5th INTERNATIONAL SYMPOSIUM ON UNDERGROUND WATER TRACING

Dye Tracing Through Thick Unsaturated Zones

by

E. ALEXANDER, M. DAVIS & J. DALGLEISH

Reprinted from Proceedings p.p. 181-188

INSTITUTE OF GEOLOGY AND MINERAL EXPLORATION
Athens 1986

Dye Tracing Through Thick Unsaturated Zones

by

E. ALEXANDER*, M. DAVIS* & J. DALGLEISH*

Abstract

Using the fluorescent dye Rhodamine WT, a field fluorometer, and direct samples of water collected from springs, wells, cave drips, and pools we have conducted two successful dye traces through thick unsaturated zones in karst regions. The first dye trace was of a proposed expansion site for a landfill in Winona County, southeastern Minnesota. The site sits on top of a narrow ridge about 150 meters above the adjacent valleys. The second trace was at Jewel Cave National Monument in the southern Black Hills of South Dakota. This trace was initiated to evaluate the impact of tourist facilities on the underlying cave. A visitor center was constructed on the surface, 50 to 100 meters directly above the cave.

In both traces, small, irregular pulses of dye began to appear (in springs and wells at the Winona Landfill site and in cave drips and pools at Jewel Cave) within days of the dye injection, and the pulses continued to emerge for months. The pulses were typically a day or less in duration and a very small (10s to 100s of parts per trillion, 10^{-12} g/g). The pulses are more frequent after major precipitation/runoff events but appear to be moving through both unsaturated zones in a very irregular, stochastic fashion.

The very low levels of dye detected in many of the pulses required some type of confirmation analysis. We have successfully used the large negative temperature coefficient of Rhodamine WT's fluorescence to discriminate between low levels of Rhodamine WT and fluorescence due to background materials.

Introduction

Dye tracing is a routine tool in karst regions. Most traces, however, involve injecting dye into either: 1) water sinking at swallow holes, in cave streams, karst windows, etc., or 2) into obvious surficial karst features such as sinkholes; and tracing the flow to resurgent springs. This paper reports the results of two dye traces through thick unsaturated zones of karstified carbonates. The goal of both traces was to determine the direction, velocity and mode of anthropogenetic pollutants through the unsaturated zones. Neither trace involved dye injection into an obvious surficial karst feature and both revealed flow behavior in the unsaturated zone that is distinctly different from the conduit flow characteristic of more mature karst systems. Both traces spanned many months. The first trace was in Winona County in southeastern Minnesota. The second trace was at Jewel Cave National Monument on the southwestern edge of the Black Hills in South Dakota.

* Department of Geology and Geophysics University of Minnesota Minneapolis, MN 55455, U.S.A.

Winona County Landfill Dye Trace

The purpose of this trace was to determine the direction and velocity of groundwater flow beneath the proposed landfill expansion on the ridge between East and West Burns Valleys, south of Winona. An understanding of the groundwater system was necessary for the design of an effective system to monitor potential groundwater pollution from the proposed expansion or from the existing landfill. A more detailed account of this dye trace is available from the authors (DALGLEISH & ALEXANDER, 1984).

The proposed expansion site is shown in Fig. 1. The site is on top of the ridge at about 1200 to 1240 feet elevation. The floor of East Burns Valley immediately east of the site is at about 780 feet elevation; i.e., about 460 feet of topographic relief exist in the vicinity of the landfill. The majority of the residents in the area occupy homesteads along the edges of the valley floors. Local water supply is either from wells or springs which emerge near the homes.

The proposed expansion site is underlain by a layer of unconsolidated material. The thickness of this material, as revealed by soil borings, ranges from a few feet to more than 40 feet. The bedrock beneath the site is a series of sedimentary rocks of lower Paleozoic age (BALABAN & OLSEN, 1984). The topmost bedrock under the ridges and the landfill site is the Oneota Dolomite of the Praire du Chien Group. These rocks are underlain in turn by the Jordan Sandstone, the St. Lawrence Formation, the Franconia Sandstone and by deeper sandstones and shales. The uppermost bedrock under the valley floors is the Franconia Sandstone. All of the bedrock beneath the site is extensively jointed. The Oneota and the underlying Jordan Sandstone were probably not saturated with water. Dye injected into the top bedrock beneath the site had to move downward through several hundred feet of unsaturated rock before reaching the local water table.

