Open File Report 91-2

The Use of Tracer Dyes for the Identification of a Mine Flooding Problem, Rico, Dolores County, Colorado

By Mark W. Davis

Including

Annotated Groundwater Tracer-Dye Selected References

By Turner Designs, Sunnyvale, California

Colorado Geological Survey
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Purpose

The Colorado Geological Survey (CGS) investigated a flooding problem in Rico, Colorado during which time a tracer dye was utillized to pinpoint the source of the flooding. Prior to and during the early stages of this investigation, the CGS was unable to locate significant literature on the use of tracers. Anne Clift of the Divison of Minerals and Geology (DMG) had a similar problem during an DMG project and discovered a useful bibliography distributed by Turner Designs, Sunnyvale, California. The CGS contacted Turner Designs and received permission to distribute this bibliography.

Introduction

The flooding problem in Rico, Colorado occurred in May 1989, and affected several residences on the banks of the Dolores River. The CGS determined that several factors may have contributed to the flooding. A portion of the Atlantic Cable Mine located in downtown Rico may have caved to the surface immediately under Silver Creek causing water to surge into the mine and discharge within a short distance of four residences. These residences, located south of the confluence of Silver Creek with the Dolores River, experienced minor flooding problems. In addition to the mine collapse problem, the water delivery system for the town of Rico appeared to have two problems which might be related to the flooding. First, the water supply system appeared to have a broken pipe and defective valve upgradient from the affected residences. And second, the pipeline ditch along Campbell Street may have served as a preferential pathway for ground water near Silver Creek to access the residences.

The Colorado Geological Survey conducted an investigation which included the use of tracer dyes, recommended trenching to divert seepage, and the installation of a culvert in Silver Creek over the collapsed area. The property owner installed the culvert over the caved portion of Silver Creek once it was positively identified, and constructed several drainage ditches near the residences. Backfill was added to the caved area and recontouring was done in selected areas.

Rico maintenence personnel repaired the broken pipe and defective valve. No work was undertaken as of December 1990 on the Campbell Street waterline ditch pending outcome of the other two remediation activities.

This report has been compiled to record the process involving dye utillization at the Rico site so that other investigators may enjoy an advantage in similar studies. A complete report covering the hydrology and chemical studies as well as the application of tracer dyes entitled *The Identification and Mitigation of a Mine Flooding Problem, Rico, Colorado with a Discussion of the Use of Tracer Dyes* (Open File Report 91-1) may be obtained from the Colorado Geological Survey.

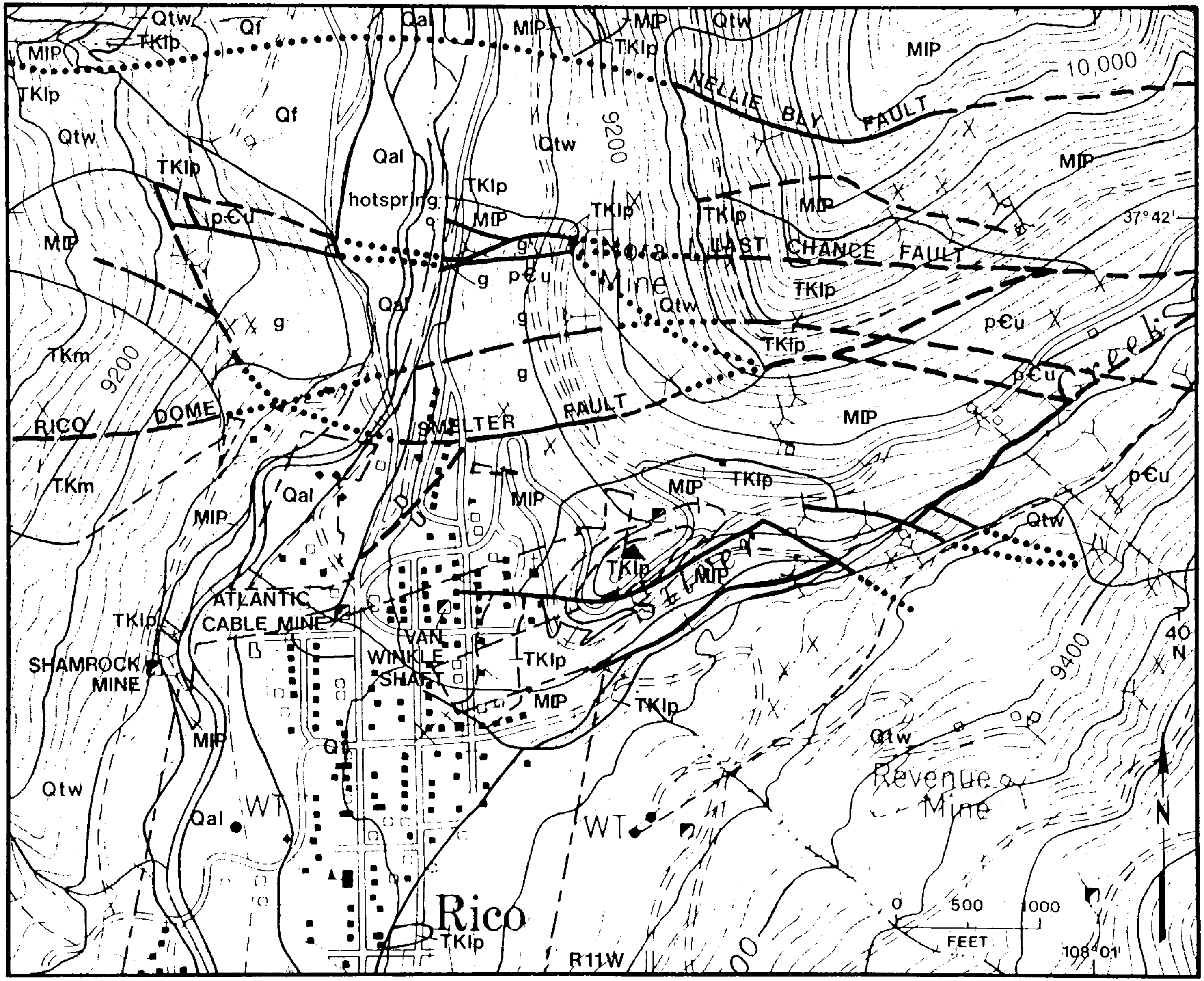
The scope of the work involved mitigation of the flooding problem with the least impact on the public utilities, private property and roads, within the budget set forth by the Department of Local Affairs and by the limited funds available in the town of Rico.

Geology

The geologic environment consists mainly of Paleozoic sedimentary rocks including limestones, shales, sandstones, and arkoses overlain in large part by Quaternary deposits of talus and slope wash, torrential debris fan deposits, landslide deposits, and alluvial gravel. The sedimentary units dip gently to the south and are cut by many east-west striking faults (Figure 1).

Quaternary alluvial deposits are coarse in texture and confined to the Dolores River valley. The torrential debris fans cover much of the town of Rico and the area of immediate interest between the Atlantic Cable Mine and the Dolores River.

Bedrock in the vicinity of Rico ranges in age from Precambrian to Permian. The Pennsylvanian Hermosa Formation is the most widespread in the area and is composed of arkoses, sandstones, shales, and conglomerates. Minor interbedded limestones occur through the 2,800-ft-thick Hermosa Formation and host much of the ore which was mined from this historic district. One of the main structural features of the area is a 10-mi-diameter dome centered just east of the monzonite intrusive.



EXPLANATION

Qal Quaternary alluvium and stream gravel

Qf Quaternary torrential debris fan

Qtw Quaternary talus and slope wash

TKm Cretaceous (?) or Tertiary (?) monzonite

TKlp Cretaceous (?) or Tertiary (?) hornblende latite porphyry

MIP Pennsylvanian Rico Formation, Hermosa Formation, and Larsen Quartzite; Mississippian Leadville Limestone

pЄu Precambrian Uncompahgre Quartzite

g Precambrian greenstone and metadiorite

—— Contact, dashed where approximate

D/U Fault, dashed where approximate; dotted where concealed; D on downthrown side

Figure 1. Generalized geology of Rico, Colorado (Modified from McKnight, 1974, Plate 1).

