain in Missouri. In F.R. Zwanzig (ed.), Transportation Research Record 612: Subsidence over Mines and Caverns, Moisutre and Frost Action, and Classification, National Academy of Sciences, pp. 31-37.

Yevjevich, V. (ed.), 1981. Karst Water Research Needs. Water Resources Publications. Littleton, Colorado, 260 pp.

FIGURE CAPTIONS

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

Fig. 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.

Fig. 3. The sampling network in relationship to the topography and surface drainage. Open circles are spring stations. Open triangles are surface-stream stations. Open squares are water well stations. The cross section shown in Figure 4 runs along the bottom of Kieffer Valley from just west of station 2 to the Terminal Sink, up the southeast fork of Kieffer Valley to the outflow pipe and then east across the Waste Treatment Facility to the vicinity of station 12.

Fig. 4. Stream profile and effluent flow regime of the 'effluent creek' in Kieffer Valley. See Figure 3 for location of the cross section.

Fig. 5. Results of Rhodamine WT measurements from selected stations in the sampling network. Spring stations 4, 6, and 8 and the surface-stream station 2 show positive results. Well stations 3 and spring station 9 are negative results. Asterisk indicates a lost bug.

Fig. 6. Scatter plot of the Fluorescene data versus integration time (ΔT) from station 9. The good correlation indicates that the measured equivalent concentrations are the result of accumulation of background fluorescent materials on the charcoal detectors.

Fig. 7. Scatter plot of the Rhodamine WT data versus integration time (ΔT) from

station 8. The poor correlation indicates that these data are not consistent with accumulation of background fluorescent materials and that Rhodamine WT was detected at this station.