The location of the injection well is shown on Fig. 1. The well penetrated 30 feet of unconsolidated materials, and 50 feet of Oneota dolomite to a total depth of 80 feet. The well was cased with 4″ PVC casing to 31.5 feet depth, leaving an open hole in the Oneota bedrock. Springs emerging from the ridge were mapped as shown in Fig. 1. Local residents were contacted to monitor the springs, wells, and selected creek locations. Residents collected water samples from six springs, six creeks and thirteen wells. Two complete sets of water samples were collected prior to injecting the dye to determine the natural background fluorescence of the water.

On October 30, 1982, ten pounds of Rhodamine WT was poured into the injection well. Additional water was continuously poured into the well for two hours to force the dye into the unsaturated bedrock.

Water samples were collected twice daily during the first two weeks and then once a day for the next 6 months. A Turner Design Model 10-005 Fluorometer was used to measure the fluoresence of each water sample. A pattern of tiny, short duration pulses of Rhodamine WT with long periods of background readings between the pulses (Fig. 2 and 3) quickly emerged. The pulses did not emerge in any discernible sequence but appeared randomly all around the ridge. Fig. 2 and 3 are typical samples of the data collected over the six months of the dye trace experiment.

The major experimental problem was how to separate pulses due to Rhodamine WT from pulses produced by other fluorescent materials. The measured concentrations are all so small that background fluctuations are a serious potential problem. We have developed a technique for confirming when a very small pulse is due to Rhodamine WT. The techni-

