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GROUNDWATER TRACING IN WATER POLLUTION STUDIES

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Groundwater tracing has been a valuable tool for water pollution investigations in soluble rock terrains. Tracing can directly demonstrate that water (and a pollutant) moves from point to point. Tracing data are understandable to the public and regulatory agencies. Groundwater tracing provides an indicator of underground travel rates and distances. Tracer tests must be properly planned and executed to insure proper results.

INTRODUCTION

Groundwater tracing can be a useful tool in water pollution investigations in soluble rock regions. It can also be used in some fractured rock areas and in other hydrologic settings with rapid movement of water through the subsurface. This paper will focus on groundwater tracing in soluble rock areas since it is in these areas that the techniques have received the greatest use.

UTILITY OF GROUNDWATER TRACING

Groundwater tracing is useful in water pollution investigations for four primary reasons:

1. Groundwater tracing can provide direct proof of movement of water from one point to another.

2. Tracing results are easily understood by the public, regulatory bodies, and the courts.

3. Properly designed tracing can provide a qualitative indication of whether or not effective natural cleansing of water contaminants should occur along the flow route traced.

4. Groundwater tracing can provide an indication of underground travel rates; such rates are often grossly underestimated by people who are not adequately familiar with the hydrology of soluble rock terrains.

Groundwater tracing can be extremely valuable in directly demonstrating that water from one point moves to another. This is particularly valuable in soluble and/or fractured rock landscapes where subsurface flow directions may or may not tend to parallel surface flow directions. There is unfortunately a prevalent myth that groundwater basin divides are either directly or almost directly beneath surface basin divides. This is an adequate general characterization for soluble rock lands.

Water pollution work must often be conducted in areas where there are very few wells where depths to water can be measured. In such areas, groundwater tracing is frequently the only practical method for delineating those areas which contribute water to the particular groundwater basins of concern. Furthermore, in some soluble rock areas, water levels in wells may drop dramatically as a result of pumping. In some cases, it may require a substantial period without pumping for the water level in the well to return to the general potentiometric elevation of the groundwater system. Potentiometric maps which include such wells may have some very significant inaccuracies.

Groundwater tracing provides data which are understandable to the public, regulatory agencies, and the courts. The significance of this in developing convincing arguments in water pollution cases is obvious. However, it sometimes occurs that personnel in regulatory agencies will become unduly impressed by groundwater tracing and will then take the stance that groundwater tracing work is needed to resolve almost all groundwater pollution issues. While groundwater tracing is a useful tool, it is not the only tool available to groundwater hydrologists working on pollution issues, and this must be recognized.

Properly designed groundwater tracing tests can provide a qualitative indication of whether or not effective natural cleansing occurs as waters travel through the groundwater system from one point to another. Some years ago I conducted several groundwater traces from dumps in sinkholes to springs (Aley, 1969; 1972; 1972a). One of the arguments raised about the tracing work was that although the dye went from a sinkhole dump to a spring, "anything really bad" in the water could probably get "filtered out" as the water moved through the groundwater system. This argument led to groundwater tracing with stained *Lycopodium* spores; the method is explained in Aley and Fletcher (1976). The *Lycopodium* spores were selected as a tracing agent because their mean diameter is 33 microns, and they are thus 10 to 15 times larger than most pathogenic bacteria (Aley et al., 1972). If the spores can traverse a particular groundwater travel route without being removed by filtration, then one can presume that smaller materials (such as bacteria and viruses) can also be transported along the same route without being removed by filtration. This does not mean that the smaller materials may not be removed from the water by adsorption or some other process.

There are several dyes used in groundwater tracing work. Some of these (such as optical brighteners, direct yellow 96, and fluorescent) have greater sorption tendencies than other dyes (such as rhodamine WT) (Smart, 1972; Jones, 1976). If the relative effectiveness of adsorption is an important issue in a particular case, one may be well advised to use a dye which is subject to appreciable adsorption. It has been my experience that it is difficult to recover optical brighteners and fluorescein from septic field systems which do not intersect discrete recharge zones (Aley, 1974). Discrete recharge zones are localized areas which can transmit appreciable volumes of water into the groundwater system (Aley, 1977; 1978). Discrete recharge zones typically do not provide effective natural adsorption, and this accounts for their ability to transport dyes with some of the higher sorption tendencies.

At present we do not have sufficient information to enable us to use some particular type and amount of dye to quantitatively measure the adsorptive effectiveness of a septic field or other waste site. There are enough variables that such an approach will probably never be possible. However, through experience with various tracing agents, we can develop qualitative insights into the relative effectiveness of adsorption in particular traces, and this obviously can be beneficial in resolving practical problems.