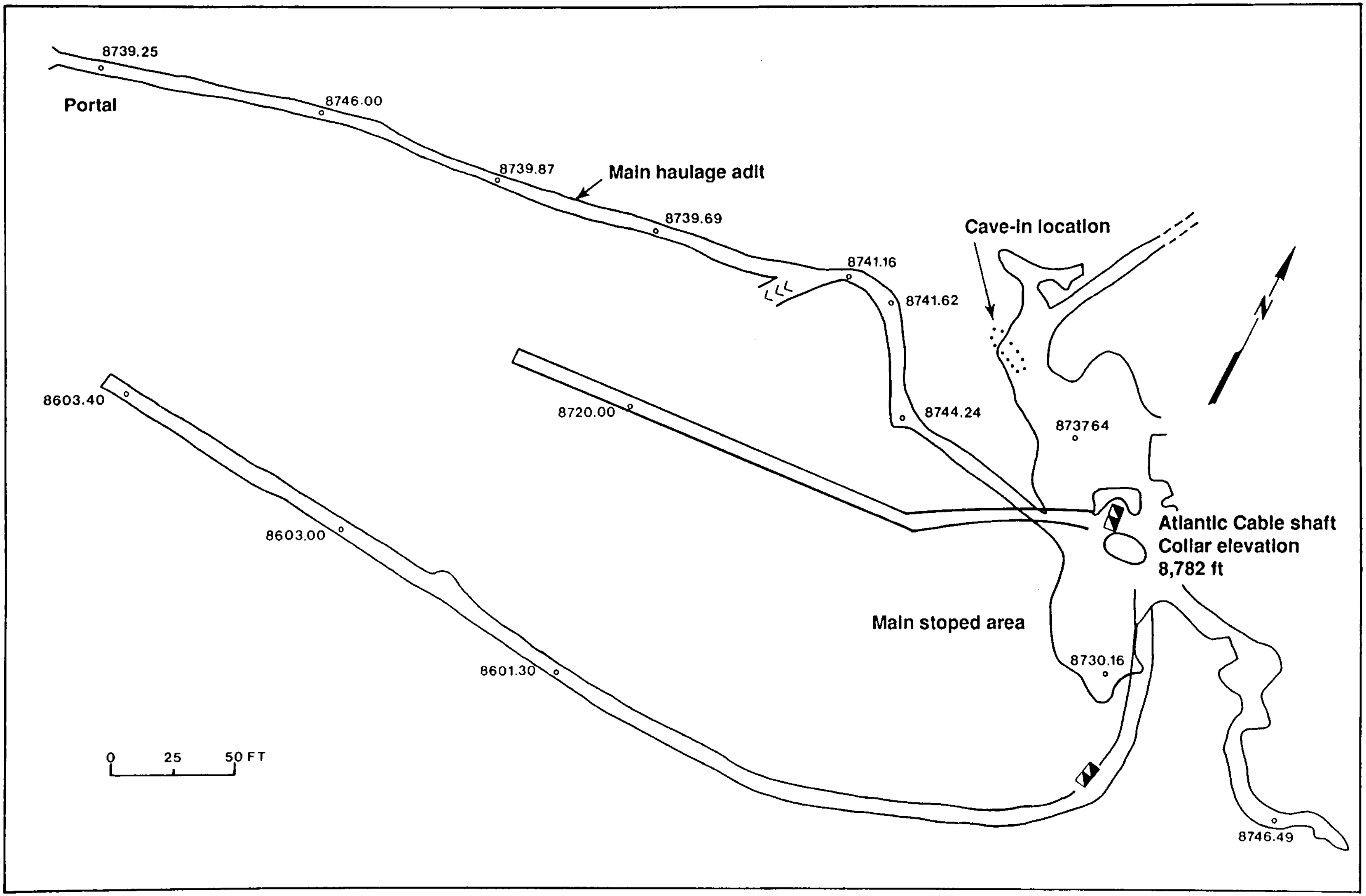


Figure 2. Atlantic Cable Mine, main haulage adit and exploration drifts.

Faults are plentiful in the area and generally strike easterly and dip steeply to either the north or south. A large horst block trends easterly from the intrusive. Most of the downtown mining has occurred within this horst.

Atlantic Cable Mine

The Atlantic Cable Mine was operated until closure in 1948. The ore deposits are replacement and contact metamorphic deposits of silver, lead, and zinc with minor copper. Mining involved shrink stoping and possibly modified room and pillar methods. These stopes could be taken fairly wide and the back held with square set timber.

The Atlantic Cable Mine was serviced by a two compartment shaft for men and equipment and for hoisting ore. There appear to be three levels served by the shaft. The main stope was developed for approximately 400 ft in a northwest to southeast direction. A drift was driven to the west from the sill of the first level at an elevation of 8738 ft. This westerly drift extends approximately 200 ft from the shaft to what is shown as an incline to the surface on mine maps. Another heading was driven westward possibly as an extension of this drift for dewatering and haulage. This 500-ft west drift was utilized to dewater the Atlantic Cable Mine to the first level (Figure 2).

Another drift was driven from 60 ft below the collar of the Atlantic Cable shaft to dewater the lower workings of the Van Winkle Mine about 1000 ft to the northeast and higher in elevation.

Site Evaluation

Mine Environment

Late in May 1989 residents noticed flooding around certain residences and also noticed a whirlpool west of the Atlantic Cable Shaft in Silver Creek (Figure 3). This whirlpool was located approximately N. 60 W, 60 to 75 ft from the shaft and on the south bank. One observer mentioned that an open hole could be seen in the bedrock and that mine timbers were encountered while he was operating a backhoe in the stream. Rico maintenance people reported that four truck loads (16 yds) of rock and soil were dumped into the whirlpool and much of this material sank into a hole. This whirlpool area overlies the first level stope suggesting that a cave-in could have occurred from the back (roof) of the stope up to the stream bed.

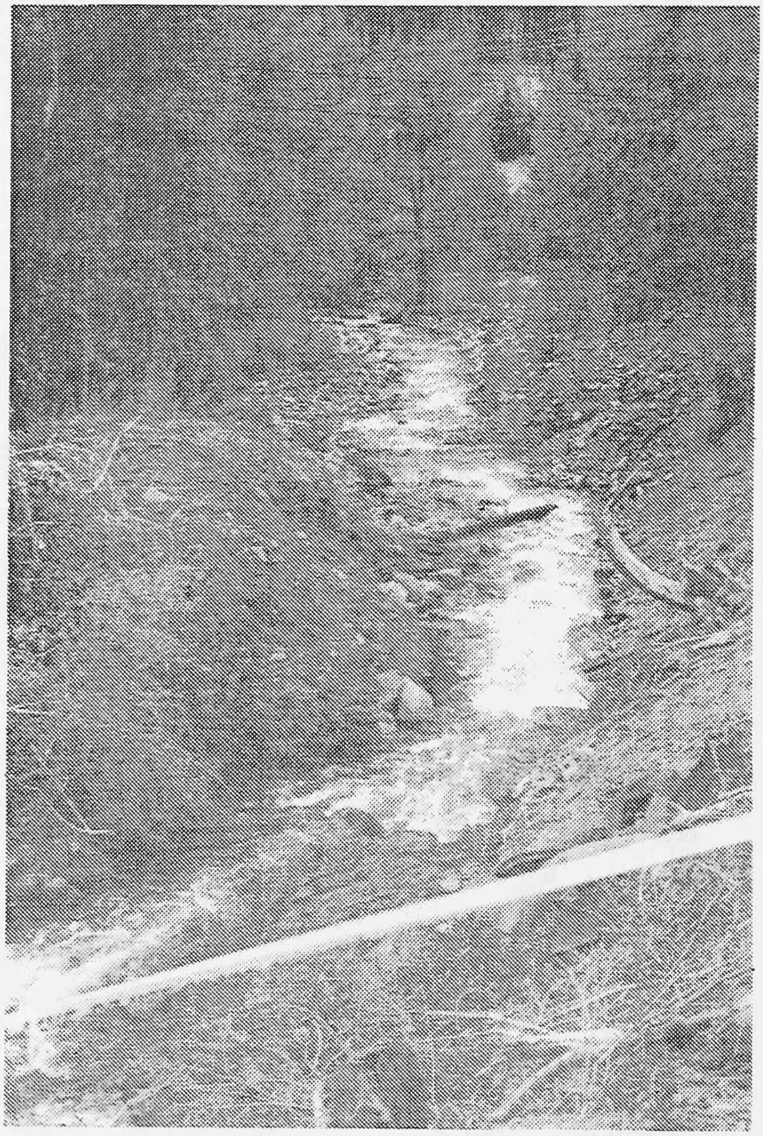


Figure 3. Location of whirlpool and cribbing encountered during re-alignment of Silver Creek Channel. The loose fill material on the left side of the creek in the center of the picture was dumped into the whirlpool.

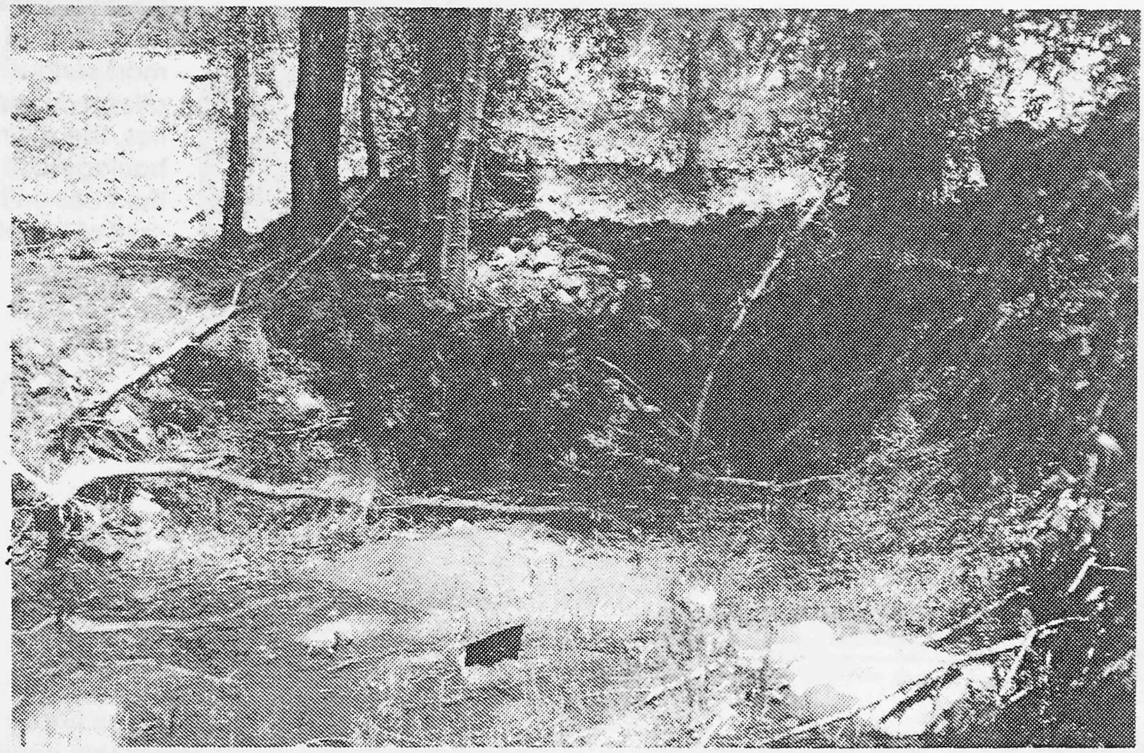


Figure 4. Recent cave-in over the west drift.

The whirlpool location was several feet lower in elevation than the point in Silver Creek adjacent to the shaft, and the mine is hydraulically connected to the Van Winkle Mine at least 100-ft higher in elevation. A large concrete wall was erected on the north side of Silver Creek during the early days of mining to reduce inflow into the Atlantic Cable shaft.