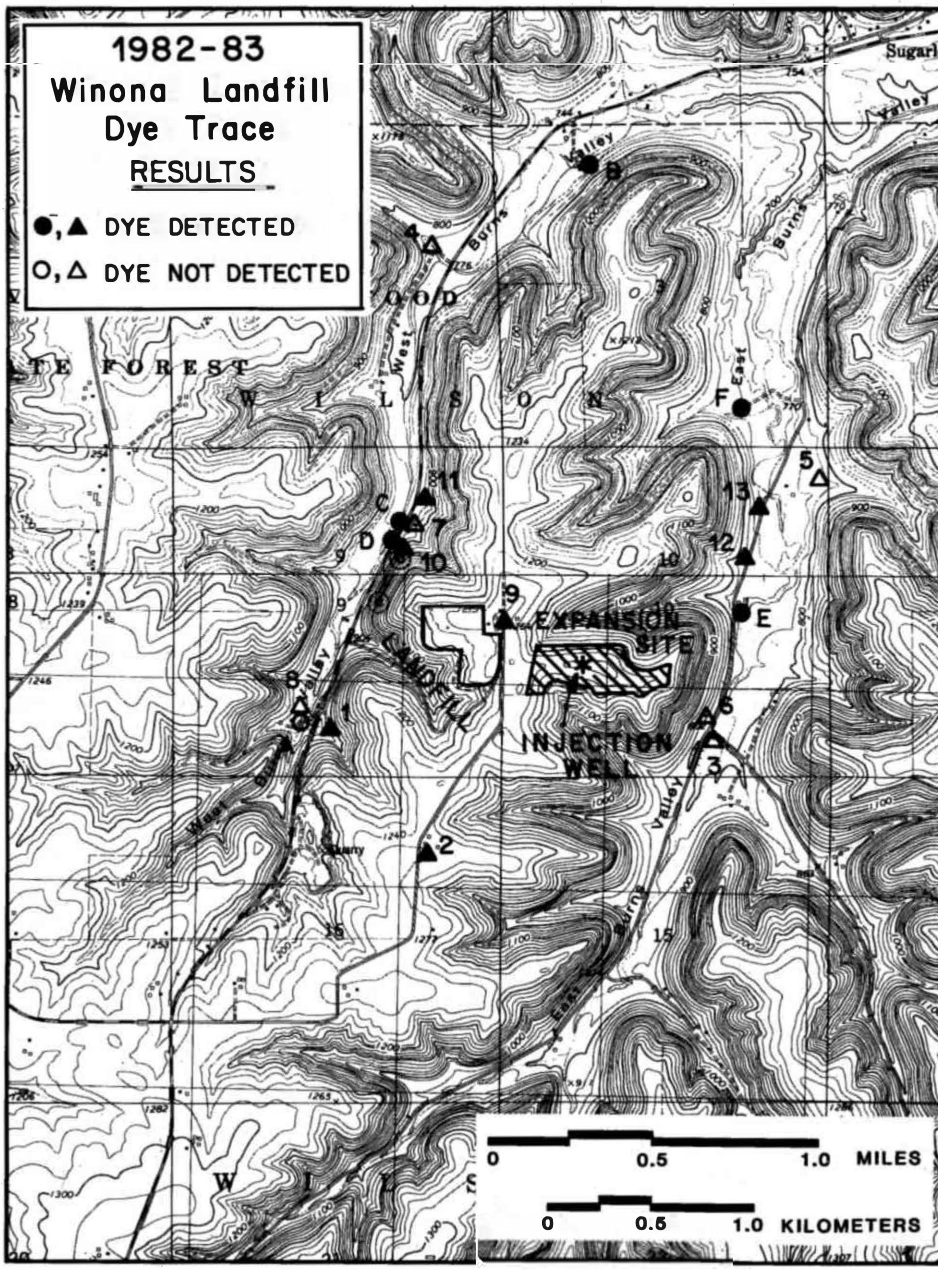

Fig. 1: Site map of the Winona County Landfill Dye Trace. The site is in Winona County in southeastern Minnesota, U.S.A. Base map adapted from the Wilson, Minnesota and Winona West, Minn 7.5 min. topographic maps - contour interval = 20 feet.

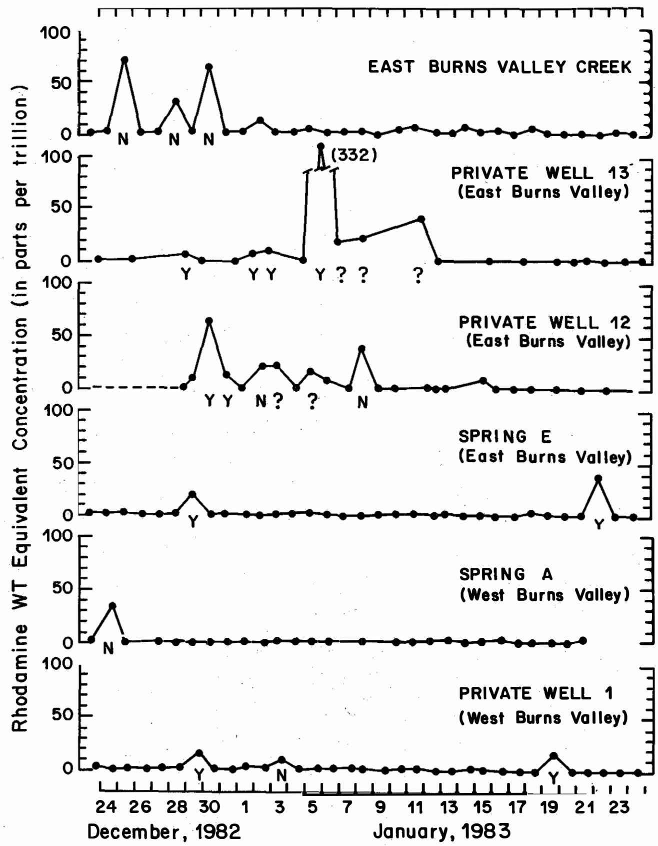

Fig. 2: Selected dye trace data for springs, wells and creeks for December, 1982 and January 1983.