Finally, groundwater tracing is often useful in water pollution investigations because it provides an indication of underground travel rates and distances. It is unfortunate, but many people who are involved in questions of subsurface migration of pollutants are either unaware of, or choose to ignore, the rapid travel rates which often characterize subsurface water movement in soluble rock areas. As an example, Pye et al. (1983) in a report which purported to characterize groundwater contamination in the United States stated (page 4): "Once in the aquifer a contaminant will generally move with the groundwater and at a similar speed, which varies between a fraction of an inch to a few feet per day."

Groundwater travel rates in soluble rock regions are often very rapid, as anyone familiar with the karst hydrology literature knows. Numerous groundwater traces that I have conducted in soluble rock areas in Missouri, Arkansas, Indiana, and Wyoming have often demonstrated straight-line travel rates in excess of 1 km/day (0.62 miles/day). Rapid travel rates can also characterize long distance groundwater transport under gentle gradient conditions in soluble rock areas. As an illustration, dye and *Lycopodium* spores injected in a losing stream segment of the Eleven Point River in Missouri discharged from Big Spring, a tributary to the Current River. The straight-line travel distance for this groundwater trace was 63.6 km; the mean gradient was 1.93 m/km; and the mean travel rate for the first arrival of the tracing agents was 4.9 km/day.

Groundwater travel rates encountered in soluble rock lands can be a thousand times more rapid than Pye et al. (1983) indicate. Soluble rocks underlie perhaps 15% of the United States, and it is foolish to ignore conditions which often typify a major portion of this nation. Slow groundwater travel rates characterize some hydrogeologic settings and some groundwater components. However, in the case of water pollution investigations in soluble rock regions, most of the problems are associated with rapid groundwater movement through flow systems which provide ineffective natural cleansing.

Limitations of Groundwater Tracing

When groundwater tracing is used in conjunction with water pollution investigations, the tracing work is often not begun until after a problem has developed or a dispute has occurred. The person conducting the tracing work in this case is typically faced with a collection of problems not normally encountered during basic hydrologic studies. The nature of these problems should be understood and fully appreciated before any attempts are made to conduct groundwater tracing.

The first and perhaps the most significant problem is that both successful and unsuccessful groundwater traces will be viewed as "proof" by some of the people involved in the problem or dispute. If dye is injected in a drill hole at a waste site and is not recovered from any sampling wells or springs, one must anticipate that one side of the issue will use this unsuccessful trace as "proof" that the site causes no problems. It may be elementary logic that you cannot prove a negative; the fact remains that unsuccessful groundwater traces will not be overlooked or disregarded in reaching decisions about a particular pollution problem.

The second problem is that an investigator often does not have an ideal site for injecting a groundwater tracing agent. Often this is due to physical limitations of the site. At other times one cannot gain permission to inject the tracer at the site where the work most needs to be done. In other cases (but less commonly) there may be problems in getting permission to sample waters where the tracer might be recovered. Furthermore, one often faces not only site limitations but also hydrologic limitations. A particular pollution problem may be associated with wet weather conditions, but the investigator is forced to do the groundwater work during dry weather conditions.

The third problem is that groundwater tracing often requires sampling at a number of sites for a period of days or weeks. As a result, the investigator cannot stay with his sampling equipment. There is always the possibility that people involved in the dispute will tamper (either intentionally or unintentionally) with the tracing effort.

The fourth problem is that the tracing effort must be done right the first time. Often, one cannot try the trace again because something went wrong in the first attempt.

Preventing Problems in Groundwater Tracing Investigations

There are five recommendations for preventing problems with groundwater tracing investigations conducted as a part of water pollution studies:

1. Do not conduct a groundwater trace in a water pollution investigation unless it is needed to answer a relevant question.

2. Do not conduct a groundwater trace unless it is designed in such a manner that it will produce results.

3. Any tracing attempts should be preceded by thorough field work to locate all possible sites where the tracing agent might be recovered.

4. Avoid injecting tracing agents into man-made pits or wells that may not be integrated with the groundwater transport system.

5. Design and conduct the tracing work in such a way as to minimize the chance of incorrect conclusions resulting from tampering.

Do not conduct a groundwater trace in a water pollution investigation unless it is needed to answer a relevant question. In groundwater tracing one injects an exotic agent into the water and then samples for it at possible recovery sites. In water pollution cases there are often exotic agents present in the water which serve quite adequately as tracers; these should be used to the fullest extent possible. This is particularly true in cases where good injection sites may not be present.

