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The Use of Tracer Techniques to Assess Groundwater Flows in Site Investigations

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Abstract

Procedures of site investigation included in BS 5930:1981 concentrate on obtaining information on ground conditions near proposed structures. Groundwater flow paths, however, are often influenced by hydrogeological conditions well beyond the area and tracer tests have been found a useful addition to investigations.

Different types of groundwater tracers are described and their uses in establishing groundwater flow paths and other hydrogeological characteristics of some regimes are outlined. Precautions are always necessary when using tracers, however, and these are especially stringent with radioactive tracers. The paper shows how groundwater tracers were employed in investigations of landslips, waste disposal studies and other investigations with which the authors have been involved.

The paper concludes that the specification of standard procedures for tracer tests is probably not appropriate but reference to the techniques available would be useful in promoting their application.

Introduction

The British Standard Code of Practice for Site Investigations, BS 5930:1981, defines the purposes of investigation as determining the suitability of a site for proposed developments and acquiring knowledge of characteristics that might affect the works and the security of neighbouring land and properties. In performing a large number of investigations of landslips and proposed waste disposal sites, experience has shown that the influence of groundwater conditions is often of paramount importance. These conditions are governed by rainfall and hydrogeological factors that reflect geological structure.

The geological structure of a site can be established from geological maps, memoirs and mapping, complemented by boreholes in which piezometers might be installed to observe groundwater levels. The hydrogeological characteristics of the soils and rocks under the site can be determined by *in situ* permeability tests, pumping tests and groundwater monitoring following the methods described in BS 5930:1981. Such tests tend to relate specifically to the site area. However, in order to appreciate fully the relationship between the site and the hydrogeological regime, it is sometimes necessary to define the groundwater conditions over a wider area in order to fulfil the objectives of the investigation. In such circumstances, groundwater tracer tests have been specified as an integral part of ground investigation contracts.

The purpose of groundwater tracer tests might be:

(i) to establish possible flow paths between groundwater catchments and observed flows;

(ii) to quantify characteristics of groundwater flow.

In essence, such tests involve the selection of an appropriate tracer, its introduction into the groundwater, and subsequent monitoring to establish the direction of movement. This paper is principally concerned with this type of test, using various artificial tracers, but mention is also made of the use of naturally occurring isotopes in groundwater studies.

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Natural Isotopic Tracers

In recent years, increasing use has been made of the distribution of the various isotopes occurring naturally in water, particularly where other tracers suffer bulk dilution. Interpretation of isotopic data can provide information on source of water, flow path, velocity, mechanism of recharge, chemical mixing and age of the water.

Isotopes commonly measured in water include the stable isotopes of oxygen, hydrogen and carbon, usually expressed as relative isotopic ratios $^{18}O/^{16}O$, $^{2}H/H$ and $^{13}C/^{12}C$ respectively, and the radioactive isotopes of hydrogen (^{3}H) and carbon (^{14}C). ^{14}C has proved invaluable in establishing flow patterns and age of groundwaters. With regard to isotopic fractionation of the stable isotopes of oxygen and hydrogen in the natural cycle, it has been found that enrichment and depletion of the heavy isotopes ^{18}O and ^{2}H within a water sample is determined by several physical processes such as condensation, evaporation, freezing, temperature phase transformation and isotopic exchange within the aquifer. Because of these effects, precipitation and water samples can be characterised to provide information as to their origin, source and climatic history.

Typical projects utilising natural isotopes as indicators include monitoring of leachate movement from landfill sites (Baedecker & Back, 1979), groundwater studies (Evans *et al.*, 1978) and landslip investigations (Halcrow, 1980). Their application is considered very specialised and they are not discussed in this paper.

Artificial Groundwater Tracers

Groundwater tracers can be grouped into the following four main categories:
(i) coloured dye-stuffs
(ii) particulate tracers
(iii) stable chemical compounds
(iv) artificial radiotracers (radioactive isotopes)
Selection of a groundwater tracer is governed by the object of the investigation and a variety of factors relating to the catchment including, inter alia, the length of the drainage path, test duration and the ground conditions. The principal requirements of tracers are listed in Table I according to properties, performance and analysis, but individual criteria may be waived in certain circumstances depending on experience, convenience and cost.