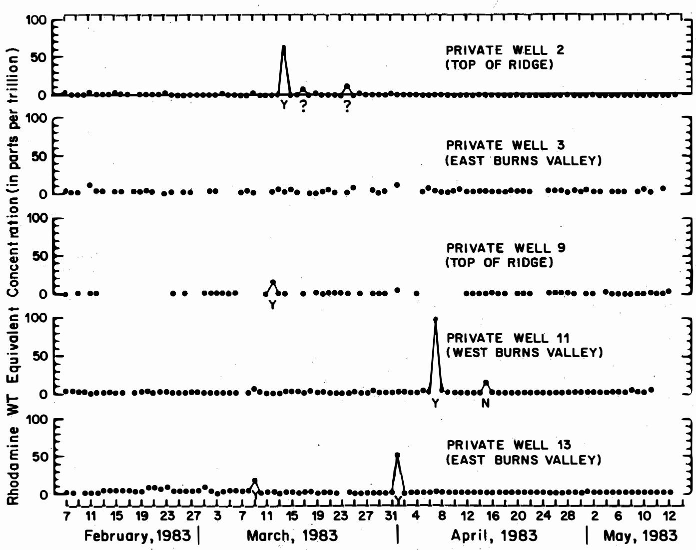

Fig. 3: Selected dye trace data from wells for February through May, 1983.

que makes use of the fact that the fluorescence of Rhodamine WT has an unusually large temperature dependence. By measuring the fluorescence of samples at several temperatures and comparing those data with that obtained from known samples of Rhodamine WT, we can distinguish between samples containing Rhodamine WT and those which do not.

The technique is illustrated in Fig. 4. The temperature dependence of the fluorescence of two of the samples is compared to that of known samples of Rhodamine WT. The sample collected from Private Well 13 on January 5, 1983, for example, agrees with the temperature dependence of Rhodamine WT. We think that sample contained small concentrations of the dye. In contrast, the sample collected on December 25 from East Burns Valley Creek does not agree with the temperature dependence of Rhodamine WT. We conclude that the material (s) causing the fluorescence in this sample was not Rhodamine WT. The Ys, Ns and ? shown beneath the peaks in Fig. 2 and 3 are the result of temperature analyses. Y stands for yes indicating that the peak is Rhodamine WT. N stands for no indicating that the peak is not Rhodamine WT. ? indicates an indeterminate case.

The dye was detected in small sporatic pulses in six private wells, five springs, and one creek station (shown as solid symbols in Fig. 1). All of these samples have been confirmed by the temperature test described above. We have no reason to think that these random pulses ended in May 1983 when sampling was terminated for economic reasons. A major, continuous pulse of dye emerging from the aquifer system was never detected. The dye did not appear in a localized area or from only one part of the aquifer system. Pulses of dye were detected in springs and private wells in East and West Burns Valleys and in wells located on the ridge.

Locations where the dye was not positively identified are also important. No dye was detected at Spring A or Wells 4, 5, and 8 (Fig. 1). These sites are probably receiving water from flows associated with adjacent ridges. Wells 3 and 6, located southeast of the injection well, did no show any pulses greater than 10 ppt.

Jewel Cave Dye Trace

Jewel Cave is located in Custer County South Dakota on the southwest flank of the Black

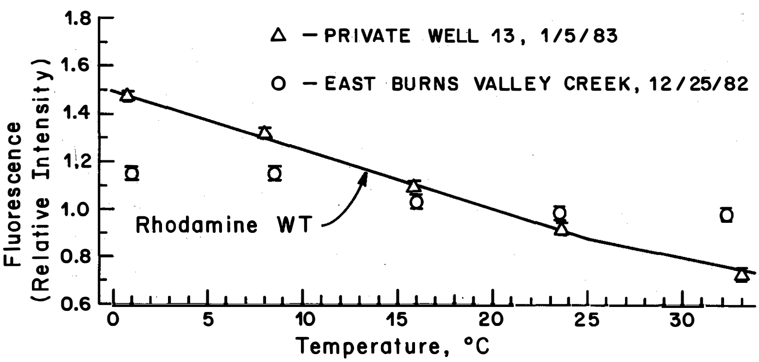

Fig. 4: Comparison of temperature dependency of fluorescence from Rhodamine WT and for background fluorescent materials.

Hills uplift (Fig. 5). PALMER (1984) is an excellent popular description of the cave and its geology. Jewel Cave is the second largest cave in the U.S.A. with 119 km of mapped passage and is developed in the Mississippian Pahasapa Limestone. The cave is located 50 to 100 meters below the surface and is entirely within the vadose zone. The dye trace was initiated as part of a hydrologic investigation of the impact of the development of tourist facilities on the underlying caves. One of the potential impacts arose from a leaky sewage system at the Visitor Center.

