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THE USE OF TRACERS TO INVESTIGATE THE RELATIONSHIP BETWEEN MINING SUBSIDENCE AND GROUNDWATER OCCURRENCE AT ABERFAN, SOUTH WALES*

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Abstract: Four groundwater tracing experiments, using sodium chloride and sodium fluorescein as tracers, were undertaken at Aberfan, in order to investigate the influence of mining subsidence on the pattern of groundwater flow. Measurements indicated that areas subject to tensional strains were characterised by rapid groundwater movement and areas subject to compressional strains by slow or negligible groundwater movement. Boundaries between zones of tensile and compressional strains should be regarded as potential hydraulic discontinuities. Mining subsidence appeared to have contributed to the enlargement of the groundwater catchment draining the tip-complex at Aberfan.

Introduction

At about 09.15 hours on Friday, 21st October, 1966, some 140000 cubic yards of colliery rubbish moved as a flow-slide down the side of Mynydd Merthyr above the village of Aberfan and was deposited on the lower slopes of the mountain side and in the village itself, causing considerable loss of life and damage to property. The sequence of events leading up to the slide and the causes of the slide itself have been considered in the report of the Tribunal established to inquire into the disaster[1]). The scientific investigations undertaken on behalf of the Tribunal and of the organizations which appeared before it, have been published separately[2]). The present paper describes in more detail some of the groundwater tracing experiments which were initiated by one of us (D.A.G.) to relate the groundwater regime beneath the tip-complex to the mining subsidence pattern and also describes further

* Communicated by permission of the Director, Institute of Geological Sciences, Exhibition Road, London, S.W.7. and the Area Director, National Coal Board, East Wales Area, Ystrad Mynach, Glamorgan.

experiments which were carried out after the results of the first experiments had been submitted to the Tribunal[3]).

The experiments were designed to determine the groundwater regime rapidly and under extremely disadvantageous site conditions. The methods used were adapted to a practical investigation and differ somewhat from the techniques which would have been adopted in a rational but more time-consuming scientific investigation. For example, the tracers which were employed were not those which would have been used if site conditions had been better, and if radio-active tracers had been acceptable. Subsequent site reclamation precludes a repetition of the original experiments.

Geology

The rocks which form the hillside of Mynydd Merthyr and crop out on its slopes are of Upper Carboniferous age and belong to the highest division of the Coal Measures, known as the Pennant Measures. They consist of a number of thick massive sandstones, separated from one another by mudstones which commonly contain thin coals and associated seatearths. A detailed geological succession has been given by Woodland[4]). The seven individual tips, which together form the tip-complex on the sides of Mynydd Merthyr, are situated upon the outcrop of a series of sandstones belonging to the Brithdir Beds which lie below the Cefn Glas Coal and above the Brithdir Coal (Fig. 1). The distribution of shales at the junction of the Brithdir and Hughes Beds in Fig. 1 has been modified subsequently to the submission to the Tribunal of the geological map prepared by Woodland[4]). In their pre-mining condition the sandstones of the Pennant Series yield sufficient water to sustain small springs but according to Ineson[5]) borehole yields in excess of a few thousand Imperial gallons per hour are exceptional. However, when subjected to displacement by mining subsidence (see below) the unweathered sandstones may yield water more freely, as although they have negligible intergranular porosity and permeability, they are able to both store and transmit water along joints and fissures. The interbedded mudstones are probably not completely fractured by mining subsidence and act as partial aquicludes resulting in the emergence of seepages and springs at their junctions with the overlying sandstones.

The lower slopes of Mynydd Merthyr are covered by glacial deposits (Fig. 1), consisting of boulder clays which pass gradually downhill into clayey gravels. In the Aberfan area a tongue of boulder clay, up to 77 ft in thickness, extends up the valley side along the line of a pre-glacial side-valley. The form of this side-valley is shown by the contours drawn on the surface of the solid rocks in Fig. 1. The boulder clay is relatively impermeable and