Fig. 1. Top
Book and Alexander

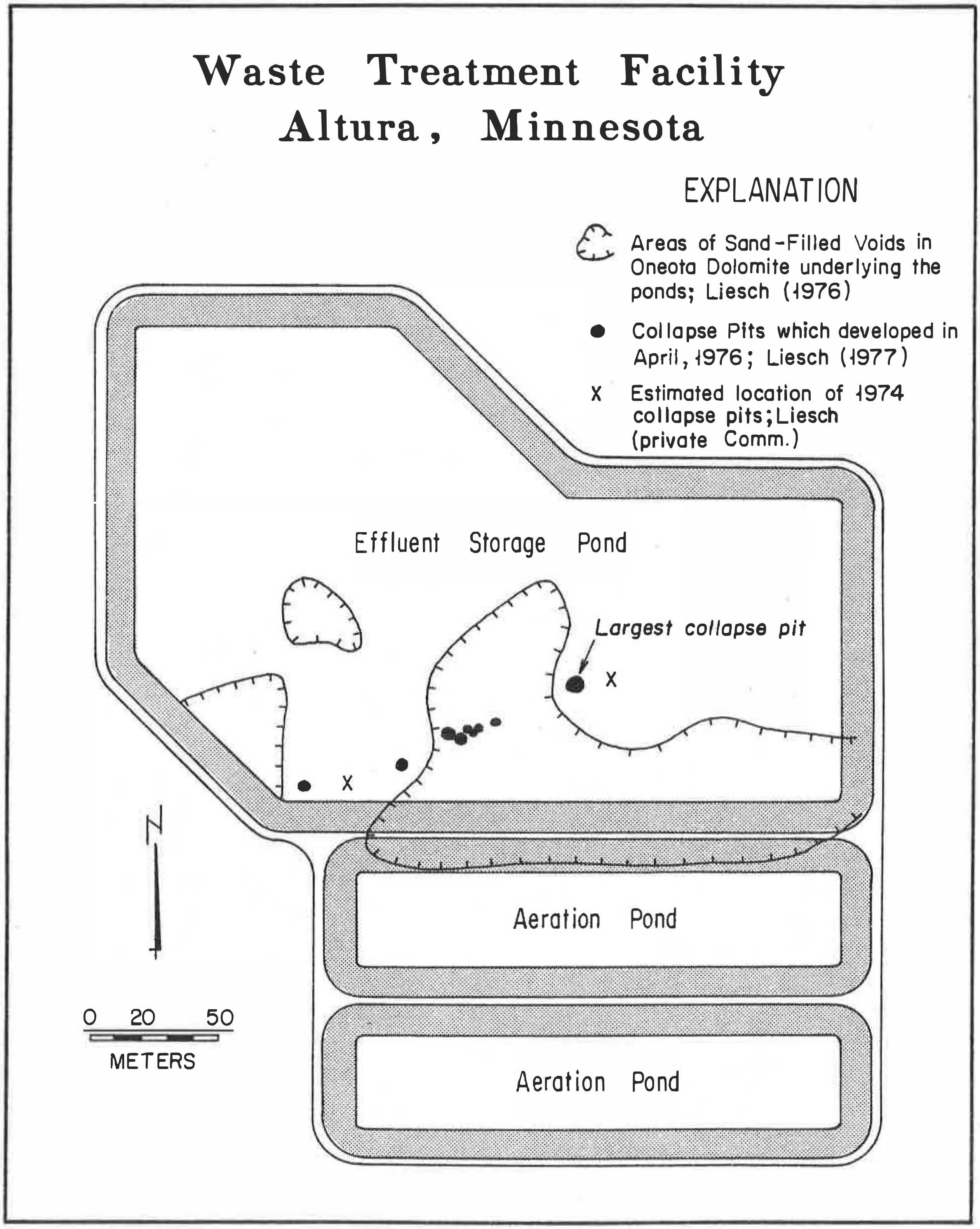


Fig. 2. Top