As an example, I was once involved in a case where a sewage lagoon system serving a hospital was suspected of leaking into a series of springs which had suddenly appeared a few hundred feet away. A state agency, utilizing personnel without expertise in groundwater hydrology, injected dyes in the lagoon system on several occasions. The hospital used a water softener, and as a result the lagoon had an atypically large chloride concentration; so did the springs. There were other water quality similarities between the lagoon and the springs; there was no reason for the injection of dyes. Due to poor design of the tracing attempt and inadequate sampling, the agency did not recover their dye from the samples springs, and concluded that the lagoon did not leak. Subsequent independent sampling of the springs found detectable concentrations of one of the two dyes injected in the lagoon. The result was a muddled problem which may well require litigation to resolve. Not only was the tracing attempt unnecessary, but it was improperly conducted and was conducted in an area where tracing difficulties were predictable.

It is often difficult to trace water from lakes and lagoons into groundwater systems. In many cases it is better to make an assessment of whether or not a lake or lagoon is leaking by analyzing water budgets rather than from groundwater tracing attempts. The quantity of water or the timing of flow pulses can be an effective groundwater tracing tool which is sometimes superior to any tracing agent.

Do not conduct a groundwater trace unless it is designed in such a manner that you will get results. Use enough tracing agent, and use a tracing agent which is appropriate for the problem at hand. Make certain that you have an adequate supply of water to transport the tracing agent. Make certain that all possible recovery sites are sampled and that the sampling duration is adequate.

Finally, make certain that the injection site will answer the questions that are relevant. As an example, if the issue is whether some part of a proposed landfill operation is within the recharge area for a spring used as a public drinking water supply, the injection site for the groundwater tracing agent must be near the landfill but between the landfill and the spring. A site on the far side of the proposed landfill from the spring may be useful in answering other questions, but it will not tell us if part of the proposed landfill area contributes water to the spring. I have seen this exact situation occur, and the consulting geologist for the landfill operator selected his injection site on the wrong side of the landfill. Since the relevant question was not answered, litigation has resulted.

There may be occasional situations where the failure to recover a tracer from any of the sampling sites could be a valid objective of the groundwater tracing effort. As an example, we have injected dyes in municipal sewers and sampled for them at springs as a reconnaissance test for sewer line exfiltration problems. Such tracing efforts must be conducted very carefully, and to the extent possible other evidence should confirm any negative results from tracing efforts.

Any tracing attempts should be preceded by thorough field work to locate all possible sites where the groundwater tracing agent might be recovered. Unsuspected springs are sometimes found discharging from the bed of perennial streams, and field work and/or sampling procedures must be adequate.

Due to the nature of flow systems in soluble rock lands (Aley, 1977; 1978), wells are often poor sampling sites in groundwater traces. If groundwater tracers are injected in a natural drainage feature (such as a sinkhole, losing stream, or other discrete recharge zone) they may be recovered at a spring some distance away but not at any of the wells lying between the injection and recovery sites. This is because the flow route between the natural drainage feature and the spring follows localized conduits. Most wells will not intersect the conduits which are transporting the tracer-tagged water flow, and for this reason tracers will not be recovered in such wells. Although this does not mean that wells should not be sampled, great care needs to be used in interpreting negative tracing results from wells in soluble rock lands. If wells must be sampled, it is best to pump them heavily during the tracing attempt. In soluble rock lands it has been my experience that non-pumping wells are almost worthless in groundwater tracing programs.

Avoid injecting tracing agents into man-made pits or wells that may not be integrated with the groundwater transport system. It is generally unlikely that a small man-made pit or well will be significantly integrated with the groundwater transport system in a soluble rock area. If such sites are used for groundwater tracer injections, the tracing agents may be detained for long periods of time in the storage component of the groundwater system rather than in the transport component needed for successful groundwater tracing.

If man-made pits or wells must be used in groundwater tracing work, it is best to inject tracers in several of them rather than rely on a single injection site. Furthermore, particularly when man-made pits or wells are used, all injections should be accompanied with substantial volumes of water (preferably at least 4,000 to 8,000 liters). Although I have successfully conducted groundwater traces using such procedures in the past, I have generally found that such work requires larger quantities of tracing agents than are required when more desirable injection sites are available.

Design and conduct the tracing work in such a way as to minimize the chance of incorrect conclusions resulting from tampering. In water pollution cases, tracing investigations should be conducted in such a way as first to minimize the chance of tampering and secondly to detect tampering if it occurs. Each groundwater tracing situation is different, and the strategy which must be employed to protect against tampering will be different. Extra sampling stations upstream and downstream of important sampling sites can be useful if they are known only to the investigator. I do not make it a practice to explain in detail to anyone potentially involved in a particular issue exactly how I plan to conduct the tracing work. In some cases I quietly re-sample to provide confirming evidence.

Conclusions

Groundwater tracing can be an important tool in water pollution studies. The tracing can provide types of information which are not obtainable or not readily obtainable using other approaches.

Prudent groundwater tracing requires a good grasp of the limitations of tracing work in water pollution studies. Groundwater tracing requires thorough and careful work to insure proper results.

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