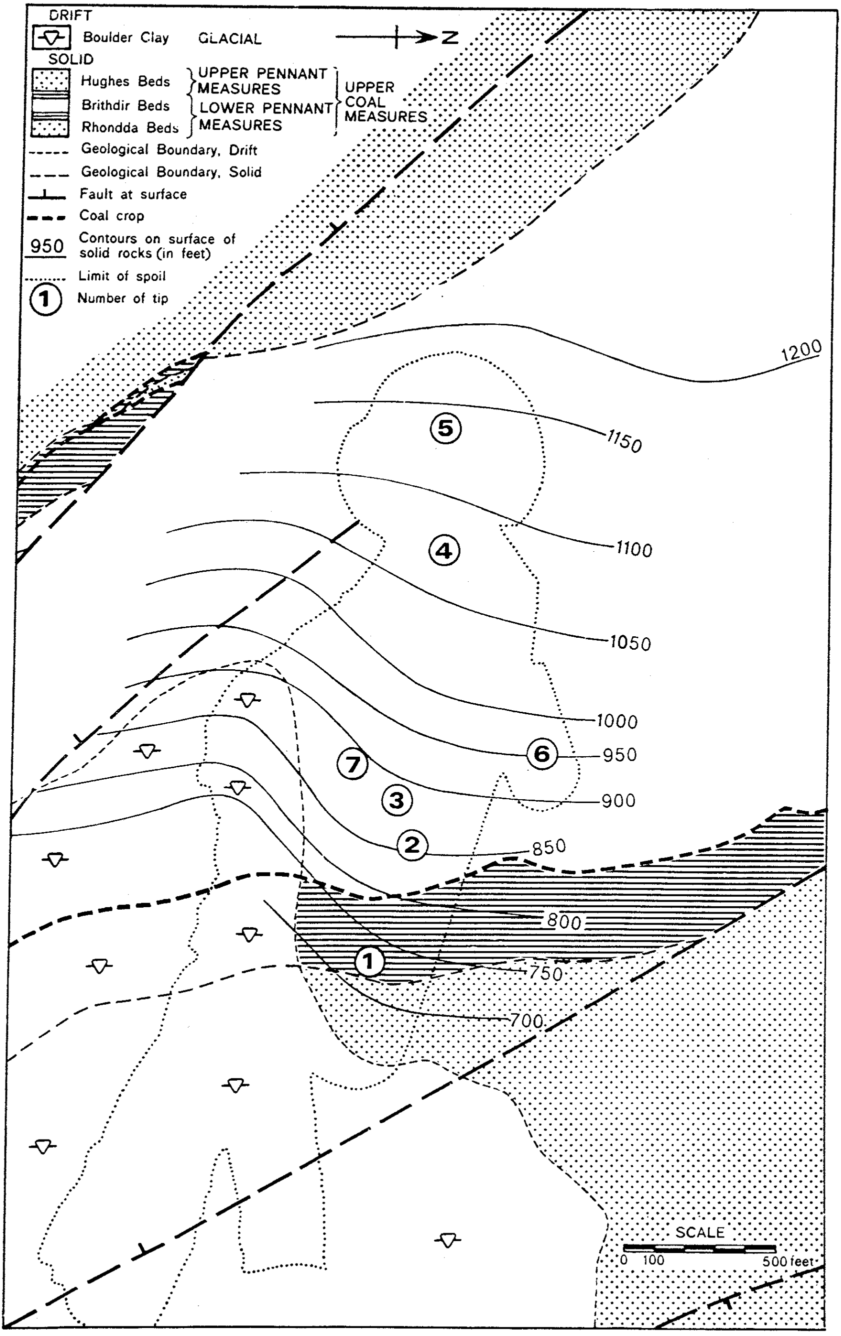

Fig. 1. Outline geological map of the area around the tip-complex at Aberfan, showing contours (in feet above Ordnance Survey Datum) of the surface of the solid rocks.

confines the groundwater in the underlying deposits. Although partially covered with tip material the boulder clay is thought to give rise to springs at its upper margin[4]).

Above the limit of the boulder clay the solid rocks are covered by the weathered debris of the rocks cropping out above them. This debris is known as Head and is up to 20 ft thick to the south side of the tip-complex. The permeability of the Head varies with its clay content. Where the clay content is high, infiltration will be inhibited and there will be an increase in surface run-off. However, where the clay content is low, infiltration capacity will be higher and water discharged from springs and seepages beneath the Head may flow downhill through the Head and emerge some way below the true position of issue.