Book and Alexander

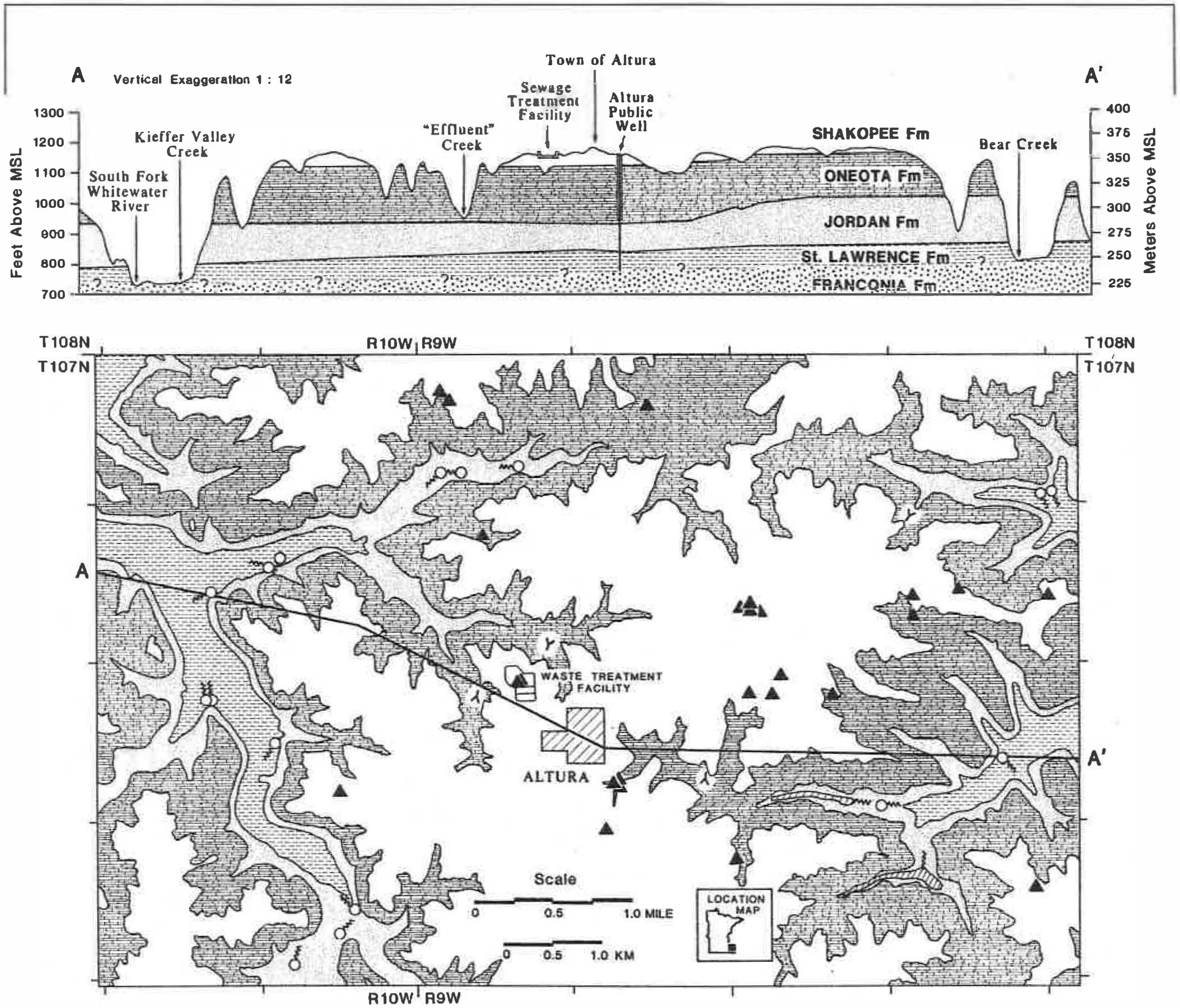
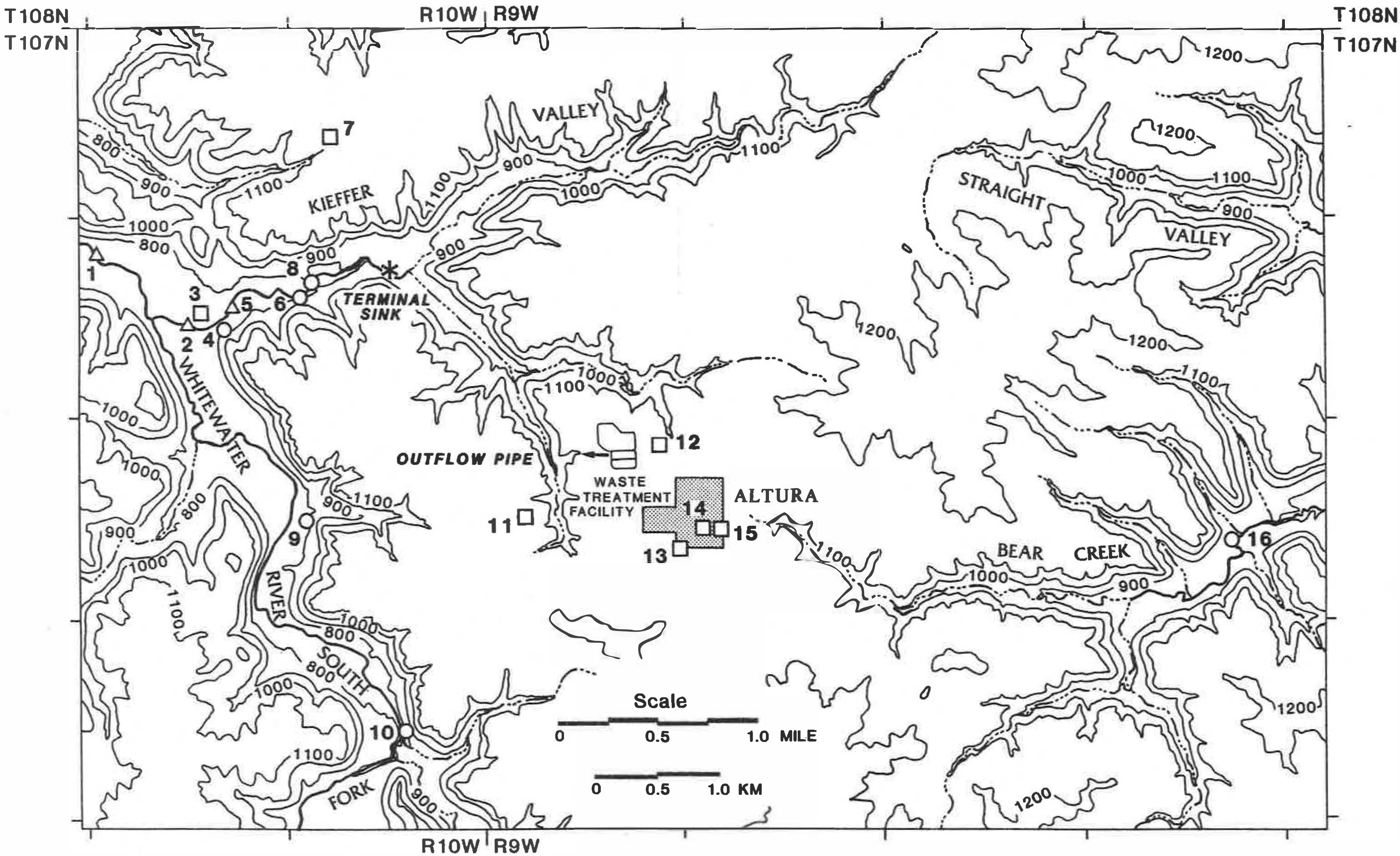