It is likely that the mine discharged a small quantity of water before the cave-in occurred. That mine water could easily be drained by the west drift even though the drift is probably caved along most of its length. The mine water would then stabilize at the first level sill at approximately the 8738-ft elevation. Upon breaking through, the mine probably flooded to a level above the drift invert level. This caused a surge and additional caving to the surface along the course of the drift (Figure 4).

A study of the surface overlying the west drift indicates that subsidence had occurred. Two of these cave-ins appeared fresh, suggesting that possible hydraulic changes such as a sudden head change could have occurred in the recent past to perturb the geohydrologic conditions. On June 8, 1989, 0.6 to 0.75 cubic feet per second (cfs) outflow was measured discharging from the caved portal. Additionally, new seeps were identified adjacent to the fresh cave-in and flowing across the surface. All of the seeps observed were south of the alignment of caved ground suggesting geologic controls unrelated to mining except as they may have become preferential pathways following recent cave-ins. There are two major aspects of the geology to consider; east-west trending water-course faults and extremely permeable gravels (estimated to be on the order of 10^{-1}, 10^{-2} cm/s hydraulic conductivity).

Seeping and minor piping occurred immediately west of the west adit and could still be seen in the road, the adjacent front yard and along the bench that extends further to the south (Figures 5 and 6).

The flow discharging from the west adit was diverted to the north and temporarily channeled across the road. Some of this flow was thought to be seeping under the road and to the front yard of the southernmost residence in the affected area (Figure 7). The owner indicated that his leach field was located at the location of the seep.

Figure 5. Looking north toward the most seriously affected properties. The main haulage adit is in the trees on the right of the picture.

City Water System

The city of Rico receives water from Silver Creek 0.75 mi east of the Atlantic Cable Mine and 300-ft upgradient. Water flows by gravity into two 100,000 gallon steel tanks protected with overflows. At a point 150-ft west of the Atlantic Cable shaft just on the north of Soda Street, there exists a valve on a 6-in. main which serves five residences to the north. Water could be heard running through this valve continuously which suggested that the major seep could be caused by city water flowing through a broken pipe and through the permeable torrential debris fan material in the area. The valve was determined to be defective when attempts to shut it off failed in late May.

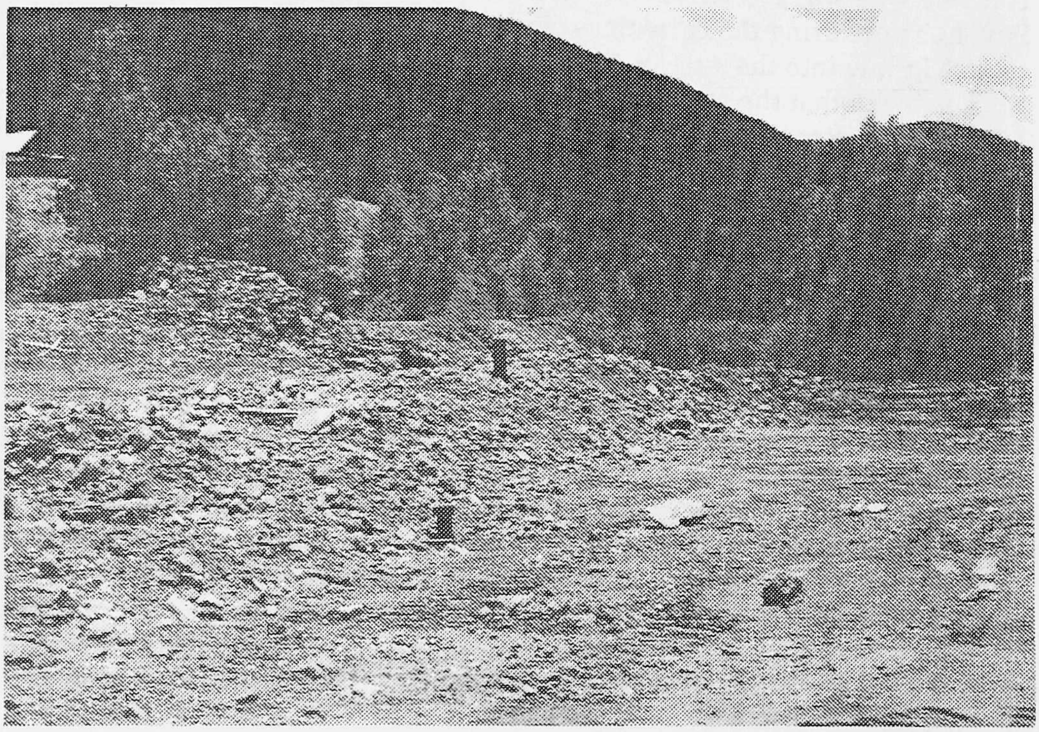


Figure 6. Water line on flooded bench. The riser pipe in the lower foreground and the hydrant are connected to the water line.

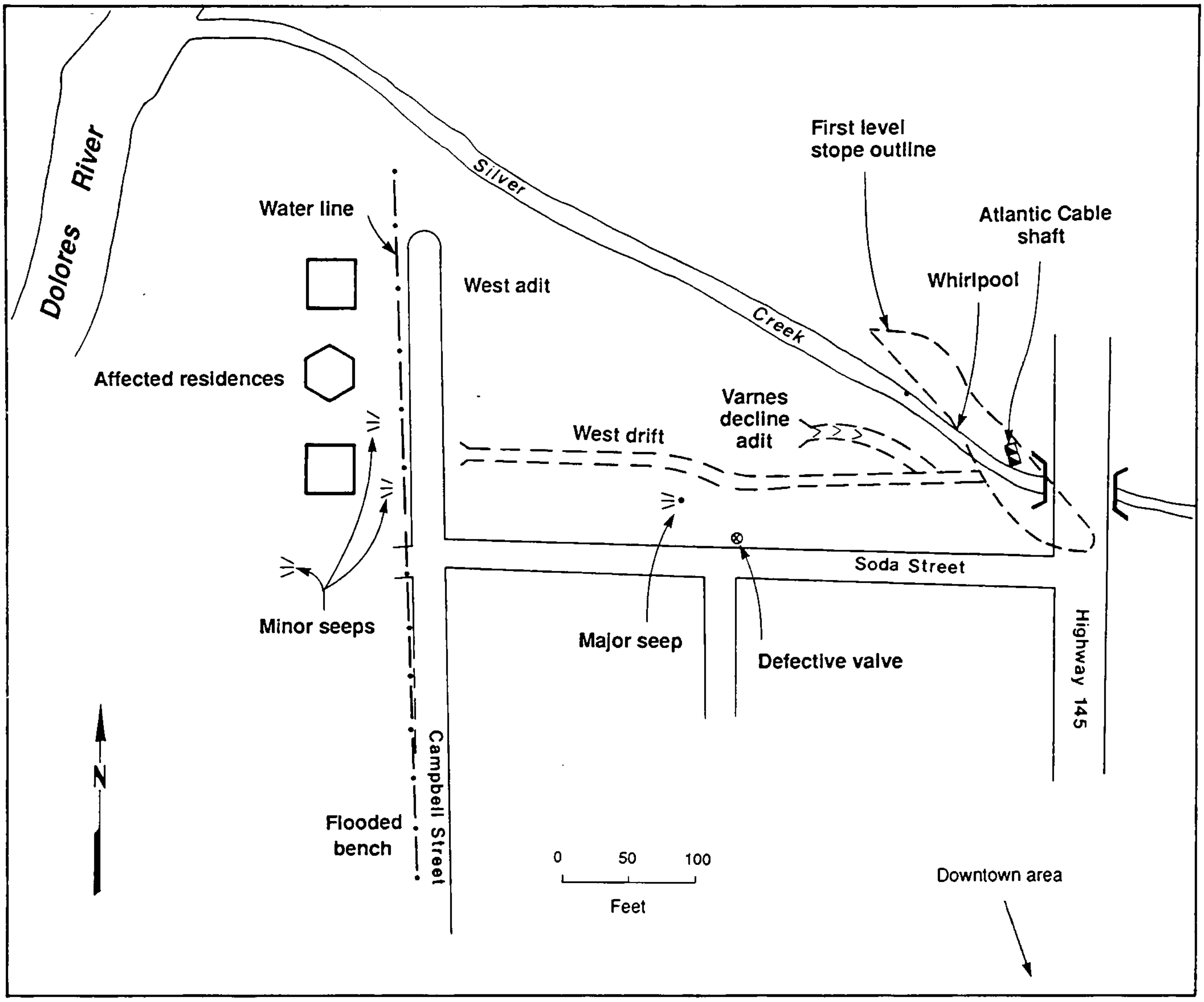


Figure 7. Affected residences and their relationship to Silver Creek and the west adit.

The major seep is 100-ft west and 10-ft lower in elevation than the watermain which this valve controls. To determine if the seep was caused by a broken watermain, the next valve higher in the system was turned off. No reduction of flow from the seep was observed in the 45 minutes that this valve was off and no bypass was heard in the defective valve. This suggests that the seep below the valve was caused by other factors than the broken pipe. A water line serves the residences on Campbell Street and undeveloped lots to the south. The line is pvc with riser pipe from the ditch which is 6-ft deep. One standpipe to the north was discharging water and many others were standing partially full. This attests to the shallow ground-water conditions present along the pipeline trench. The location of one seep several-hundred feet south of the subject residences suggests that this line may be distributing ground water preferentially through the backfill material located in the pipeline trench.

Hydrography

Stream flow quantity was determined at two stations, one approximately 300-ft upstream from the highway culvert and the other 100-ft downstream from the Atlantic Cable shaft and downstream from the whirlpool location. These sites were selected to bracket and isolate the mine and any of the known workings so that stream water loss could be determined. The upstream flow was 20.6 cfs and the downstream flow was 17.6 cfs. The 3 cfs difference between the upstream and downstream measurements is indicative of some type of loss. Measurements on other reaches of Silver Creek downstream from the mine area showed no reduced flow suggesting that the losses were entering the mine and not simply recharging the torrential debris fan aquifer.

Tracer Dye Testing

Tracer dye testing was recommended initially by Mined Land Reclamation Division personnel who have conducted similar studies as a common practice in mine drainage identification (Anne Clift, pers. comm., 1990). The use by CGS at this site was generally inconclusive. No pathways were observed which categorically identified the cause of the flooding.