Effects of mining subsidence

The underground mining of coal results in settlement of the surface of the ground above and around the area from which coal has been extracted. This subsidence takes the form of a basin or trough with its deepest point over the worked-out area. Calculations of subsidence in the vicinity of the tip-complex have been made separately for each seam extracted at Merthyr Vale Colliery by Wardell and Piggott[6]). The composite picture of subsidence and strain at the time of the disaster (after Wardell and Piggott) is shown in Fig. 2. The subsidence gives rise to an irregular pattern of zones characterized by either tensional or compressional strains. A narrow zone of high tensile strain runs north-west to south-east across the tip-complex beneath Tip No. 7. The trend of this "tensional corridor" is parallel to the direction of the main joint planes of the Brithdir Beds. To the east and beneath tips 1, 2 and 3 is a zone of compression and a second compressional zone underlies the southern parts of tips 4 and 5 and extends south-eastwards. To the north and west of the tip-complex is an extensive area of relatively slight tensile strain.

Apart from the seams extracted at Merthyr Vale Colliery, the Brithdir Coal has been mined at a depth of approximately 100 ft. These workings were developed prior to 1869 from Hafod Tanglwys Colliery[7]). The seam was extracted by a form of pillar mining and Wardell and Piggott[6]) consider that the pillars would have been sufficiently substantial to prevent any subsidence.

Relationship of subsidence and hydrogeology

The effects of mining upon the hydrogeology, in those areas subjected to tensional strains, are three-fold[3]).