Fig. 3. Top
Book and Alexander



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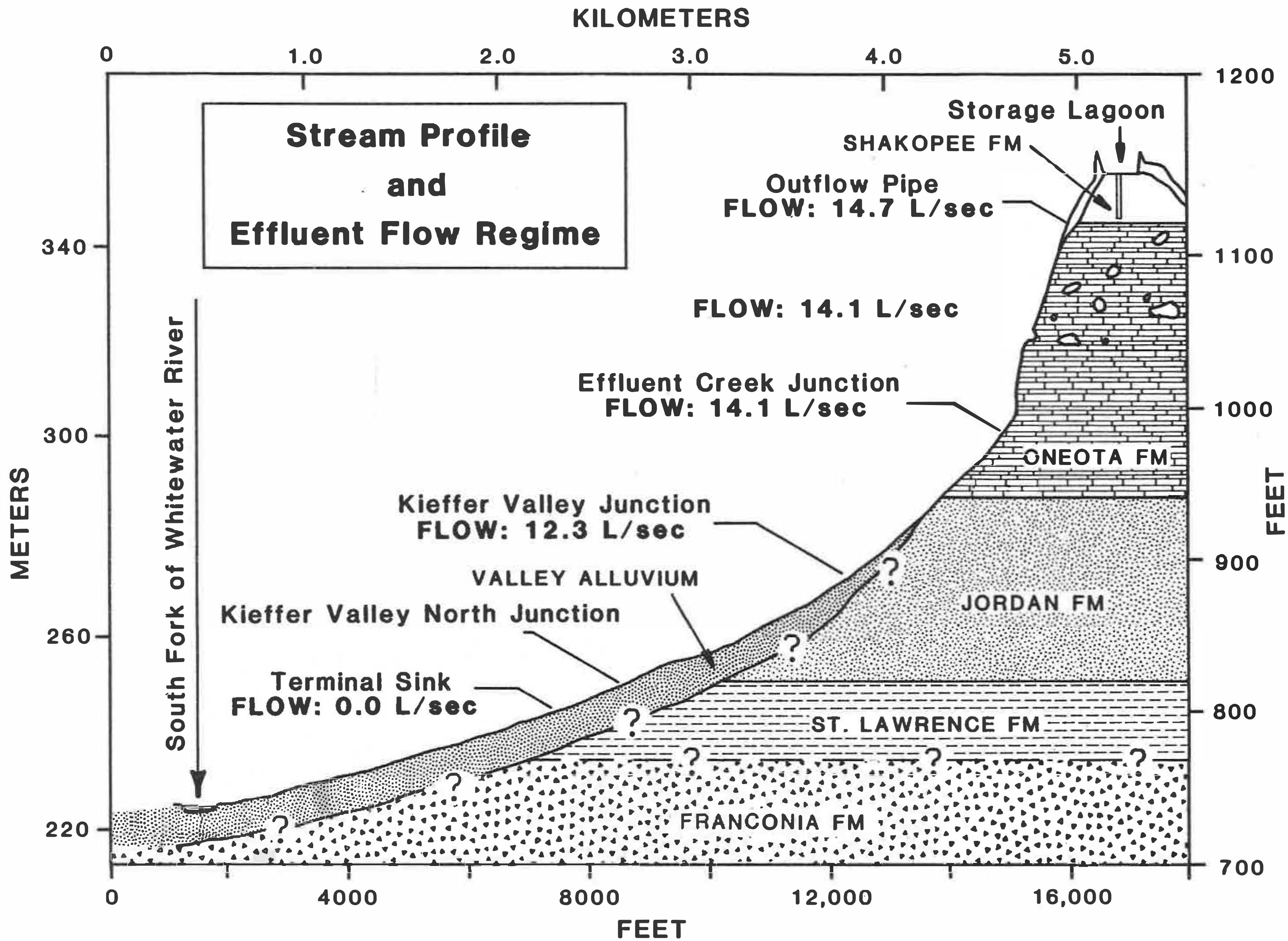