The use of tracers is fairly wide spread in many different environments and an understanding of their reactions and limitations is critical to any specific project. The user should contact the appropriate health department and fish and wildlife department before use.

The State had Sulpho-Rhodamine B available so the Rico-Silver Creek testing was limited to its use. Sulpho-Rhodamine B is reddish purple and visible in amounts as dilute as one part per million. Although it is reported to be susceptible to sorption onto clay this was not considered to be detrimental to the study.

Dye was placed in the small ponded area at the mouth of the west adit. Approximately 100 ml of dye was mixed with two litres of water and this concentrate was added to the pool water. The purpose of this test was to observe the dye movement and strength before applying any larger measures. The secondary purpose was to observe the effects of dye flow for the short distances to the affected front yards. Dye surfaced in neither of these locations indicating that portal flow may not be a major factor in these areas. Since all previous observations by the respective property owners concluded that the cave-in of the old stope and the large slug of portal drainage did cause the flooding, the lack of tracer identification of a pathway was enigmatic.

A larger measure of dye (400 ml in 3 l of water) was added to Silver Creek 40-ft upstream of the whirlpool area. This was done to determine if water was entering the mine and exiting at the portal of the west drift or at any of the observed seeps. A very rough approximation of volume was made of the flooded portions of the Atlantic Cable mine so that a quantity of dye could be added which would not be diluted to less than the one ppm visible range. A factor was used to estimate the path since dilution throughout the entire mine workings was thought to be unlikely in the dynamic areas of primary concern. This factor for path length took into account that water entering the mine at the breach would immediately follow the flow path to the drainage drift and discharge from the caved portal 500 ft to the west.

The June 14, 1989, flow measurement of Silver Creek above and below the breach showed a 6.2 cfs loss indicating that at least one-third of the stream flow and therefore one-third of the dye was flowing into the mine. Observers were positioned at the west drift portal, at the south seeps, in the affected yards, at the major seep by the broken valve, at the watermain standpipe to the south, and at the mouth of Silver Creek. These points were observed for 1.5 hours and no dye was seen at any of the locations except for Silver Creek and the Dolores River. The sites were all revisited on an hourly basis until nightfall and during the next day without observing dye. The dye has a suitably long half-life especially when not in direct sunlight to be observed over this time period.

Rico maintenance personnel were able to insert a pipe into an interstice between stream boulders in the bed of Silver Creek to a depth of 3.5 ft. This was near the original whirlpool area and thought to be the hole into the mine. With observers stationed as on the previous day, dye was injected into this pipe. This was done at a trickle rate of approximately 1 liter of concentrated dye every 10 minutes until 4 liters had been injected. No dye was observed at any of the stations.

A large measure of dye was added to Silver Creek in quiet waters just upstream of the Highway 145 culvert. This was to identify any pathway through mine workings including directly down the mine shaft without regard to the exact location for the pathway. No dye was observed in any of the locations. Dye was placed at the major seep below the broken valve to determine if this seep might have another pathway besides the surface flow as there appeared to be a slight diminution of flow away from the seep. No dye flowed into the nearest affected front yard from surface or seep. Dye did however, flow underground for a comparable distance to that of the first day's test (40–50 ft) when dye was added to the portal flow but did not surface at the adjacent residence. This suggested that the negative observation results were a function of pathway and not chemical reaction or absorption with soil. Furthermore, the velocity of the dye in the ground-water system between the points observed was compatible with velocities calculated using Darcy's equation. This suggests that the portal flow at the time of dye testing was not seeping to the adjacent residence.

Dye was added to the waterline ditch which was partially open near the manhole at the northernmost of the four affected residences to determine if the watermain ditch represented a preferential pathway from Silver Creek to the affected properties. No dye was observed in any of the down gradient locations.

Dye tracer testing was inconclusive with respect to pathways from the mine to the major seep but literature review of the results from similar studies indicates that non-observation of the dye event is not substantial evidence that the pathway does not exist. If further testing is undertaken Rhodamine WT may be more effective. Furthermore, there are detection systems available such as fluorometers which are a continuously monitoring system that can detect concentrations measured in parts per trillion. These are also effective in mine discharge which may contain iron compounds which impart a distinct color to the water and would ordinarily mask the dye.

References

Vanderwilt, J.W., 1947, Mineral resources of Colorado: State of Colorado Mineral Resources Board: Colorado Geological Survey Miscellaneous Information 1, 547 p.

Varnes, D.J., and Wadsworth, A.H., Jr., 1943, Atlantic Cable Mine—geology and transit survey of mine workings: U.S. Geological Survey, Strategic Mineral Investigation Preliminary Map, scale 1:250.

McKnight, E.T., 1974, Geology and ore deposits of the Rico District, Colorado: U.S. Geological Survey Professional Paper 723, 100 p.

Clift, Anne, Groundwater tracers: Division of Minerals and Geology Memorandum, February 15, 1990.

Annotated Groundwater Tracer-Dye Selected References

Turner Designs, Sunnyvale,California 94086 supplied the Colorado Geological Survey with the following bibliography pertaining to groundwater tracing. The following has been edited by the CGS.

The user of this bibliography is urged to read the summary of reference 4190. We have included the Colour Index (CI) indentification of dyes if it was given by the author(s) or we have added it when we are certain or reasonably sure of it. In some papers, however, it is not possible to identify the dye used.

Note that the term fluorescein is usually erroneously employed in the English language literature to describe the sodium salt of fluorescein, sodium fluorescein, which is known in Europe as uranine. Depending upon the usage of the cited authors, this bibliography will interchangebly use both fluorescein and uranine. All three of these dyes are CI Acid Yellow 73.

An excellent review of the science of dyes (not dyeing) has been written by McLaren. Reference: McLaren, K., 1986. *The Colour Science of Dyes and Pigments*, 2nd ed.: Hilger, Bristol. 201 p.

This annotated bibliography is presented by Turner Designs as a service to those concerned with tracing, but the company has had no editorial control of its content. The four-digit number preceding each reference is a unique Turner catalog number for it. Most of the references cited can be found in libraries of major universities, but copies of those which cannot be found may be obtained from Turner Designs.

Users of this series of annotated bibliographies are invited to send copies of any new or additional publications relevant to the employment of dyes as tracers in any type of aquifer to the first author, to the third author, and also to Turner Designs. Doing so will enhance the quality and thoroughness of future bibliographies in this series.

4145. Adams, M.C., 1985. Tracer stability and chemical changes in an injected geothermal fluid during injection-backflow testing at the East Mesa geothermal field. *Workshop on Geothermal Reservoir Engineering* (10th, Stanford University, Calif.), *Proceedings*, p. 247–252.

The stability of several tracers was tested using the injection/recovery method in a geothermal reservoir (120–170 °C) comprising lacustrine and deltaic sediments. In tests of 12 hours duration, fluorescein (CI Acid Yellow 73) behaved in a conservative manner, with high percentage recoveries comparable with chloride. Results for two longer tests lasting more than five months were not presented.

4146. Alexander, E.C., Davis, M.A., and Dalgleish, J.B., 1988. Dye tracing through thick, unsaturated zones. *Symposium on Underground Water Tracing* (5th, Athens, 1986), *Proceedings*.

Rhodamine WT (CI Acid Red 388) was used in Minnesota to trace recharge through an unsaturated zone greater than 100-m thick and composed of fractured dolomites, sandstones, and shales. The dye was injected into a borehole near a landfill to investigate the impact of a proposed extension to the site. Short, very dilute pulses of dye appeared at wells and springs up to 1.5 km distant after a few days and persisted irregularly for more than 6 months. Temperature dependence of Rhodamine WT fluorescence was used to distinguish the response of the dye from that of small concentrations of other fluorescent compounds present as background. In a second trace, in South Dakota, Rhodamine WT from the leaky sewage system of the Wind Cave National Park visitor center was detected in cave drips and pools, 70 to 100 m below, with a similar pulsed response.

4147. Aulenbach, D.B., Bull, J.H., and Middlesworth, B.C., 1978. Use of tracers to confirm groundwater flow. *Ground Water*, v. 16, p. 149–157.

Rhodamine WT (CI Acid Red 388) was used to trace the movement of sewage effluent recharged from sand percolation beds into a permeable sand and gravel aquifer. Vertical flow in the unsaturated zone was monitored using porous-cup lysimeters, the tracer taking 30 days to reach the water table at a depth of 20 m. Horizontal movement in the saturated zone was monitored using observation wells. The tracer moved a maximum of 320 m over a period of 54 days. No differences between the behavior of Rhodamine WT and tritium injected simultaneously were observed, but

Rhodamine B (CI Basic Violet 10) was rapidly absorbed.

4148. Aulenbach, D.B, and Clesceri, N.L., 1980. Monitoring for land application of wastewater. *Water, Air and Soil Pollution*, v. 14, p. 81–94.

In the same experiment described in reference 4147, attenuation of Rhodamine WT relative to tritium in the unsaturated zone was reported. This was attributed either to degradation by ultraviolet light prior to infiltration or to sorption, although the latter was not thought to be important in the saturated zone.

4149. Batsche, H., 1982. De Einfluss der Randbedingungen, insbesondere des Pumpryhthmus in Ben brunnen, auf das Ergebnis eines Markierungsversuches. *Beiträge zur Geologie der Schweiz-Hydrologie*, v. 28, p. 321–333.

Four simultaneous tracing tests were made using Sulpho Rhodamine G extra (CI Acid Red 50), Rhodamine B (CI Basic Violet 10), eosine (CI Acid Red 87), and uranine (CI Acid Yellow 73) during two experiments at a groundwater abstraction site on an island in the Danube River. Recharge from the adjacent river, induced by a complex of nine pumping wells, was traced using injections at boreholes on the island. Rhodamine B was not detected at any of the sampling sites, but the other dyes proved successful over distances up to 168 m and were still detectable 85 days after injection. Average groundwater velocities under conditions of continuous pumping were in the range 6 to 16 m/d. Tracer breakthrough curves during intermittent pump operation were complex, but careful interpretation of the multiple injections allowed a good understanding of the transient groundwater flow patterns to be obtained.