Water samples were collected from cave drips and pools in the cave to determine the background fluorescence in the area's waters. On September 15, 1985, 417 grams of Rhodamine WT was injected into the system by literally flushing it down the toilets in the surface buildings over the cave. Samples of the cave drips and pools were then collected, initially daily then weekly over the winter, and analyzed.

Fig. 6 shows the results from two cave drips and two cave pools. Fig. 6a and 6b are data from two cave drips in the "New Wet Area" of Jewel Cave. The area is so named because the drips did not develop until after the surface buildings were built. The pattern of short

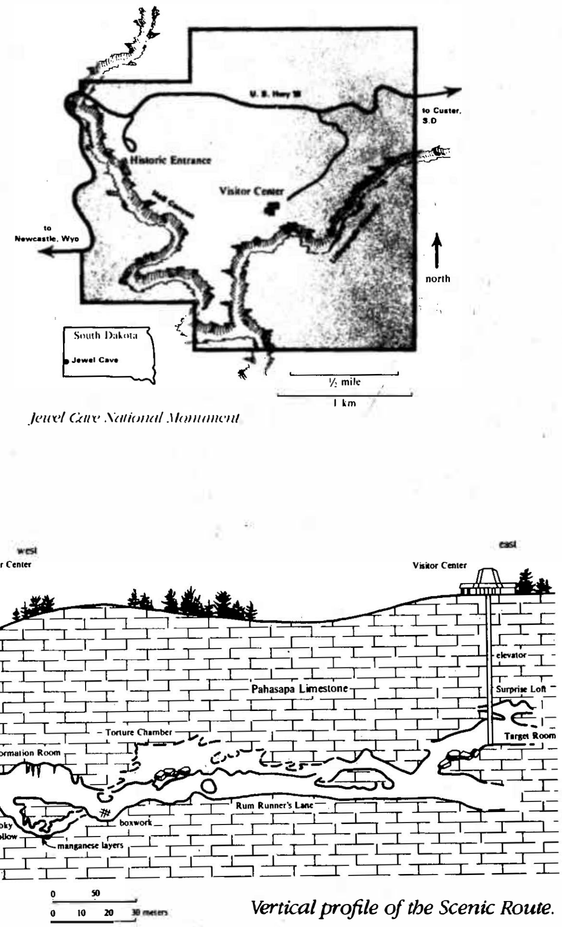

Fig. 5: Location map and generalized cross-section of Jewel Cave National Monument (from Palmer, 1984, copyright 1984 by the Wind/Cave Jewel Cave National History Association).

duration, random pulses is very similar to that seen in the Winona Landfill trace. The first pulse reached the New Wet Area-East drips before the bulk of the dye reached the Monument's sewage lagoon (which overlies part of the cave and is partially unlined). Fig. 6c and 6d are data from two cave pools. Bacon Pool recorded one isolated pulse about two months after injection while the Pre-formation Pool simply recorded a high, fluctuating level of background fluorescence.