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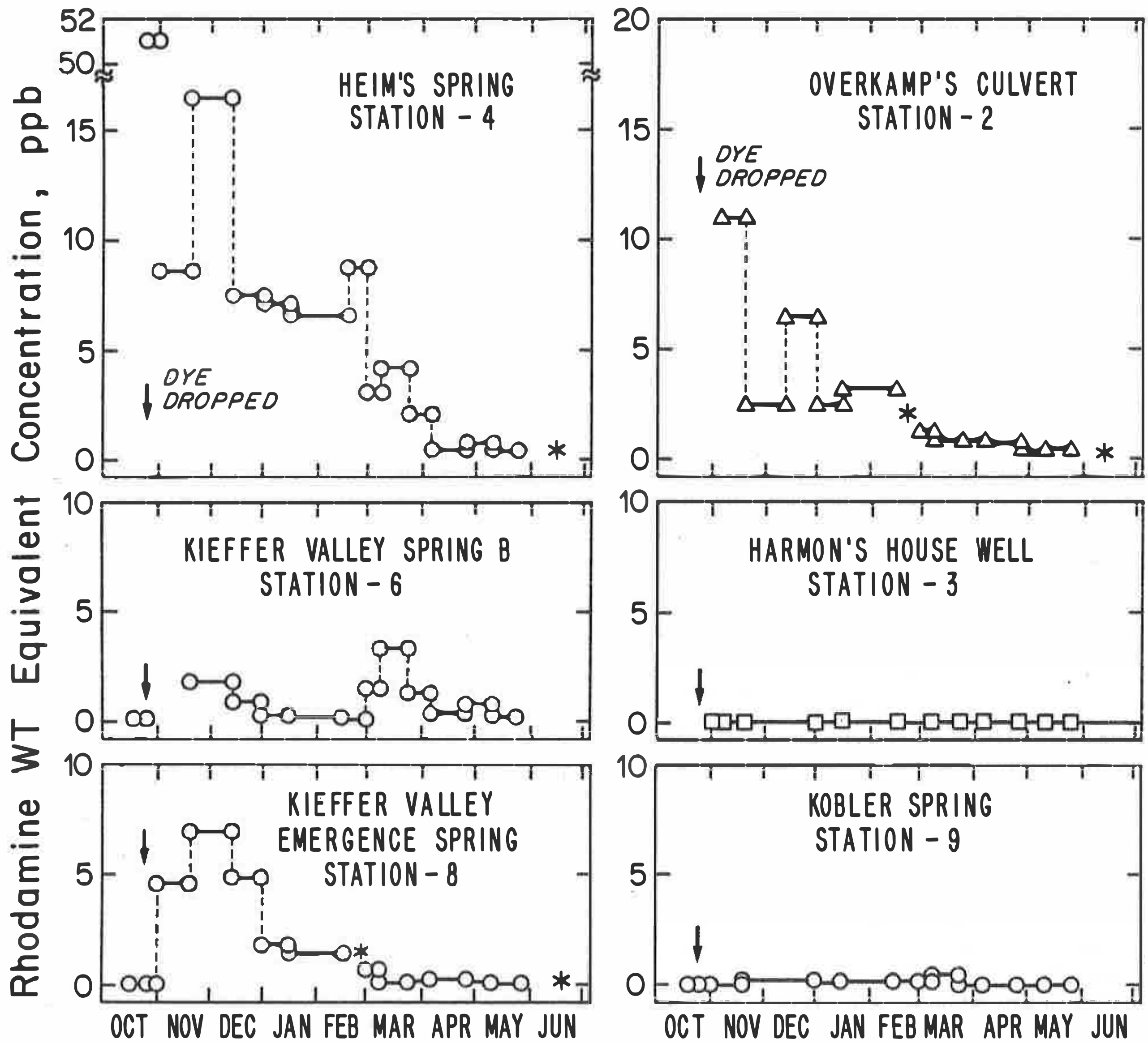