4150. Bauer, F., Behrens, H., Drost, W., Käss, W., Leibundgut, Ch., Moser, H., Perlega, W., Rajner, V., Rank, D., Stichler, W., and Wernli, H.R., 1981. Tracerhydrologische Untersuchungen im Langetental (Schweiz). *Steirische Beiträge zur Hydrogeologie*, v. 33, p. 5–123.

Two long distance traces, using eosine (CI Acid Red 87) and uranine (CI Acid Yellow 73) in fluvioglacial terrace gravels 3- to 20-m thick, are described in detail. Substantial amounts of these tracers (tens of kg) were injected into boreholes with small amounts of water, and recovered at monitoring wells and springs along the terrace margin. The uranine traveled 3.5 km via three intermediate boreholes to a spring an gave a recovery of 100% over the one-year sampling period. Borax injected simultaneously was significantly retarded. The eosine was still detectable at some sites 20 months after injection and traveled a distance of 3 km via two intermediate boreholes. A simultaneous injection of Tinopal ABP (an optical brightener) was only detected at the first borehole (1.2 km away) because of high levels of natural background fluorescence. Use of activated carbon detectors improved the minimum detection for both dyes, defining both the distal and lateral dispersion of the plume better than the grab samples of water. Both tracers moved along well-defined flowpaths without extensive lateral mixing, with average groundwater velocities in the range 4 to 24 m/d. Irregular recovery at some boreholes was due to periodic recharge of fresh water from the irrigated fields overlying the aquifer. These are some of the longest traces reported in the literature for intergranular flow.

4151. Baxter, K.M., Edworthy, K.J., Beard, M.J., and Montgomery, H.A.C., 1981. Effects of discharging sewage to the Chalk, in van Duijvenbooden W., Glassbergen, P., and van Lelyveld, H., eds., Quality of Groundwater. *Studies in Environmental Science*, v. 17, p. 245–251.

Sewage infiltrating from a lagoon on a chalk aquifer was traced using Rhodamine WT (CI Acid Red 388). The dye was successfully detected at the water table 8 to 10 m below the site after 18 hours but not in a monitoring well some 150 m distant. The breakthrough of viruses and other microbes was at substantially lagged with respect to that of the dye.

4152. Behrens, H., and Seiler, K.-P., 1980. Hydrogeologische Erfahrungen bei Grundwasseruntersuchungen mit Tracern in Quartären Oberbayerns, in Traceruntersuchungen in Hydrogeologie und Hydrologie. *Gesellschaft für Strahlenund Umweltforschung mbH München, Intitut für Radiohydrometrie, Jahresbericht 1980, R-250*, p. 51–73.

See summary of reference 4153. Includes 15 figures.

4153. Behrens, H., and Seiler, K.-P., 1981. Field tests on propagation of conservative tracers in fluvio-glacial gravels in Upper Bavaria, in van Duijvenbooden, W., Glassbergen, P., and van Lelyveld, H., eds., Quality of Groundwater. *Studies in Environmental Science*, v. 17, p. 649–655.

In studies of groundwater flow and dispersion in morainic fluvioglacial valley gravels, eosine (CI Acid Red 87) and fluorescein (CI

Acid Yellow 73) behaved in a similar manner to 82Br. More than 25 tracer tests between injection boreholes, monitoring wells, pumping boreholes, and springs in three different areas are described. The longest trace reported was over a distance of 2.6 km and was followed for 125 days. Groundwater flow velocities were typically in the range 20 to 25 m/d. Dispersion was higher in experiments tracing concentrated recharge to the aquifer from a losing stream than for borehole injection.

4154. Behrens, H., Seiler, K.-P., and Neumaier, F., 1980. Geländeversuche mit Fluoreszenz-tracern zur Wasserrungesättigtem Lockergestein in den Täkern der Bayerischen Alpen. *Zeitschrift der Deutsche Geologische Gesellschaft*, v. 131, p. 129–138.

Recharge into a valley gravel aquifer from a losing stream on an alluvial fan in an alpine valley was traced using uranine (CI Acid Yellow 73) and eosine (CI Acid Red 87). Both tracers were successfully detected in monitoring wells in the gravels more than 800 m away over a 32-day period. Groundwater flow rates were between 20 and 30 m/d, similar to the rate of percolation in the unsaturated zone. Greater tracer dispersion was observed for the recharge waters than in groundwaters traced from a borehole. This was attributed to their movement transverse to the bedding in the aquifer, while flow of the groundwater was predominantly parallel to the bedding.

4155. Brauns, J., and Hötzl, H., 1982. Kombinierte Pump- und Markierungsversuche zur Dimensionierung von Schutzzonen. *Beiträge zur Geologie der Schweiz-Hydrologie*, v. 28, p. 309–320.

In order to define the "50-day line" used in the protection of groundwater abstraction sites, a combined pumping and tracing test was used to assess the influence of aquifer inhomogeneity on model calculations. Fluorescein was injected in a borehole 360 m from an abstraction well in permeable valley gravels 10-m thick. The dye was first detected after 20 days and was still detectable after 60 days. The average groundwater velocity was 10 m/d, as compared to 34 m/d from a second trace only 20 m from the well. Eosine (CI Acid Red 87) injected into silty sands overlying the gravels 80 m from the injection well was not recovered, probably because of the lower permeability of the sands.

4156. Cole, J.A., 1974. Some interpretations of dispersion measurements in aquifers, *in* Cole J.A., ed., *Groundwater Pollution in Europe*. Water Information Center, New York, p. 86–93.

The results of an unpublished tracing experiment by Bierschenk, using fluorescein (CI Acid Yellow 73) in the coarse, permeable aquifer underlying the Hanford reactor site, are presented. The tracer traveled 3.5 and 4.0 km under natural flow conditions to 2 monitoring wells, with time of first arrival of 60 days and mean travel times of 137 to 125 days. The breakthrough curves indicated a great difference in dispersion at the two sites, which was attributed to the extent of mixing between multiple flow paths with different travel times in the aquifer, an interpretation supported by the multi-peaked nature of the curves.

4157. Davis, S.N., Campbell, D.J., Bentley, H.W., and Flynn, T.J., 1985. *Ground Water Tracers*. National Water Well Association, Worthington, Ohio, 200 p.

This is a general review of water tracers and their applications. It includes an unsatisfactory section on the use of fluorescent dyes. See the critical discussion by Quinlan (1986) and the reply by Davis (1986). References: Quinlan, J.F., 1986. Discussion of "Ground Water Tracers" by Davis et al. (1985), with emphasis on dye-tracing, especially in karst terranes. Ground Water, v. 24, p. 253–259; p. 396–397; p. 398–399 (reply by Davis). An unpublished response to Davis's reply is available from Quinlan.

4158. Dosche, F., 1967. Technik un Ergebnisse von Schictenfärbeversuchen in Grund- und Oberflächenwassern sowie in gespeicherten Trinkwassern. *Steirische Beiträge zur Hydrogeologie*, no. 18-19, p. 185–204.

Uranine (CI Acid Yellow 73) was used to trace water 110 m to a borehole. Tracer recovery was 70% after 50 days. In a second experiment, rhodamine (type unspecified) was used to trace water from an injection borehole into the adjacent canal (where it was detected by divers) and to a sampling borehole on the opposite bank of the canal. Groundwater velocity was 10 m/d. In both experiments the aquifers were probably sands and gravels.

4159. Evarts, C.J., Kanwar, R.S., Alexander, E.C., Jr., and Alexander, 1988. A comparison of chemical tracers for study of solute transport in the vadose zone. *American Society of Agricultural Engineers*, Paper no. 88-136. 13 p.

Lithium cations and Rhodamine WT (CI Acid Red 388; anionic) are very significantly delayed (relative to bromide anions and nitrate anions) in their transit through an 18.6 cm column of laboratory-packed soil, as described by their breakthrough curves. However, when these four tracers were simultaneously sprinkled onto a field of the same soil and recovered form a tile drain 1.1 m below, their peak concentrations occurred simultaneously, within 70 min. of the start of the simulated rainfall. Not only do these experiments prove once again the importance of macropore flow in soils, but they readily explain why nitrates and pesticides from cultivated fields commonly occur in groundwater in far higher concentrations than predicted by laboratory tests and computer simulations.

4160. Finkner, S.C., and Gilley, J.E., 1986. Sediment and dye concentration effects on fluorescence. *Applied Engineering in Agriculture*, v. 2, p. 104–107.

Laboratory studies showed that Rhodamine WT (CI Acid Red 388) and Sulpho Rhodamine B (CI Acid Red 52) are significantly adsorbed by three soils (collected from North Dakota, Maine, and Texas). Although the adsorptive dye loss for Lissamine FF (CI Acid Yellow 7) was less than for the two other dyes, the minimum detectability of Lissamine FF was much less and its linear range of detectability was much shorter than for the other two dyes. Sulpho Rhodamine B was the best dye to use for the soils tested. Statistical analysis of data is good, but the study would have been significantly enhanced if the clay mineralogy of each of the soils had been determined and if the study had included examination of the relations between dye adsorption and the amount of clays present in the soil and their mineralogy.

4161. Fletcher, S.J., and Pedler, I.V., 1985. Underseepage at the Loy Yang settling pond dam. *Engineering Geology*, v. 22, p. 71–81.

Under seepage occurred below an earthfill dam impounding a large settling pond in two thin aquifers comprising fine sands, silts, and a fractured clay which is a buried soil. Fluorescein (CI Acid Yellow 73), Rhodamine WT (CI Acid Red 388), and amino G acid were used to determine hydraulic conductivities by borehole dilution. After 7 days dye was also present in boreholes 50 m downstream of the injection sites on the dam embankment.

4162. Garnier, J.M., Crampon, N., Préaux, C., Porel, G., and Vreulx, M., 1985. Traçage par ^{13}C, ^{2}H, I^-, et uranine dans la nappe de la craie Sénonienne en écoulement radial convergent (Bethune, France). *Journal of Hydrology*, v. 78, p. 379–392.