A summary of the different groundwater tracer groups and representative types most commonly used is given in Table II; the list is not exhaustive and the performances of other tracers are described by White (1976). The principal merits and limitations of the representative tracer types are outlined and they are compared using a simple rating system based on the criteria set out in Table I. Coloured dyes are often used to establish short hydraulic connections for qualitative assessments, whilst chemical tracers, such as sodium chloride, although requiring relatively elaborate injection procedures, can provide results for quantitative analysis using *in situ* detection methods. For tests involving long drainage paths, particulate and radioactive tracers can offer some advantages.

Dosing, Sampling and Detection

In operation, a measured quantity of tracer is prepared, introduced into a specific catchment and its passage monitored by *in situ* methods or by sampling and laboratory analysis. Methods employed in groundwater tracer tests depend on the type of tracer and a summary of procedures for each is given in Table III. References are provided where detailed test specifications can be consulted. In tests influencing flows in natural water courses, approval of the Regional Water Authority must be obtained. Radiotracers also require authorisation from the Department of the Environment Radiochemical Inspectorate but this process normally involves a specialist contracted to perform the test and can take about two months. This period can be spent in collecting reference samples for analysis of background standards prior to introducing the tracer.

The quantity of tracer required is governed by its minimum detectable concentration, the volume of groundwater flow and an appreciation of possible losses of tracer into the system owing to adsorbtion, dispersion and percolation into deeper strata. Guidelines for the quantities of dyes and lycopodium spores are given by Drew & Smith (1969) and

TABLE I. *Summary of requirements for groundwater tracers*

		REMARKS
A. PROPERTIES	1. Unique	The tracer should not occur naturally in the project area or might otherwise be present only in uniformly low concentrations.
	2. Immutable	The tracer should be unaffected by sunlight or pH of the groundwaters, and should be resistant to adsorbtion by minerals.
	3. Non-toxic	The tracer should be free from contaminants and should not be harmful to vegetation or animals.
	4. Inoffensive	Tests should be carried out without offending landowners and residents in or downstream of the project area.
B. PERFORMANCE	1. Transmission	The tracer should reflect the movement of water in soils and rocks.
	2. Accurately dosed	The injection procedure should permit controlled introduction of tracer into a specific aquifer.
	3. Sampled reliably	Samples should represent concentrations existing in issues and boreholes.
	4. Accurately detected	The tracer should be detectable at low concentrations.
C. ANALYSIS	1. Qualitative assessment	Tests should indicate positive hydraulic connections.
	2. Quantitative analysis	Quantitative analysis of results should provide information on flow rates and tracer recovery.

TABLE II. *Comparison of main tracer groups*

TRACER GROUPS	REPRESENTATIVE TRACER TYPES	DESCRIPTION	TABLE OF COMPARISON WITH RESPECT TO TABLE 1										REMARKS
			A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	
COLOURED DYE-STUFFS	*Fluorescent dyes* Sodium fluorescein Pyranine	Distinctively coloured-dyes detectable by direct visual observation or by means of equipment capable of measuring fluorescence.	+	0	0	−	−	+	0	0	+	−	All coloured dyes might prove offensive to water users and there is a suspicion that fluorescent dyes might be carcinogenic. Fluorescent dyes are readily detectable and can be used for quantitative analysis. Fluorescein is altered by acidic waters and sunlight and is adsorbed by clay minerals. The movement of dyes is slower than the rate of groundwater flow.
	Non-fluorescent dyes Rhodamine WT Malachite green		+	0	+	−	0	+	−	−	+	−	Coloured dyes might prove offensive but rhodamine WT is extensively used but can cause an astringent taste in chlorinated water. These dyes are less readily detected than the fluorescent equivalents.
PARTICULATE TRACERS	Lycopodium spores	Lycopodium spores are discrete particles approx. 25 microns in diameter, carried as a suspended load in subterranean flow passages.	0	+	+	0	−	0	0	0	+	0	Lycopodium might not be unique to the catchment but the spores can be dyed to facilitate simultaneous analysis of more than one catchment. Their size limits their use to cavern and fissure flow regimes but the rate of movement is slower than the water flow.
	Type 2 Aerobacter aerogenose 243	A specific culture of micro-organisms (viruses) some 150×10^{-10} m in size that are detected using conventional microbiological techniques in the laboratory.	+	0	+	+	0	+	0	−	0	0	Bacteriophage are viruses which live off specific bacteria and are harmless to animal and vegetable life. Bacteriophage can permeate through soil deposits but can be destroyed in acidic waters. Representative sampling needs care but different phage types can be used to facilitate simultaneous analysis of many catchments.