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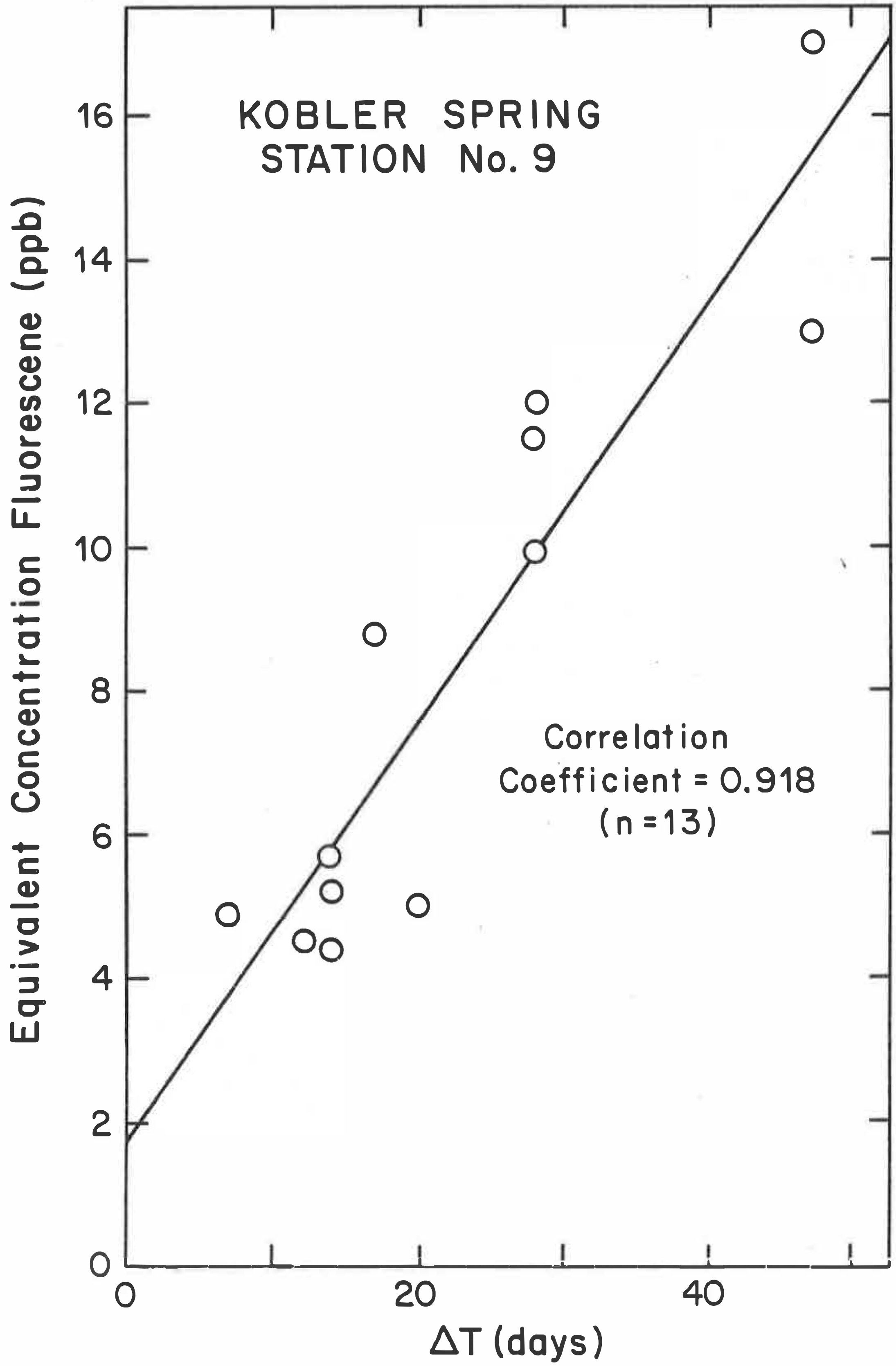

Fig. 7. Top
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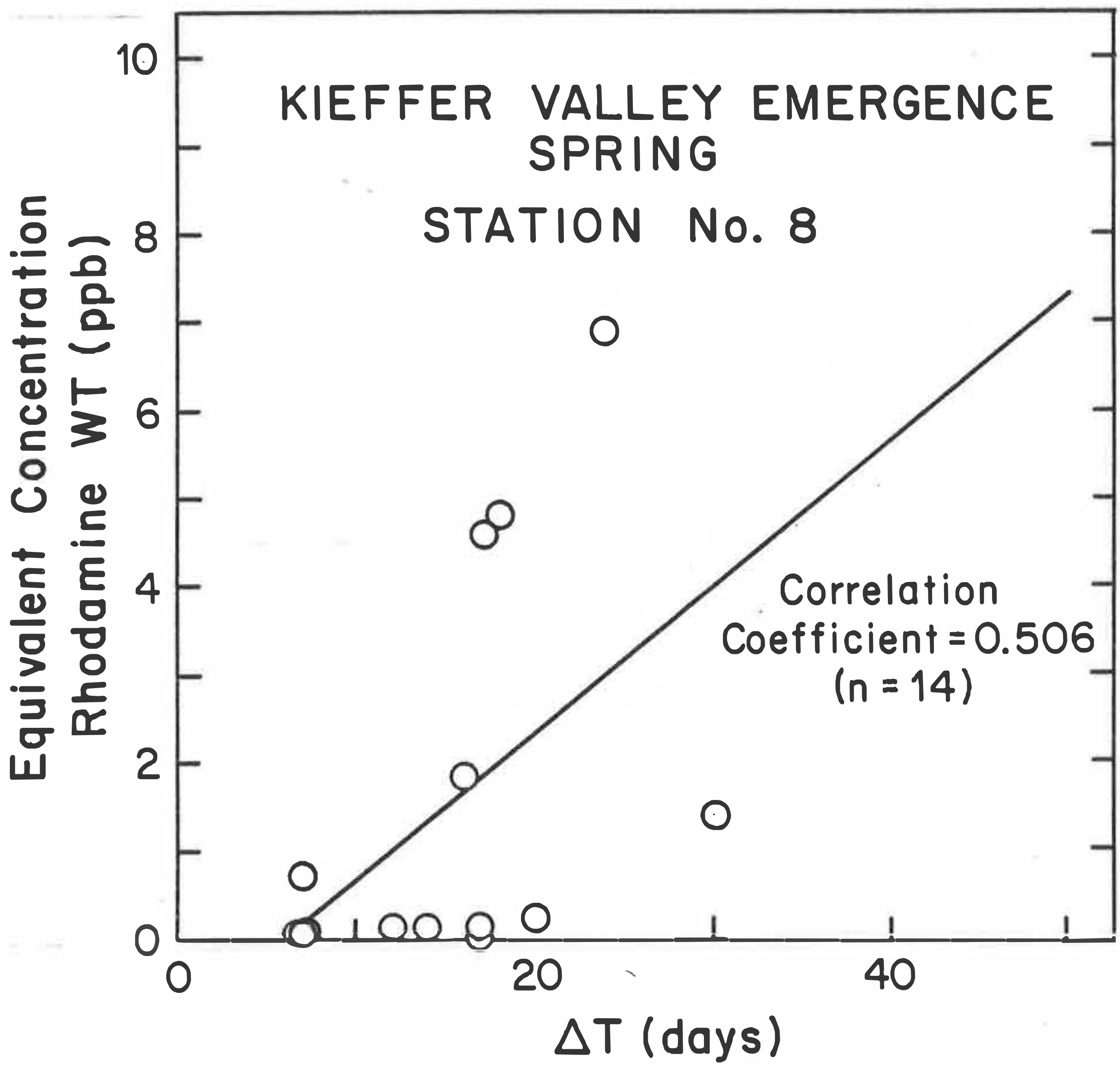