The behavior of uranine (CI Acid Yellow 73) and three other tracers was examined in a semi-confined chalk aquifer for radial flow from an injection borehole to a pumping well, a distance of 10.2 m. Usually, the uranine arrived and peaked before both the tritium and the iodide ion, and the time/concentration curve exhibited less tailing, giving lower dispersivities for the uranine than for the other tracers. This was attributed to a "molecular sieve" effect in the smaller pores of the chalk through which tritium and iodide could pass but from which the larger uranine molecules were excluded. Tracer recovery of uranine was greater than for iodide but less than for tritium, due to adsorptive loss.

4163. Gudmundsson, J.S., Huaksson, T., Thorhallsson, S., Albertsson, A., and Thorolfsson, G., 1984. Injection and tracer testing in Svartsengi Field, Iceland. *New Zealand Geothermal Workshop* (6th), *Proceedings*, p. 175–180.

In order to investigate the hydrology of a deep, fractured geothermal reservoir, tracing experiments were conducted using continuous injection of a brine/condensate mixture an sampling at a producing well 200 m distant. Rhodamine WT (CI Acid Red 388) and iodide concentrations peaked simultaneously 4 days after injection; both tracers were still detectable after 32 days. The iodide showed considerably greater tailing then the Rhodamine WT. This was attributed to irreversible adsorption or breakdown of the ye at high temperature (220–235°C). Total recovery of iodide was low (16%), but no comparable information was presented for the dye.

4164. Harvey, R.W., George, L.H., Smith, R.L., LeBlanc, D.R., Garabedian, S.P., and Howes, B.L., 1987. Transport of bacteria through a contaminated freshwater aquifer, in Franks, B.J., ed., U.S. Geological Survey Program on Toxic Waste—Ground-Water Contamination: Proceedings of the Third Technical Meeting, Pensacola, Florida, March 23–27, 1987. *U.S. Geological Survey, Open-File Report 87-109*, p. B29–B31.

DNA-specific fluorochromes were used to label bacteria, and the transmission of these was compared with that of fluorescent microspheres of different sizes. Both were injected simultaneously into a sewage-contaminated stratified sand and gravel aquifer, and sampled 3.2 m downgradient under conditions of natural head. The technique demonstrated that smaller particle sizes (0.2 micrometer) were preferentially removed compared to large particle sizes (0.7 and 1.2 micrometers), but that bacteria were concentrated compared to particles of the same size. The breakthrough of bacteria was followed by that of bromide ions, suggesting preferential transport through large pores. In a second experiment, microspheres with different surface functional groups were used to demonstrate that these were also significant in controlling the transport of bacteria. Carboxylated microspheres lagged uncharged microspheres by 8 days over a distance of 6.9 m. This new technique offers considerable potential as an exploratory tool for studies of pollutant transmission in aquifers.

4165. Heitfeld, K.H., and Tatzler, E., 1967. Ergebnisse eines Färbeversuches in tonig-sandigen Gesteinen an der Biggetalsperre (Sauerland). *Steirische Beiträge zur Hydrogeologie*, no. 18-19, p. 205–217.

As part of the investigations for the design of a dam and associated grout curtain, tracing experiments were conducted between two mined galleries excavated in fissured sandstones, shales, and greywackes in the unsaturated zone. Uranine (CI Acid Yellow 73) injected into a borehole under pressure in an upper gallery was sampled from boreholes in an underlying level 25 m below, the tracer arriving after about 6 days. It was also detected 200 m laterally at a surface spring. Groundwater velocities were in the range 4 to 10 m/d. A mylonitised zone in a fault proved a barrier to water movement, but there was strong flow in the adjacent fractured zone.

4166. Hoehn, E., and Santschi, P.H., 1987. Interpretation of tracer displacement during infiltration of river water to groundwater. *Water Resources Research*, v. 23, p. 633–640.

The rate of movement of a plume of tritium, which entered a shallow, bedded sand and gravel aquifer following an accidental release to a surface river, agreed well with that derived from an earlier tracer test. Uranine (CI Acid Yellow 73) was injected at a well adjacent to the river and sampled at two pumping boreholes a maximum of 10 m distant. The dye breakthrough curve was bimodal due to the presence of layers with different permeability. Groundwater velocities were between 1 and 3 m/d.

4167. Hötzl, H., 1982. Die Kluftmarkierung—eine Anwendung der Markierungstechnik zur Ermittlung von Durchlässigkeitseigenschaften kluftiger Gesteine. *Beiträge zur Geologie der Schweiz-Hdrogeologie*, v. 28, p. 381–393.

Rhodamine (type unspecified), methylene blue (CI Basic Blue 9), and eosine (CI Acid Red 87) were injected via drill holes into a fractured granite. The frequency of occurrence of the dye-stained joint faces was significantly different from the joint-frequency obtained by mapping the major joint sets, indicating differential penetration by water.

4168. Kanz, W., 1982. Zur Bestimmlung der Grundwasserlaufzeiten in der Umgebung von Förderanglagen. *Beiträge zur Geologie der Schweiz-Hydrologie*, v. 28, p. 335–343.

Eosine (CI Acid Red 87) and uranine (CI Acid Yellow 73) were used to trace groundwater flow lines perpendicular to the river bank at a river-infiltration abstraction site in 4 m of fluvial gravels. Times to peak tracer concentrations were 3 and 16 days for boreholes 29 and 69 m, respectively, from the pumping well. Average groundwater flow velocities were 3.5 to 8.3 m/d. Uranine was still detectable 30 days after injection. Hydraulic conductivities calculated from the tracer data were significantly lower than those derived from sediment grain-size data or laboratory permeability tests. Pyronin B (CI no. 45010; no CI Generic Name) injected 29 m away was not detected in the monitoring well.

4169. Käss, W., 1970. Die Anwendbarkeit der hydrogeologischen Markierungsmittel zur Untersuchung der Beziehungen zwischen Grundwasser und oberirdischen Wasser-allgemeine Gesichtspunkte. *Zeitschrift der Deutsche Geologische Gessellschaft, Sonderheft*, p. 109–115.

Uranine (CI Acid Yellow 73) injected into a surface stream flowing on alluvium overlying a fractured, porous sandstone aquifer, 6- to 50-m thick, first appeared after 1.5 hours in an abstraction borehole 1 km downstream. During the next four days the tracer progressively appeared at the other pumped boreholes up to 1 km further downstream. Average groundwater velocity was reported to be 0.9 km/d, but the tracer recovery was low (less than 1%).

4170. Käss, W., 1979. Bemerkung zur Dissertation GALLIARD Grenoble, 1976. *Steirische Beiträge zur Hydrogeologie*, no. 31, p. 163–165.

A comparative tracer experiment reported by Galliard (1976) is briefly described. The experiment was through 13 m of sandy alluvium and lasted 35 days. The breakthrough curves for Rhodamine WT (CI Acid Red 388), uranine (CI Acid Yellow 73), and Rhodamine B (CI Basic Violet 10) lagged from 5 to 10 days behind those of 131I, and recoveries were 70%, 33%, and 26%, respectively. Reference: Galliard, B., 1976. Methode de traceurs pour la determination des parameters de transfert de substances en solution dan l'eau des aquifères (thesis presented to Université Scientifique et Medicale de Grenoble).

4171. Käss, W., 1985. Chemische Transportmechanismus in der ungesättigten Zone-Untersuchung mit Markierungsmitteln. *Zeitschrift der Deutsche Geologische Gesellschaft*, v. 136, p. 481–496.

Uranine (CI Acid Yellow 73) and eosine (CI Acid Red 87) were used to trace recharge from the surface of a brown earth soil to a lysimeter at 5-m depth. The eosine emerged three months after injection following a dry period, and both uranine and eosine were still present 6 years later, although complete details were not given. A second test, using eosine and uranine in a fractured sandstone aquifer, is briefly reported. Tracer recovery at a distance of 160 m was less than 1% after 10 months.

4172. Käss, W., Drobne, F., and Bukvic, B., 1976. Investigations in Quaternary sediments of Savinja Valley 1973, in Gospodaric, R. and Habic, P., eds., *Underground Water Tracing Investigations in Slovenia 1972–1975*. Institute for Karst Research, Ljubljana, p. 233–246.

A comparative tracing experiment using chloride, *Serratia marcescens* (bacteria), uranine (CI Acid Yellow 73), and eosine (CI Acid Red 87) was carried out in a stratified sand and gravel aquifer. The tracers moved over 25 m in less than one day in a well-defined plume. The average groundwater velocity was 8.4 m/d. The fluorescein was also reported to be present in a borehole 900 m distant after 6 months.

4173. Klotz, D., and Seiler, K.-P., 1980. Labor- und Geländeversuche zur Ausbreitung konservativer Tracer in fluvioglazialen Kiesen von Oberbayern, in Traceruntersuchungen in Hydrogeologie und Hydrologie. *Gesellschaft für Strahlen- und Umweltforschung mbH München, Institut füur Radiohydrometrie, Jahresbericht 1980, R-250*, p. 74–89.

See summary of reference 4174.

4174. Klotz, D., Seiler, K.-P., Moser, H., and Neumaier, F., 1980. Dispersivity and velocity relationship from laboratory and field experiments. *Journal of Hydrology*, v. 45, p. 169–184.

In column experiments done to calculate dispersivity coefficients for fluvioglacial gravels, uranine (CI Acid Yellow 73) was a conservative tracer, behaving similar to chloride and 82Br. In a 13-m-thick aquifer of the same material, all three tracers proved conservative over 10 m with long-term (3 months) recoveries of 80% under conditions of natural flow an 100% when pumping. Groundwater flow velocities ranged from 17 to 400 m/d.

4175. Laidlaw, I.M.S., 1986. Use of fluorescent tracer dyes in determining leakage from canals, in Gameson, A.L.H.l, ed., *Tracers for the Water Industry*, Water Research Center, Medmenham, p. 143–146.

Sulpho Rhodamine B (CI Acid Red 52) was used to demonstrate the leakage of a 70-m-long concrete-lined section of canal on an embankment. The tracer appeared at basal seepages up to 60-m away within 29 hours; it was still detectable at some sites 6.5 days later.