1. The development of surface fissures (an example is shown in Fig. 3)

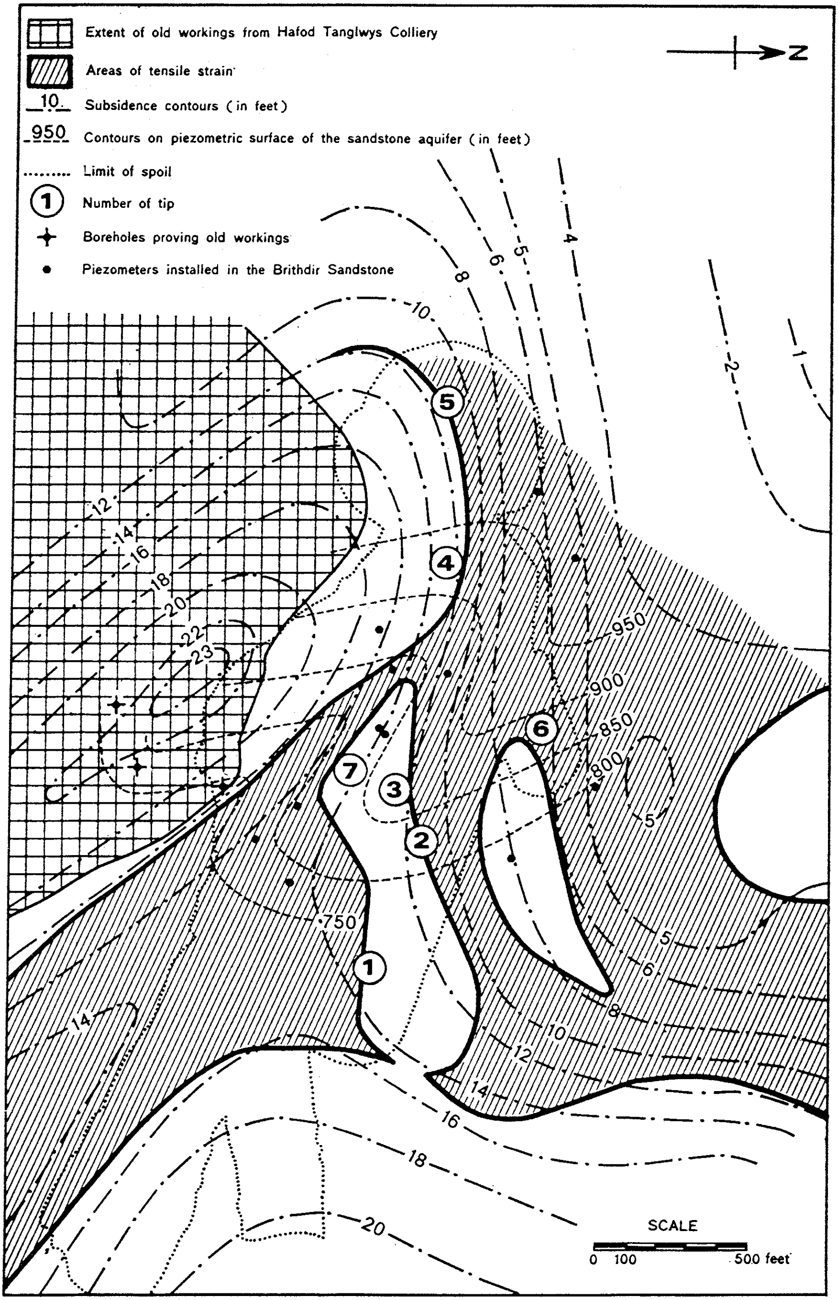

Fig. 2. Map showing mining subsidence features, distribution of old workings and contours (in feet above Ordnance Survey Datum) on the piezometric surface of the sandstone aquifer together with the distribution of the piezometers.

Fig. 3. Mining subsidence fissure at ground surface.

allows surface run-off to gain access to the underlying Pennant Sandstone and thus increase aquifer recharge.

2. Enlargement of pre-existing underground fissures increases the storage capacity of the Sandstone.
3. This fissure enlargement also increases the capacity of the formation to transmit water.

Gray[3]) suggested that a combination of these three factors may account for the apparently enlarged groundwater catchment of the streams draining the Central Complex (surface catchment boundaries are shown on Fig. 4). The existence of this enlarged groundwater catchment is indicated by an analysis of the stream hydrographs. Although the data were collected under adverse conditions and are not ideal, they show that after heavy rainfall the groundwater component of flow from the Central Complex is sustained at a higher rate for a longer time than is that from either the South Stream or the

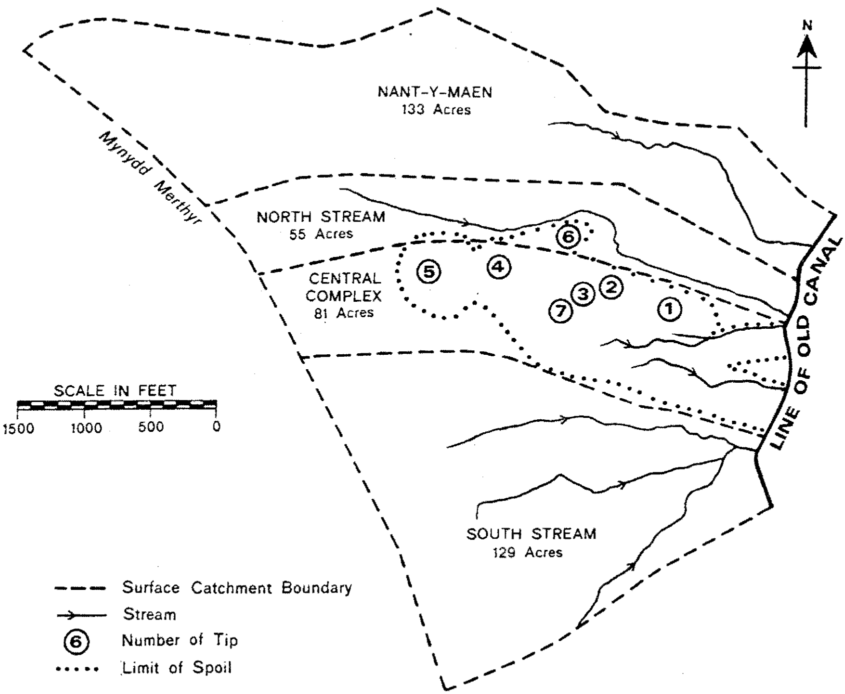

Fig. 4. Distribution of surface catchment boundaries, after Moore[12]).

Nant-y-Maen. During the period 31st October 1966 to 25th December 1966, the groundwater component of the hydrograph of the stream draining the Central Complex amounted to approximately 75%. This percentage is thought to be high for a drift-covered area of Pennant Sandstone and suggests that the groundwater catchment of this stream is much larger than the surface-water catchment. Analysis of the time/discharge relationships for the three streams confirms this conclusion.