Table 1. Sampling Station Locations

Station Number	Name	Location[a]	Comments
1	Whitewater River South Fork; Surface Water Station	NE/SW/NW/NW Sec 11 T107N R10W	Highway Bridge
2	Overcamp's Culvert Surface Water Station	SW/SW/SW/NE Sec 11 T107N R10W	In Kieffer Valley Twp Road Culvert
3	Harmon's House Well	NE/SW/SW/NE Sec 11 T107 R10W	
4	Heim's Spring	NW/NE/NW/SE Sec 11 T107 R10W	Discharges at Jordan-St. Lawrence Contact
5	Kieffer Valley Culvert, Surface Water Station	SW/SE/SW/NE Sec 11 T107N R10W	
6	Kieffer Valley Spring B	SW/NW/SW/NW Sec 12 T107N R10W	Discharges just above Jordan-St. Lawrence Contact
7	Brosig's Farm Well	NE/NE/NW/SW Sec 1 T107N R10W	
8	Kieffer Valley Emergence Spring	NW/NE/SW/NW Sec 12 T107W R10W	Discharges from fluvial material
9	Kobler Spring	SE/SW/SW/NW Sec 13 T107N R10W	Discharges a few feet below Jordan-St. Lawrence Contact
10	Chaffe's Spring	NE/NW/NW/SE Sec 24 T107 R10W	Discharges from Jordan
11	Hilke's Farm Well	NE/SE/SW/NW Sec 18 T107N R9W	
12	Bartz's Farm Well	SW/NE/NE/NE Sec 18 T107 R9W	
13	Kalme's Well	NE/NE/NE/SE Sec 18 T107N R9W	On public water supply
14	Standard Station Well	NW/NW/NW/SW Sec 17 T107N R9W	On public water supply
15	Altura Public Well	NE/NE/NW/SW Sec 19 T107N R9W	Source of public water supply. Well #2
16	Bear Creek Spring	SE/NE/NW/SE Sec 15 T107N R9W	Discharges from St. Lawrence Formation

[a] Locations read from smallest to largest, i.e. NE1/4 of the SW1/4 of the NW1/4 of the NW1/4 of section 11 ..., etc. All the sampling stations are in the area shown on the Altura, Minnesota, 7.5-minute U.S.G.S. topographic sheet.