4176. Lewis, D.D., Kritz, G.J., and Burgy, R.H., 1966. Tracer dilution sampling technique to determine the hydraulic conductivity of fractured rock. *Water Resources Research*, v. 2, p. 533–542.

Dye dilution measurements using fluorescein (CI Acid Yellow 73) were conducted in boreholes in a fractured crystalline rock with low groundwater velocities. Hydraulic conductivities derived from tracer dilution over an 8-day period agreed favorably with those derived from pumping tests.

4177. Liebundhut, Ch., 1975. Farbversuche in Grundwasser des Oberargaus. *Jahrbuch des Oberargaus* 1975. Universität Bern, Geographisches Institut. 171 p.

Six experiments using uranine (CI Acid Yellow 73) to trace groundwater in fluvioglacial valley gravels and alluvium were all successful. For borehole injection and recovery at an abstraction well, dye recoveries were high (82% and 87%), the maximum distance traced being 240 m. Infiltration of dye from the surface gave much lower recoveries (17%), but in one such experiment tracer was recovered in 9 separate springs at the foot of the terrace and over 700- m distant. Dye in this test was still detectable after 137 days, despite a first arrival time of only a few days. Average groundwater velocities were in the range 4 to

19 m/d, but breakthrough curves often showed rapid first arrival, multiple peaks, and long tails.

4178. Liebundgut, Ch., 1981. Zum Adsorptionsverhalten von Fluoreszenstracern. *Festschrift für J. Zötl.* Vereinigung für Hydrogeologische Forschungen, Graz, p. 111–129.

Adsorption of uranine (CI Acid Yellow 73) and three optical brighteners [Tinopal MSP (CI Fluorescent Brightener 353), Tinopal ABP, and Uvitex 3778] on brown-earth soil and building sand was investigated. A solution of the tracer was passed several times through a column of the absorbent; tracer recovery was monitored after each passage. The column was then repeatedly flushed with clean water and the release of the adsorbed tracer was monitored. Uranine and Tinopal ABP were significantly adsorbed on building sand but were released almost completely on elution with clean water. In the case of uranine, this release was almost immediate, although the results are not directly comparable because of the much lower concentrations of this dye used. For the soil, all tracers were bound more strongly, but progressive elution caused their slow release. Tinopal MSP and Uvitex 3778 were both very strongly adsorbed and would not make good groundwater tracers. (Note: There is some confusion in the labelling of the two Tinopal tracers on Figure 10 of this reference.) These results demonstrate the significance of irreversible adsorption for the retardation and tailing of tracer breakthrough tests in the field.

4179. Lloyd, J.W., Ramanathan, C., and Pacey, N., 1979. The use of point-dilution methods in determining the permeabilities of landfill materials. *Water Services*, p. 843–846.

The use of point-dilution tests using fluorescein (CI Acid Yellow 73) in a variety of materials, including domestic waste, clayey sands and silts, colliery spoil, and medium-grained sands, at a landfill site were described. A correction procedure for adsorption of the tracer on suspended material in the borehole, by comparison of filtered and unfiltered samples over 14 days, is described but no correction was made for wall adsorption. Initial mixing of the tracer in deep boreholes and sampling from boreholes with limited waste depth were found to be problems.

4180. Luft, G., 1980. Kennzeichnung der Fliestrichtung und der hydraulischen Leitfahigkeith in schluffigen Aquiferen mitels Uranin-Markierungsversuchen-Teil 1. *Deutsche Gewässer Kundliche Mitteilungen*, v. 24, p. 37–42.

Details of two tracing experiments with uranine (CI Acid Yellow 73) under natural groundwater flow conditions in a shallow silty aquifer are described. A series of sampling boreholes downgradient from the injection well and 3 m radially from it allowed the lateral dispersion of uranine to be investigated. The dye pulse was well defined over a 7-month period at one site (4 months at the other), although the breakthrough curve was somewhat irregular, and there was a long, structureless tail.

4181. Luft, G., 1981. Zur Schätzung der Parameter Abstandsgeschwindigkeit un Kispersionkoeffizienten aus Markierungsversuchen mit Uranin in schluffigen Aquiferen. *Deutsch Gewässer Kundliche Mitteilungen*, v. 25, p. 12–18.

Average interstitial velocity and the longitudinal and transverse dispersion coefficients are estimated from the traces described in reference 4180 using a 5-parameter numerical model. The fit is good for one experiment but only moderate for the second.

4182. Luft, G., and Morgenschweis, G., 1982. Ermittlung von Abstandsgeschwindigkeit, hydraulischer Leitfähigkeit und Dispersionskoefficient aus Markierungsversuchen in kiesigen und schluffigen Aquiferen. *Beiträge zur Geologie der Schweiz-Hydrologie*, v. 28, p. 283–295.

Three tracer experiments were used to test the performance of a groundwater solute transport model and to estimate aquifer parameters. Eosine (CI Acid Red 87) and uranine (CI Acid Yellow 73) injected in a borehole were sampled in radial monitoring wells 12 m distant in a medium gravel aquifer and 3 m distant in a silt aquifer. Groundwater velocities were 0.18 to 0.26 m/d in the gravel and 0.045 m/d in the silt aquifer, with peak travel times from 40 to 65 days. The tracer remained detectable for over 250 days, with substantially greater tailing in the gravel aquifer than predicted by the model.

4183. McLaughlin, M.J., 1982. A review of the use of dyes as soil water tracers. *Water SA*, v. 8, p. 196–201.

This is a brief but thorough review that includes summaries of many earlier reviews and papers, not cited herein, that were more concerned with micro-scale hydrology than with meso-scale or macro-scale hydrology. More than a dozen dyes are mentioned from the literature, but most of the cited papers do not discuss why a given non-traditionally used dye was selected and why it was thought to be best suited for study of a given problem. In many soils, the use of another dye might have been easier and more efficient. No mention is made of tracing with several dyes simultaneously.

4184. Mather, J.D., Gray, D.A., and Jenkins, D.G., 1969. The use of tracers to investigate the relationship between mining subsidence and groundwater occurrence at Aberfan, South Wales. *Journal of Hydrology*, v. 9, p. 136–154.

Four tracing experiments are described from an investigation of groundwater conditions below a failed pile of coal-mining waste overlying a fractured sandstone aquifer affected by mining subsidence. Fluorescein (CI Acid Yellow 73) was added as a visual indicator in amounts of 3, 3, and 35 lbs to 336, 2240, and 4480 lbs of rock salt in three successful attempts to trace over distances up to 560 m, but no fluorescein was detected in these tests. Thirty pounds of fluorescein was successfully detected in a similar tracer test that did not use any salt. Poor recovery of fluorescein was attributed to the low pH of groundwater, but it should also be noted that detection of the dye was by visual observation under ultra-violet light. Also, the presence of chloride ions tends to quench the fluorescence of fluorescein.

4185. Naymik, T.G., and Barcelona, M.J., 1981. Characterization of a contaminant plume in ground water, Meredosia, Illinois. *Ground Water*, v. 19, p. 517–526.

In an experiment to model the movement of a contaminant plume from a distribution terminal for liquid ammonia, Rhodamine WT (CI Acid Red 388) was used to determine the permeability of a 27 m thick sand and gravel aquifer. The dye introduced at an observation well was rapidly transmitted to adjacent pumping wells 15.2 and 25 m distant, with tracer breakthroughs in 40 and 150 minutes, respectively.

4186. Naymik, T.G., and Sievers, M.E., 1985. Characterization of dye tracer plumes: in situ field experiments. *Ground Water*, v. 23, p. 746–752.

Tracer tests were used to model the geometry of a migrating plume under conditions of natural groundwater flow, in both glacial outwash material and the overlying finer aeolian sands. Rhodamine WT (CI Acid Red 388) and amino G acid were detected in the outwash aquifer over a distance of 7.6 m with an average velocity of 0.06 m/d, but Lissamine Yellow FF (CI Acid Yellow 7) was not detected at 5 m, even after pumping. This was ascribed either to distortion of the flow paths or to excessive dilution because of slow release from the injection well. Comparison between ideal and calibrated simulation mode results suggested significant dye losses between the 3- and 15-m-sample stations. These were attributed to greater lateral dispersion than simulated by the model, rather than to tracer sorption.

4187. Oakes, D.B., and Edworthy, K.J., 1976. Field measurements of dispersion coefficients in the United Kingdom. *Groundwater Quality, Measurement, Prediction and Protection*. Water Research Center, Medmenham, p. 274–297.

Two experiments were carried out in the thick, saturated zone of a porous sandstone aquifer to investigate the mechanism of dispersion and measure effective dispersivity for regional groundwater quality studies. Mixtures of Rhodamine WT (CI Acid Red 388), lithium salt, and potassium iodide were introduced into boreholes 3 and 6 m from a pumping well. Tracers were detected after 16 and 24 hours, respectively. Rhodamine WT was used only as an on-site indicator and no quantitative analyses for it were carried out.

4188. Omoti, U., and Wild, A., 1979. The use of fluorescent dyes to mark the pathways of solute movement through soils under leaching conditions: 2. Field experiments. *Soil Science*, v. 128, p. 96–104.

Pyranine (CI Solvent Green 7) and fluorescein (CI Acid Yellow 73) distributions were recorded using ultraviolet photographic techniques to study solute movement under field conditions with short-term irrigation and with long-term leaching by winter rainfall on a free-draining, poorly structured loamy soil. The vertical distribution of pyranine, 36Cl, and tritium were similar, but the great reduction of pyranine fluorescence under field conditions meant that ultraviolet photography was unsuccessful. The greater adsorption and higher fluorescence of fluorescein permitted identification of bypassing flow-routes along earthworm channels, fissures, and other macropores.

4189. Pickins, J.F., Cherry, J.A., Gilham, R.W., and Merritt, W.F., 1977. Field studies in dispersion in a shallow sandy aquifer. *Invitational Well-Testing Symposium* (1st, Berkeley, Calif.) *Proceedings*, LBL-7027, p. 55–62.