The presence of the narrow tensional corridor, with a north-west to south-east orientation, which lies beneath Tip 7 may be a significant factor in increasing the underground catchment area of the stream now issuing from the Culvert constructed after the disaster at the foot of Tip No. 7, and of the other springs (see Fig. 5) which contribute to the discharge from the Central Complex. Its importance in the groundwater regime beneath the area of the tip-complex is indicated by the contours plotted on the piezometric surface of the sandstone aquifer (Fig. 2). The measurement of water levels used to compile this diagram were all made on March 1st, 1967 in the boreholes shown in Fig. 2. The contours show a pronounced groundwater valley beneath the tensional corridor with groundwater mounds beneath the border-

Fig. 5. Aerial photograph of the tip-complex showing the injection boreholes and sampling sites.

ing areas, which are subject to compressional strains. Water levels from those boreholes marked with a cross may be unreliable as they overlie, and in some cases penetrate the shallow workings in the Brithdir seam. The piezometers in these boreholes were dry when first constructed and water levels measured subsequently show little or no fluctuation. The form of the water-level contours suggests that groundwater is being discharged into the old workings, the extent of which are shown in Fig. 2 (after Piggott[7]).

Description of the tracing experiments

Groundwater tracing experiments were initiated to obtain an estimate of the velocity of groundwater flow through the tensional corridor beneath Tip No. 7, and to define more precisely the importance of this tensional feature in the flow pattern of groundwater in the area beneath and to the north of the tip complex. Four tracing experiments were performed using the injection

TABLE 1

Injection boreholes and sampling points used in tracer experiments.

Expt. No.	Injection Borehole		Sampling point (X tracer identified: 0 tracer not identified)										
	No.	+O.D. * in ft	A	B	C	D	E	F	G	H	J	K	L
1	1	993.1	0	0	0	0	0	–	–	–	–	–	–
2	2	1046.7	X	X	X	0	0	–	–	–	–	–	–
3	2	1046.7	X	X	X	0	0	–	–	X	X	0	0
4	3	1114.5	X	–	–	–	–	0	0	–	–	–	–

* Elevation above Ordnance Survey Datum (Newlyn)
– Site not sampled during experiment

boreholes and sampling points listed in Table 1 and shown on Fig. 5. The injection sites are boreholes which were put down for the purpose and which proved the following strata:

No. 1 – Depth 180 ft Superficial Deposits 81.3 ft Sandstone 98.7 ft
No. 2 – Depth 257 ft Superficial Deposits 62 ft Sandstone 194 ft Coal 1 ft
No. 3 – Depth 250 ft Superficial Deposits 24 ft Sandstone 226 ft

The Superficial Deposits consist of Head, Boulder Clay and Tip Material and in each case the borehole was lined with solid steel casing to below the base of these deposits.

The sampling points are as follows:

A – A vertical borehole at the head of the Culvert which has been constructed on the site of the pre-disaster base of Tip No. 7. The top of the borehole is 818.2 ft above O.D. and groundwater overflows from it after heavy rain. The borehole proved 8 ft of Head and 122 ft of Pennant Measures and was completed 50 ft below the Brithdir coal horizon.

B – The discharge from the mouth of the Culvert, which is a combination of the flow from A, from springs which rise along the floor and sides of the Culvert and from the surface drainage of a rectangular area of superficial deposits excavated from beneath tip material and situated to the south-west of the Culvert. The excavation was not completed until after the first experiment and there was no contribution from this source during the first experiment.

C – The total flow from the Central Complex, which includes the discharges from A, B, H, J, K and L together with surface run-off.

D – The total flow from the South Stream catchment.

E – The total flow from the North Stream catchment.

F – Injection Borehole 2, which was sampled using a depth sampler at depths of 225 ft and 240 ft below surface.

G – The flow of the North Stream 425 ft east-south-east of the base of Tip 6 at the confluence of the discharges from a number of small springs.

H, J, K, L – A series of springs contributing to the discharge from the Central Complex.

The horizontal distances between the injection boreholes and sampling points and their differences in pressure head at the start of each experiment are shown in Table 2.