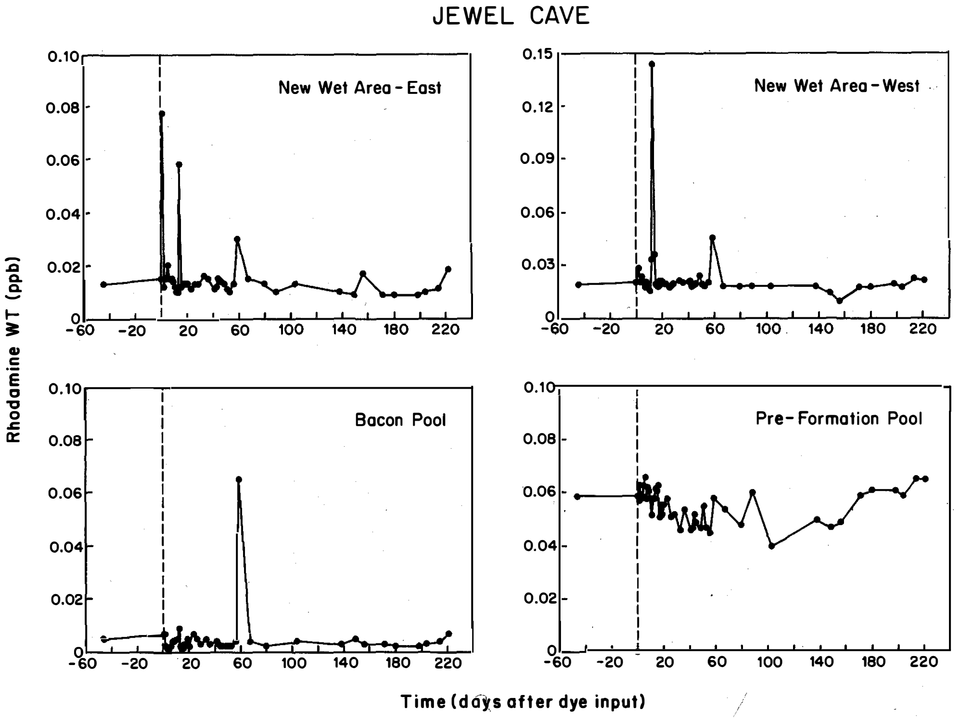

Fig. 6: Selected dye trace data from cave drips and pools in Jewel Cave.

Discussion

Although these two dye traces were separated by about 1000 km and in rather different karst environments, the results are remarkably similar. Both traces indicate that pollutants moving through 50 to 100 meter thick unsaturated zones in karst terrains move as random, short duration pulses. These thick unsaturated zones represent an important, but different hydrologic flow system. These zones are neither mature karst zones dominated by conduit flow nor porous medium zones dominated by diffuse flow. Flow in this type of environment is in random pulses which move horizontally as well as vertically. The characteristics, importance and location of thick unsaturated karst environments are poorly defined.

Any attempt to monitor the movement of pollutants through this type of karst hydrologic environment will require both frequent (daily to hourly samples) and long term (months to year) sampling protocols. Such protocols will be neither simple nor economical.

Acknowledgments

The Winona County Landfill dye trace was supported by grants from Winona County and the Legislative Commission on Minnesota Resources. The dye trace of Jewel Cave was supported by a grant (USDI-CX-1200-5-A047) from the National Park Service. We gratefully acknowledge many hours of help from the citizens of Winona County and from the staff of Jewel Cave National Monument.

References

Balaban, N.H., & Olsen, B.M. (editors), 1984: Geologic Atlas Winona County, Minnesota. Minnesota Geological Survey County Atlas Series, Atlas C2, 8 plates.

Dalgleish, J., & Alexander, E.C., Jr., 1984: Hydrogeologic investigation of the proposed expansion site of the Winona County (Murphy) Landfill. Final Report, April, 1984, 34 pp.

Palmer, A.N., 1984: Jewel Cave: A Gift from the Past. Wind Cave/Jewel Cave Natural History Association, Wind Cave National Park, Hot Springs, SD. 41 pp.

Discussion

P. ALDOUS: In your first example, low concentrations of Rhodamine WT dye were detected. You determined that the increase in fluorescene was due to the presence of Rhodamine WT, by the ingenious and clever method of using the Rhodamine WT dyes temperative and fluorescence characteristics. Would the use of passive (presence - absence) activated carbon charcoal detectors, be of any additional use, because as the carbon is cavenges dye, it is an accumulative process?

E. ALEXANDER: We probably would have gained increased sensitivity but would have lost resolution — unless we changed charcoal detectors daily. There is also the practical problem that individual private well systems do not have very good places to place charcoal detectors.

H. BEHRENS: We found in karst water tracing experiments through thick unsaturated zone correlation between individual peaks and preceeding rain events with a delay of up to several weeks. Could your peaks be explained by the same mechanism?

E. ALEXANDER: Partially yes. At Winona there was a partial correlation with precipitation/runoff events. At Jewel Cave the first pulses were detected before any precipitation event occured. We think that precipitation/runoff plays a role in the multiple peak, random behavior — but not necessarily the dominant role.

H. HÖTZL: Does there exist any estimation of the remnant moisture content in the unsaturated zone after dry periods?

E. ALEXANDER: Only in the most general sense. The time period of the Winona trace was wetter than average in the area. The time period of the Jewel Cave trace was dryer than normal for its area.