A detailed three-dimensional monitoring network of piezometers, wells, and multi-dimensional monitoring were used to study hydrodynamic dispersion in an 8.5-m-thick glacial-outwash sand aquifer. Point dilution tests using Rhodamine WT (CI Acid Red 388) and a recirculating packer system for sampling were useful for identification of high transport zones within the aquifer. Dispersivities obtained from a single well injection/with-drawal test using 51Cr-EDTA and those from integration of the results for individual layers in a two-well circulation test were comparable. Higher dispersivities were obtained in the latter test from analysis of the tracer break-through curves, which were attributed to mixing of water from different layers in the abstraction borehole.

4190. Quinlan, J.F., and Smart, P.L., 1976. Identification of dyes used in water tracing: A suggestion to improve communication. *International Symposium of Underground Water Tracing* (3rd, Ljubljana), *Proceedings*, v. 2, Institute of Karst Research, Ljubljana, p. 263–267.

In order to aid communication and to avoid ambiguity, it is suggested that in all papers dealing with tracer dyes authors should cite the Colour Index (CI) Generic Name or the CI Constitution Number, as well as the name and location of the manufacturer of each dye. Unfortunately, this is rarely done. The CI Generic Name is preferable to the CI Constitution Number because the former is more easily remembered and recognized. Reference:; Society of Dyers and Colourists and American Association of Textile Chemists and Colourists, 1971. Colour Index (Volumes 1 to 4), Supplementary Volumes 5 and 6, and subsequent annual updates. The dye manufacturer's name can be important because various manufacturers use different amounts of diluent and different diluents in a given dye. In other words, a kilogram of fluorescein from Manufacturer A may not have the same tinctorial power and properties as a kilogram of fluorescein from Manufacturer B; one of the fluoresceins could have twice as much active ingredient as the other. The need for careful identification of dyes used for water-tracing—particularly if one is discussing their chemical properties, toxicity, or excitation or emission spectra—is made obvious by examination of the Color Index itself. For example, 12 structurally different kinds of Rhodamine are sold under more than 60 different names by more than 40 manufacturers. Also, at one time two structurally different dyes were sold as Rhodamine B.

4191. Rahne, R.M., Hagedorn, C., and McCoy, E.L., 1979. A comparison of fluorescein and antibiotic-resistant *Escherichia coli* as indicators of pollution in groundwater. *Water, Soil and Air Pollution*, v. 11, p. 93–103.

The movement of water from a simulated septic tank drain was studied on 1 14% slope, 15-m long, using spray irrigation and sampling piezometers in a thick, well-drained, structured silty loam soil underlain by a sticky clay subsoil. E. coli were recovered in large concentrations at the slope base after only 4 hours for injections in both the A and B horizons, but fluorescein (CI Acid Yellow 73) appeared to be attenuated either by quenching or by adsorption.

4192. Ransom, M.D., Phillips, W.W., Rutledge, E.M., and Mitchell, D.T., 1975. Wastewater disposal by septic tank systems in selected soils of northwest Arkansas. *Project Report* (for) *Northwest Arkansas Regional Planning Commission* (Project no. ARK CPA-06-37-1032). Springdale, Arkansas. 76 p.

Five different soil units were evaluated at 15 sites for the development of septic tank filter fields. Percolation tests were performed and pits dug to enable visual observation of the percolation of Rhodamine B (CI Basic Violet 10). In two soil units the dye revealed lateral flow along more permeable horizons and above hardpans. Such macropore flow could not have been detected by percolation tests.

4193. Smart, P.L., 1985. Applications of fluorescent dye tracers in the planning and hydrological appraisal of sanitary landfills. *Quarterly Journal of Engineering Geology*, v. 18, p. 275–286.

Lissamine Yellow FF (CI Acid Yellow 7), Rhodamine WT (CT Acid Red 388) and fluorescein (CI Acid Yellow 73) were used to est the integrity of clay-lined cells in a landfill and to trace the movement of leachate to springs in a fissured limestone aquifer. High background fluorescence precluded the use of blue-fluorescent dyes. The tracers proved to be persistent but not conservative when used to trace water injected into the domestic refuse and were successfully detected both on-site and in the adjacent aquifer, giving a good understanding of the site hydrology and enabling the planning of remedial works. The fate of water infiltrating downstream of a spray plot used for the treatment of leachate was also investigated by tracing. The water passed vertically into an underlying silty sand aquifer, from which it emerged via numerous small springs up to 2.5 km in distance after some 3 weeks.

4194. Smith, D.I., and Greenaway, M.A., 1983. Fluorometric dye techniques; their application to groundwater tracing and borehole studies. *International Conference on Groundwater and Man* (Sydney), *Proceedings*, p. 311–320.

Rhodamine WT (CI Acid Red 388) and amino G acid were used in single borehole dilution tests and borehole-to-borehole traces under natural and pumped conditions to determine groundwater velocities in a 14-m-thick rubbly limestone aquifer. Maximum distance traced was 9 m using amino G acid; the time of first arrival was 22 hours.

4195. Smith, D.I., and Jacobson, G., 1981. The application of fluorometric dye techniques to groundwater pollution problems with special reference to studies in Canberra. *Proceedings of the Groundwater Pollution Conference, Perth, Western Australia, 1979.* Australian Water Resources Council Conference, Series no. 1, p. 183–198.

In an investigation of pollution in an alluvial, fractured mudstone aquifer underlying an urban area, tracing experiments using Rhodamine WT (CI Acid Red 388), fluorescein (CI Acid Yellow 73), and "Leucophor" (an unspecified optical brightener) were carried out. Rhodamine WT was detected under natural flow conditions at distances up to 78 m from the injection site, with peak concentrations being reached after three months. The dye was still detectable in the groundwater more than a year after injection. High background levels, probably caused by organic pollutants, limited the detection of fluorescein and Leucophor, which were therefore less successful than Rhodamine WT.

4196. Sturm, P.W., and Johnson, W.E., 1950. Field experiments with chemical tracers in flood waters. *Producers Monthly*, v. 15, no. 2, p. 11–17.

A series of experiments using fluorescein (CI Acid Yellow 73) and several other tracers was undertaken in a sandstone oil reservoir to investigate permeability anisotropy and the presence of fissure flow. Successful traces were obtained between water-flood injection wells and producing wells up to 77-m apart with times of first arrival up to 77 days. Injection of a wetting agent caused additional release of fluorescein in one experiment. Laboratory experiments using a sand column indicate that fluorescein is persistent over a 160-day period but suffers from some adsorptive loss.

4197. Tilstra, J.R., Malueg, K.W., and Powers, C.F., 1973. A study of disposal of campground wastes adjacent to Waldo Lake, Oregon. *National Eutrophication Research Program, Working Paper 7*,. 22 p.

Rhodamine WT (CI Acid Red 388) and sodium chloride were used to trace effluent from the septic tank drain-field of a rural camp site. Natural sewage flows were supplemented to design levels using tap water. The bedrock aquifer comprised 3.5 to 5.0 m of fractured basalt rhyolite underlain by a thin, highly permeable horizon. The tracers were detected a maximum distance of 46 m from the drainfield after approximately one month and showed similar behavior.

4198. Trudgill, S.T., 1987. Soil water tracing, with special reference to the use of Rhodamine WT, Lissamine FF and amino G acid. *Hydrological Processes*, v. 1, p. 149–170.

There are severe limitations on the use of Rhodamine WT (CI Acid Red 388), Lissamine FF (CI Acid Yellow 7), and amino G acid as soil-water tracers, but practical applications are possible. Rhodamine WT is highly sorbed and has a deleterious effect on soil structure, but background values for it are extremely low. It is the dye of choice when pathways are to be determined. If travel times are more important, Lissamine FF is more useful. Amino G acid could be used for either purpose, but photodecomposition may be a significant problem.

4199. Trudgill, S.T., Pickles, A.M., Smettem, K.R.J., and Crabtree, R.W., 1983. Soil water residence time and solute uptake. 1. Dye tracing and rainfall events. *Journal of Hydrology*, v. 60, p. 257–270.

Adsorption of amino G acid, Lissamine FF (CI Acid Yellow 7), and Rhodamine WT (CI Acid Red 388) was examined in batch and column experiments. Breakthrough curves of amino G acid and Lissamine FF were comparable, while Rhodamine WT was lagged with lower recoveries of 5% and 10% in disaggregated soils and column experiments, respectively, compared to 19% and 60% for Lissamine FF. In later experiments the dyes were used to trace recharge over a 2 m slope segment to sampling sites at the slope base.

Results indicated that dye output was not predictable by a simple storage model but was related to the occurrence of intense rainfall events.

4200. Wernli, H.R., 1986. Napthionat - eine neuer Fluoreszenztracer zur Wassermarkierung. *Deutsche Gewässerkundliche Mitteilungen*, v. 30, p. 16–19.

Industrial-grade sodium-naphthionate (4-amino-napthalene-1-sulphonic acid, sodium salt) is recommended as a new tracer and has been successfully tested in granular aquifers and fractured sandstone. It is less detectable than uranine (CI Acid Yellow 73), so a greater quantity must be used, but it is very useful. Contrary to the claim of the author, however, napthionate is not a dye. It, like amino G acid (7-amino-1, 3-napthalene disulphonic acid), is a dye-intermediate (a compound used in the manufacture of dyes). Although the excitation and emission maxima for both napthionate and amino G acid are slightly different from those of optical brightener, the reliable detection of low concentrations of either dye-intermediate would be difficult if there is a significant brightener background in an area.

4201. White, K.E., 1976. Tracer methods for the determination of groundwater residence-time distributions. *Groundwater Quality Measurement, Prediction and Protection*. Water Research Center, Medmenham, p. 246–273.

Two comparative experiments using Rhodamine WT (CI Acid Red 388) are briefly presented in the introduction to a more general review of tracers. In a porous, fractured sandstone aquifer the dye moved in less than 12 hours from an injection borehole to a pumped borehole 6 m away and was still present 4 days later. Rapid transmission (less than 20 minutes) of this dye was also observed in a chalky limestone aquifer over a distance of 1 m under conditions of pumped flow. No tracer recoveries are given, and the comparative performance of lithium and iodine injected simultaneously is not discussed.