Note: − Poor, 0 Average, + Good.

STABLE CHEMICAL COMPOUNDS	Sodium chloride Potassium chloride	Concentrated inorganic substances dissolved in an aqueous solution to permit injection into the catchment. Detection carried out by measuring conductivity of the sample fluid.	0	–	+	+	+	–	+	+	+	0	Chemical tracers have been frequently used but can be adsorbed by some clay minerals and might also affect the racte at which ground water moves through the catchment.
ARTIFICIAL RADIOTRACERS	*Gamma-emitting isotopes* Bromine—82 Iodine—131	Radio-active elements incorporated in stable chemical compounds and diluted in solution.	+	+	0	–	0	0	+	+	+	+	Artificial radiotracers provide a very sophisticated groundwater tracer but are often considered offensive. Gamma emitting isotopes can be detected readily and remotely but most have a short half-life. They may not fully reflect the groundwater flow rates.
	Beta-emitting isotopes Tritium		+	+	0	0	+	0	+	+	0	+	Tritium is a useful tracer since it is combined within the water molecule. It also has a long half-life which means that it can be used in tests of long duration. It cannot be detected remotely.

Note: – Poor, 0 Average, + Good.

TABLE III. *Methods of dosing, sampling and detection of major types of tracer*

TRACER GROUP	DOSING	SAMPLING	DETECTION	REMARKS
DYES Fluorescent	Usually in aqueous solution. Alkaline solution preferable with fluorescein if groundwaters are acidic	Detectors of activated charcoal suspended in nylon bags at sampling point.	Visual detection possible. Otherwise, laboratory method of removing dye and examination under UV light or fluorimeter.	Background fluorescence may preclude use.
Non-fluorescent	Usually in solution ± wetting agent.	Detectors of specially treated cotton strips.	Visual detection possible. Otherwise laboratory method of enhancing colour.	Neither can be relied upon to give positive results. Continual sampling not necessary (Drew & Smith, 1969).
PARTICULATE Lycopodium spores	In a slurry of dyed spores. Several colours available. Laboratory technique for dyeing spores.	Conical plankton nets. Washer bottle to flush sediment in net to sample bottles.	Centrifuge at 2500 rpm, pour off liquid and visual count under microscope.	Possible to perform several tests simultaneously using different colours. Continual sampling not necessary. Stringent precautions to avoid contamination (Drew & Smith, 1969).
Bacteriophage	In a suspension.	Conventional water samples in sterilized containers.	Add to jelly-like bacteria and allow to incubate. Visual count under microscope.	Survival rate decreases with rise in temperature, acidity and UV light. Portable blow lamp useful for sterilizing sampling equipment (Martin & Thomas, 1974).
CHEMICAL	In aqueous solution. Mixing tank, pumps and bowsers required. Vacuum-dried evaporated salt easier to dissolve.	Conventional water sampling in conjunction with on-site conductivity measurements.	Possibility of on-site detection with conductivity meter. Laboratory analysis of samples by titration.	Large quantities of tracer required for all but very small tests (Mather *et al.*, 1969).
ARTIFICIAL-RADIOTRACERS Gamma emitters	In solution.	Not usually required. *In-situ* monitoring.	Automatic *in-situ* detectors (gamma emitters).	Reference to Radiochemical Inspectorate for authority prior to use. Stringent precautions necessary (White *et al.*, 1980).
Beta emitters (tritium)	Tritiated water, dissolved in larger volume of water. Mixing tank, pumps and bowsers required.	Conventional water samples.	Laboratory analysis by liquid scintillation counting or gas counting.	

experience with sodium chloride in fissured sandstone aquifers in South Wales indicates that a dose of about 0.04 kilogrammes per metre flow path per litre/sec is sufficient to allow direct field detection with a conductivity meter. Bacteriophage tracers are cultured to a concentration of about 10^{14} phage/litre. Martin & Thomas (1974) describe tracing using 10 litres through 680 m of sandstone. Criteria on the permitted quantities of radiotracers are based on maximum concentrations in drinking water as laid down by the International Commission on Radiological Protection but higher concentrations are permitted if rapid dilution can be demonstrated.

A tracer can be introduced from the surface or rockhead using sink holes or by infiltration from bottomless containers sealed onto a prepared surface. For specific aquifers, tracers are injected below the water table from a borehole. Chemical tracers and radiotracers are mixed with quantities of water and the dosing system should be checked by performing a simulated test beforehand. After dosing, the system is flushed with clean water to ensure all the tracer is introduced.