In experiments 1, 2 and 4 the tracer used was sodium chloride in the form of rock salt. Sodium fluorescein was added as a supplementary tracer in order

TABLE 2

(a) Horizontal distances between injection boreholes and sampling points (ft)

Injection Borehole	Sampling Point										
	A	B	C	D	E	F	G	H	J	K	L
1	380	425	1715	1830	1755	–	–	–	–	–	–
2	565	610	1920	2035	1065	–	–	740	1105	1275	1500
3	1225	–	–	–	–	670	1320	–	–	–	–

(b) Pressure head differences between injection boreholes and sampling points at start of experiments (ft)

Expt. No.	Injection Borehole	Sampling Point										
		A	B	C	D	E	F	G	H	J	K	L
1	1	38	43	338	338	338	–	–	–	–	–	–
2	2	20	25	320	320	320	–	–	–	–	–	–
3	2	11	16	311	311	311	–	–	54	129	176	230
4	3	134	–	–	–	–	112	161	–	–	–	–

to give a visual indication of a successful tracer recovery, prior to the completion of chloride determinations. In Experiment 3 fluorescein was the only tracer injected.

Experiment 1. At 12:00 hours on the 22nd February, 1967, 3 pounds (lbs) of powdered fluorescein and 336 lbs of sodium chloride in the form of rock salt were introduced into the sandstone aquifer at Injection Borehole 1. The fluorescein was released from a tube below water level and the salt was first dissolved in a surface tank and then flushed down the borehole with 300 Imperial gallons of water. Rain was falling at the time of injection and there had been heavy rain beforehand. The flow from the Culvert, at Sampling Point B, was 21 500 Imperial gallons per hour (g.p.h.) at 09:55 hours on the day of the injection and the total run-off from the Central Complex was 74 000 g.p.h. Samples were taken from the sampling points shown in Table 1 at 15 minute intervals for the first 2 h of the experiment, every 30 min for the next 22 h and subsequently every hour until 12:00 hours on 24th February. Samples were then taken three times daily until the 1st March.

The samples were subjected to on-site examination under ultra-violet radiation to detect fluorescein before despatch to the National Coal Board's Laboratory at Ystrad Mynach for determination of chloride. No trace of fluorescein was detected in any of the samples nor was there any significant increase in the concentration of the chloride ion above the background level of 13 milligrammes per litre (mg/l).

Experiment 2. In the second experiment 3 lbs of powdered fluorescein and 2240 lbs of rock-salt were introduced at Injection Borehole 2. The fluorescein was released in the borehole between 225 ft and 235 ft below surface at 12:00 hours on 8th March, 1967. This depth was chosen as electrical conductivity logs carried out prior to the injection showed a conductivity interface between 225 and 230 ft. The salt was mixed at the surface with 800 gallons of water and flushed down the Injection Borehole between 12:26 and 13:25 hours. A further 400 gallons of water were then discharged into the borehole, this process being completed by 13:46 hours. The salt mixture contained some undissolved material and when the borehole was flushed with fresh water a few days later approximately 560 lbs of salt were recovered.

The water level in the borehole was 207 ft below the surface at the start of the injection, rose to a maximum level of 119 ft at 13:56 hours and had returned to 207 ft below surface by 14:04 hours. The flow conditions during the course of the experiment are shown in Table 3.

Samples were taken from the same sampling points as in Experiment 1, every 15 min for the first 6 h, every half an hour for the following 18 h and hourly for the final 24 h. Sampling ceased at 12:00 on the 10th March. The methods of sample analysis used in the first experiment were again employed.

TABLE 3

Discharge rates from Culvert and Central Complex during second tracer experiment

Date and Time	Culvert flow (g.p.h.)	Date and Time	Central Complex run-off (g.p.h.)
8.3.67 – 09:00	7000	8.3.67 – 11:40	25000
9.3.67 – 09:10	4000	9.3.67 – 11:55	42000
10.3.67 – 15:30	6000	11.3.67 – 12:20	41000

No fluorescein was detected in any of the samples, but a significant increase in the chloride ion concentration was detected at sampling points A, B, and C. Plots of chloride concentration (in mg/l) against time for sampling points A and C are shown in Fig. 6.

Experiment 3. On the morning of 21st March, 1967, 30 lbs of fluorescein and 10 lbs of caustic soda were introduced in solution at Injection Borehole 2. The injection took thirteen minutes and the tracer was flushed down with 800 gallons of water, the addition taking five minutes. The water level in the Injection Borehole was 217 ft below surface at the start of the experiment and had returned to this level within five minutes of the completion of the injection. The flow from the Culvert at the site of Tip No. 7 dropped from 2900 g.p.h. at the start of the test to a few hundred g.p.h. nine days later, by which time the artesian discharge from the borehole at Sampling Point A had ceased.