Table 2. Equivalent Concentrations[a] of Rhodamine WT in Study Sample

Station Number	1980 Oct 18,19- Oct 25,26	Oct 25,26- Nov 1	Nov 1- Nov 5	Nov 1- Nov 18	Nov 5- Nov 18	Nov 18- Dec 12	Nov 18- Dec 30	Dec 12- Dec 30	Dec 30- Jan 14,16	1981 Jan 14,16- Feb 14	Feb 14- Feb 28	Feb 28- Mar 7	Mar 7- Mar 24	Mar 24- April 5	April 5- April 25	April 25- May 9	May 9- May 23	May 13- July 20
1	—	0.41[b] 0.17	0.69	—	0.46	0.23	—	0.38	0.14	*	*	0.07	0.06	2.9	0.04	*	0.40	—
2	—	—	—	—	11.0	2.5	—	6.5	2.5	3.2	*	1.2	0.78	0.8	0.73	0.37	0.40	*
3	—	—	0.04	—	0.01	—	0.01	—	0.01[b] 0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0	0.0
4	—	51.0	—	8.6	—	16.5	—	7.5	7.2	6.60	8.8	3.1	4.2	2.1	0.51	0.73	0.35	*
5	—	3.5	8.7	—	6.6	3.2	—	0.95	0.24	0.92	0.77	0.35	0.89	0.36	0.20	*	0.20	*
6	0.16[b] 0.07	—	—	—	—	1.8	—	0.9	0.3	0.23	0.08	1.5	3.3	1.3	0.34	0.79	0.28	—
7	—	0.01	—	0.03	—	—	0.05	—	0.01	0.01	0.06	0.02	0.01	0.04	0.0	0.0	0.0	0.0
8	0.09	0.04[b] 0.04	—	4.6	—	6.9	—	4.8	1.85	1.40	*	0.71	0.1	0.11	0.21	0.11	0.02	*
9	0.04[b] 0.05	0.05	—	0.02	—	—	0.25	—	0.16	0.19	0.15	0.16	0.43	0.04	0.04	0.01	0.04	—
10	0.07	0.07	—	0.03	—	—	0.4	—	0.025	0.23			0.07[c]		0.04	0.04	0.04	0.04
11	0.03	0.01	—	0.07	—	—	0.08	—	0.02	*	0.02	0.02	0.04	0.07	0.03	0.0	*	*
12	—	—	—	—	—	—	—	—	—	—	—	0.01	0.01	0.01[b] 0.06	0.02[b] 0.03	—	—	—
13	—	—	—	—	—	—	—	—	—	—	—	—	0.01	0.00[b] 0.00		0.0	0.0	0.0
14	—	—	—	—	—	—	—	—	—	—	—	0.01	0.01	0.06[b] 0.08	0.00	0.0	0.0	0.0
15	—	—	—	—	—	—	—	—	—	—	—	—	0.01	0.04	0.0	0.0	0.0	0.0
16	0.04	0.05[b] 0.05	—	0.04	—	—	0.23	—	0.18	0.16	0.50	0.1	0.18	0.1	0.09	0.06	0.03	*

Notes: [a] all concentration values in ppb (10^{-9} g/g)
[b] duplicate bug measurements
[c] bug in from Feb. 14 to April 5
— no value
* lost bug

Table 3. Equivalent Concentrations[a] of Fluorescene (Disodium Fluorescene) in Study Samples

Station Number	1981 Feb 14-Feb 28	Feb 28-Mar 7	Mar 7-Mar 24	Mar 24-April 5	April 5-April 25	April 25-May 9	May 9-May 23	May 23-July 20	Aug 14-Sept 11
1	*	2.55	2.7	2.6	2.0	*	5.0	—	—
2	*	4.4	1.5	3.3	2.0	4.4	3.5	*	—
3	1.5	1.8	1.8	0.25	0.25	0.55	0.60	0.65	—
4	5.9	4.7	3.8	3.4	3.4	3.2	5.0	*	—
5	4.5	3.5	4.2	2.6	1.25	*	4.2	*	—
6	1.8	5.7	2.8	1.5	1.7	1.8	3.4	—	—
7	1.4	1.55	1.5	0.36	0.25	0.3	1.0	3.05	—
8	*	3.8	2.9	0.43	0.55	3.0	0.6	*	—
9	5.2	4.9	8.8	4.5	5.0	5.7	4.4	13.[b] 17.	10.0[b] 12.0 9.9[b] 11.5
10			2.5[c]		1.85	4.0	5.0	2.5	8.6[b] 9.3
11	1.45	1.45	1.5	0.69	1.0	0.2	*	*	—
12	—	1.4	1.4	0.33[b] 0.33	0.1 1.75	—	—	—	—
13	—	1.8	1.8	0.5	0.2	1.05[b] 1.0	0.6	2.5	—
14	—	1.4	1.6	0.33[b] 0.27	0.2	0.5	0.5	1.4	—
15	—	—	2.6	0.65	0.55	0.8	0.8	1.0	—
16	5.9	3.1	3.7	2.8	2.65	2.6	4.0	*	—

Notes:
[a] all concentration values in ppb (10^{-9} g/g)
[b] duplicate bug measurements
[c] bug in from Feb. 14 to April 5
— no value
* lost bug