Sampling procedures for the different tracers are set out in Table III. Coloured dyes can be observed directly and can also be discerned on specially prepared detectors left in place during the test. The arrival of the peak concentration of an ionic chemical tracer can be detected on site with a conductivity meter. *In situ* detectors can also be employed with gamma-ray emitting radioisotopes. Bacteriophage and beta-ray emitting tracers, however, can only be detected by sampling and laboratory analysis. In all cases, care is required to prevent contamination of samples.

Quantitative analyses of tracer tests require a knowledge of groundwater flows, groundwater levels and rainfall. Groundwater flows can be measured using vee-notch weirs, flow meters or a bucket and stopwatch. Groundwater levels are read using a dip-meter probe and rainfall data are obtained from either a temporary gauge or the Meteorological Office records. These data help to evaluate the extent to which the results can be considered representative.

The main costs of a groundwater tracer test are incurred in the injection procedure, sample collection and analyses. It is often possible to analyse samples on an intermittent basis, back-tracking on those which prove positive for the intervening dates of sampling. The cost of analysing some tracers makes it economic to test composite samples, back-tracking on their components if positive.

Presentation of Results, Analysis and Interpretation

The amount of information obtained from a tracer test depends on the scale and method of test used, which dictate the extent to which the data need to be or can be processed to obtain hydrogeological parameters. Reporting details can vary from qualitative visual observations of connections between points of injection and issues to evaluations of transit times and groundwater distribution.

Concentration–time distribution

The amount of tracer detected at issues is conventionally plotted as a histogram or graph of concentration against time. The maximum velocity of the tracer can be calculated from the time of first arrival but the time of travel of the peak concentration or mean transit time as defined below are considered to give a more representative value of seepage velocity. It is known, however, that some tracers do not truly reflect groundwater flow (ref. Table II) and the results therefore have to be viewed accordingly.

The coefficient of permeability is determined using D'Arcy's Law in the form:

$$K = \frac{Vn}{i}$$

where K = coefficient of permeability
V = seepage velocity
n = porosity
i = hydraulic gradient

The porosity is based on laboratory determinations and measurements of joint dilation. The hydraulic gradient is determined from groundwater levels. If the aquifer is anisotropic, the coefficient of permeability obtained from a tracer test will usually be higher than that derived from pumping tests (Daughton *et al.*, 1976).

Tracer Recovery

The amount of tracer recovered at monitoring points is a function of concentration and flow rate, both of which vary with time. It is usual to plot cumulative recovery against time (Fig. 1) from which the mean transit time (time for recovery of half the tracer at that point) can be established. It is important to appreciate that recovery is affected by variations in flow and, for this reason, plots of cumulative recovery against cumulative flow are advocated (Fig. 2). This type of plot shows when the recovery rate has diminished to negligible amounts, enabling sampling to be terminated. The plots permit the total amount of tracer recovered at each monitoring point and the overall total to be quantified. For tracers not susceptible to losses during transport, some meaningful data can be obtained on the distribution of groundwater flow from the dosing point within the aquifer.

Applications

Groundwater tracers are particularly useful in hydrogeological investigations where preferential

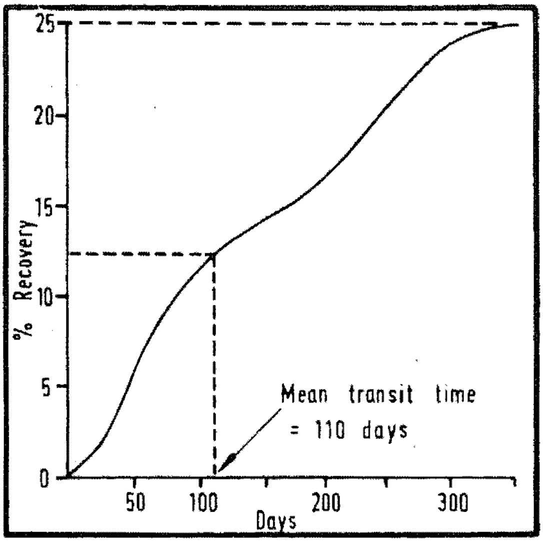

FIG. 1. Cumulative recovery vs. time.

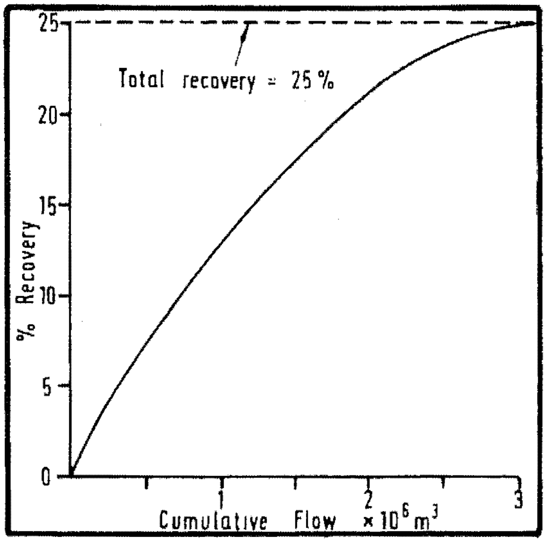

FIG. 2. Cumulative recovery vs. cumulative flow.

pathways for groundwater movement exist. Failure to consider such flow paths may result in a simplistic interpretation of conditions and the omission of a factor of predisposing importance. Many of the landslip investigations performed in the valleys of the South Wales Coalfield have involved assessments of the influence on stability of springlines at the base of perched sandstone aquifers which crop on the valley sides. In these locations, the sandstones have been affected by cambering and tensional strains created by differential mining subsidence. These factors, together with shallow workings of coal seams at the base of the sandstone, often control the directions of groundwater movement and enhance flows towards certain parts of the springline, where problems of instability are often found.

A typical example of the use of a tracer in landslip studies is illustrated by that performed at National Colliery spoil heap, which overlies an area of landslip on the crop of an aquiclude, the Brithdir Rider coal seam (Fig. 3).

Interpretation of groundwater levels measured in piezometers seemed to indicate a predominant south-westerly flow of groundwater to issues in the landslip. However, several dye tracers injected in boreholes 22, 23 and 25 showed that groundwater velocities to the issues were slow and unrealistic given the observed rapid response of the issues to rainfall. A brine tracer test (Fig. 4) from borehole 27, however, confirmed a connection with the catchment north of the landslip, representing flow paths not necessarily orthogonal to the groundwater contours. Seepage velocities of about 8 m/hour were recorded which seemed consistent with the response to rainfall.

A similar application was made during investigations for the A470 Taff Vale Trunk Road, where it crosses the Taren Landslip, a major ancient failure of rock and superficial deposits. Hydrogeological investigations of the landslip area included tracer tests with sodium chloride, pumping tests and groundwater monitoring (Halcrow, 1980). The tracer tests indicated preferential directions of groundwater flow in a sandstone aquifer which creates artesian pressures

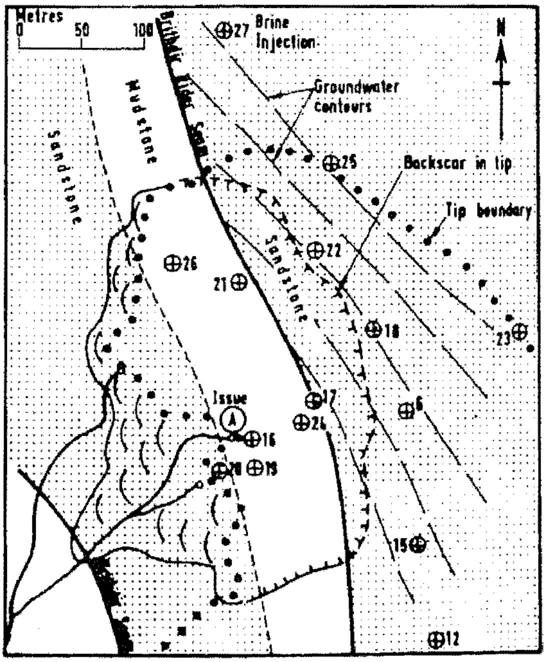

FIG. 3. Hydrogeology of the National Colliery spoil heap.

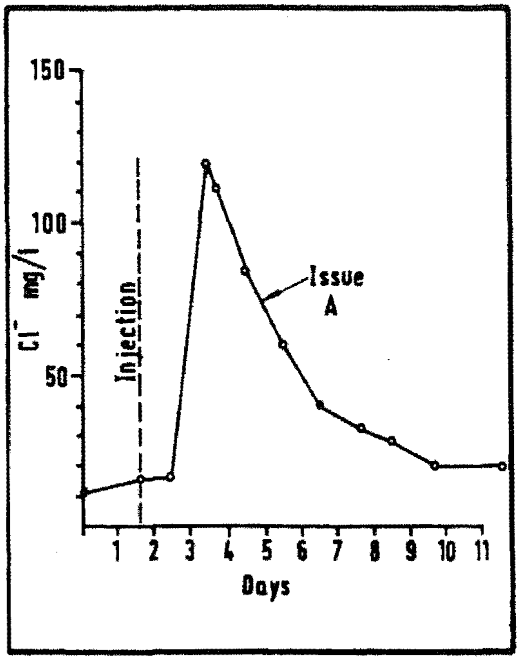

FIG. 4. Sodium chloride tracer test.

further downhill beneath the embankment of the proposed road. The anisotropy within the aquifer revealed by the investigations was taken into account in the spacing and arrangement of pressure relief wells.

A tritium tracer test was performed to determine the main directions of groundwater flow at Marine Colliery tip complex (Fig. 5) prior to constructing a drainage gallery (Halcrow, 1973).

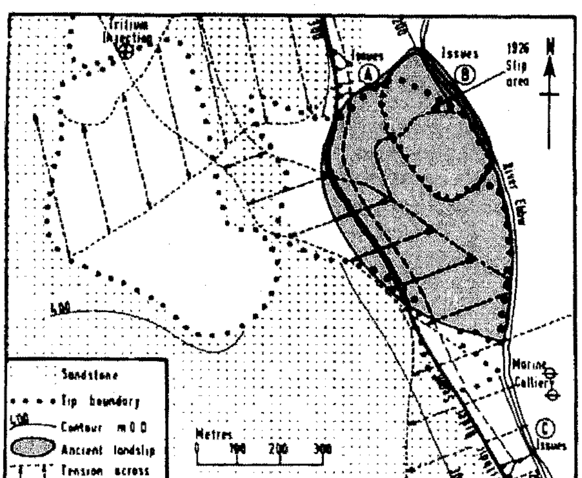

FIG. 5. Marine Colliery tip complex.

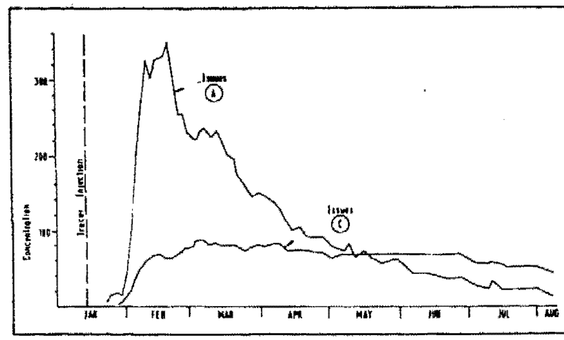

FIG. 6. Marine Colliery tip tritium tracer test.

The tip overlies an ancient rock failure which had displaced the river, and tipping caused further movements at the toe of the landslip, the most notorious occurring in 1926. In the test, tritium injected into the sandstone north-west of the landslip moved east to issues 'A' north of the tip and to issues 'B' in the area of the 1926 failure. It also travelled south-east to issues 'C', south of the tip. The main flow paths appeared to follow tension zones associated with mining subsidence, as shown on the plan.

The concentration of tritium in the issues 'B' rose to a peak after about five weeks and then declined steadily (Fig. 6). The concentration in issues 'C', however, rose less quickly to a lower peak after some seven weeks and declined slowly, indicating dispersion into a larger body of groundwater than that represented by concentrations at 'A'.

The degree of dilution obtained in tracer tests and the location of rapid groundwater flow paths are important aspects in the investigation of proposed waste disposal sites. Quantitative analysis of the results of tritium tracer tests performed at sites in Gwent and Mid Glamorgan enabled the impact of leachate generated at the sites on local ground and surface waters to be determined.

In Gwent it was proposed to fill an area of old opencast coal workings with domestic refuse, enclosed by the high wall of the workings and mound of spoil (Fig. 7). A desk study indicated that leachate was likely to enter a flooded area of shallow mine workings beneath the hill south of the site, and probably drain southwards to deeper abandoned mine workings, away from streams flowing north into the River Usk. As part of an investigation of the mine drainage (Halcrow, 1982), tritium was introduced into the workings at the level 'A'. An unexpected connection was established to adit 'B', indicating potential for pollution of a northerly flowing stream. However, it was established that only a small amount of tritium moved in that direction and this was accommodated in the proposals for site management.

The investigation in Mid Glamorgan was carried out at a site on an unconfined sandstone aquifer. It was considered that leachate infiltrating to the water table

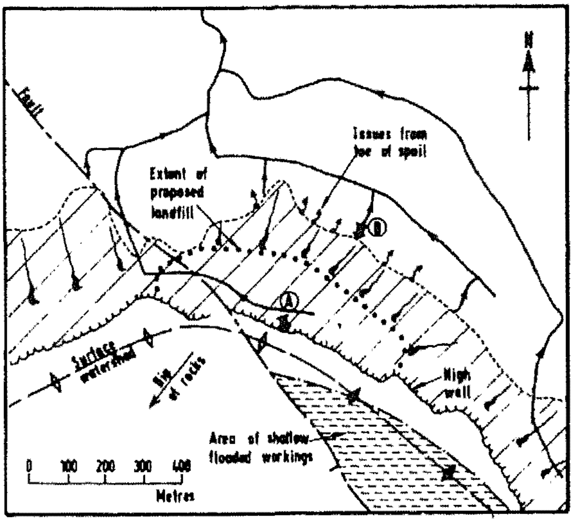

FIG. 7. Tracer test for waste disposal site.

in the aquifer could reappear in issues in sensitive areas. The tracer test confirmed these hydraulic connections, allowed prediction of leachate concentrations emerging at the issues and alternative schemes for the development of the site to be evaluated. Details of this work will be published elsewhere.

At Dubai Dry Dock (UAE) in a more unusual application (Fig. 8) a tracer was used to determine the seepage velocity of sea water beneath one of the piers under the hydraulic gradient between the inner harbour and floor of the dock.

The test was performed to find out whether settlement of part of the pier could be explained by internal erosion of weathered layers within the gypsiferous carbonate sandstone bedrock. Iodine-131 was injected between packers in a borehole drilled through the pier and its passage monitored by *in situ* detectors in another borehole and a pressure relief well. The seepage velocity was found to be 4×10^{-5} m/s, which was considered to be too slow to cause piping. The development of a gypsum solution front has been proposed as an alternative explanation of the settlement (Fookes *et al.*, in press).

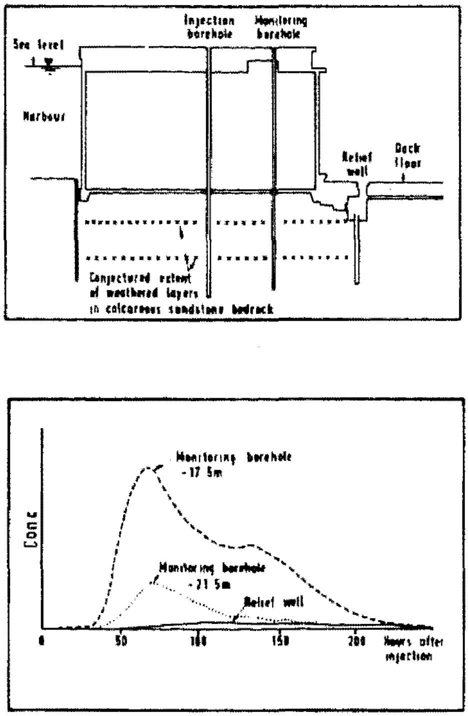

FIG. 8. Tracer test at Dubai Dry Dock.

Conclusions

This paper has described representative groundwater tracers, has set out some general guidelines and procedures and has discussed different methods of presenting the results. Examples of the application of the groundwater tracing tests to civil engineering projects were illustrated to show their merit when included in ground investigations.

A review of the techniques available has indicated that, apart from qualitative tests using dyes, only chemical tracers offer a degree of quantitative sophistication to an operator not possessing laboratory facilities. The other techniques require laboratory back-up analyses, which does not lie within the scope of most site investigation contractors.

Most quantitative tracer tests, like geophysical surveys, are generally controlled by specialists in situations which are often unique and it is not always possible to define a routine procedure. However, groundwater tracers have proved useful in stability, waste disposal and other studies and it is concluded that a description of groundwater tracer techniques along the lines of that of geophysical techniques would be a useful addition to BS 5930:1981.

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