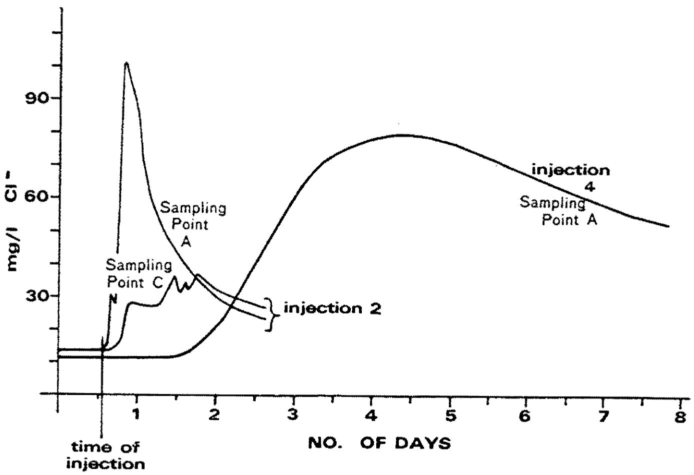

Fig. 6. Concentration/time curves for sampling points A and C following injections 2 and 4.

No formal sampling scheme was adopted but a watch was kept at each of the sampling points shown in Table 1, and arrival times of the leading edge of the tracer cloud and of the maximum concentration of tracer were noted. Coloration first showed at Sampling Point A some 3½ h after injection, and reached a peak of 3.0 mg/l after approximately 9 h. Coloration was seen in the spring at Sampling Point H seven hours after injection and a peak of 0.3 mg/l was attained after approximately 24 h. Sampling Point J began to show traces of dye 12 h after the injection and a peak of 0.2 mg/l was reached after approximately 30 h. Peak fluorescein concentrations were determined by comparison with solutions of known concentration in 100 ml Nessler tubes. No dye was detected at sampling points D, E, K or L in the ten days following the injection, during which visual observations were made. Colouration was seen for at least ten days at Sampling Point B, which is located at the mouth of the Culvert.

Experiment 4. Thirty five lbs of fluorescein were dissolved in approximately 300 gallons of water and introduced into the sandstone aquifer at Injection Borehole 3 between 10:30 and 11:00 hours on the 6th June, 1967. Following this 4480 lbs of rock salt were dissolved in 1200 gallons of water and injected between 11:00 and 13:00 hours. After injection of the tracers a further 800 gallons of water were pumped into the Borehole. On this occasion site conditions had improved and care was taken to ensure that no undissolved salt entered the Injection Borehole.

Heavy rain fell a few days before the tracer injection but no rain fell during the period of the experiment. The flow from the Culvert at the site of Tip No. 7 dropped from 6000 g.p.h. at 17:00 hours on the 5th June to 1000 g.p.h. at 09:30 hours on the 13th June. When sampling ceased at 17:15 hours on 13th June the artesian discharge from the borehole at Sampling Point A had almost ceased. Prior to the experiment the water level in the Injection Borehole was 160.5 ft below the surface. It rose during the injection but rapidly returned to its pre-injection level. By the time sampling was stopped on the 13th June the water level had fallen to 172.25 ft below the surface. Similar analytical techniques to those employed in the first three experiments were again used, except that on this occasion both fluorescein and chloride determinations were performed on-site. No fluorescein was detected in any of the samples but a significant increase in chloride ion concentration was detected at Sampling Point A; a plot of chloride concentration against time is shown in Fig. 6.

Interpretation of results

Before commenting on those experiments in which positive results were obtained, the injections in which the tracer was not detected will be considered.

These negative results involved fluorescein and salt in the first experiment and fluorescein in the second and fourth experiments. After both of the latter injections an increase in the concentration of chloride ion (Cl^-) due to the salt injection was recorded but no fluorescein was detected. In the second experiment the Cl^- concentration at Sampling Point A was approximately 90 mg/l above the background level and if a similar dilution of the injected fluorescein had occurred its concentration should have been 0.12 mg/l. Similarly the concentration of fluorescein detected at Sampling Point A in the fourth experiment should have been 0.55 mg/l. Such concentrations should have been readily visible in the samples collected from Sampling Point A, because fluorescein at a concentration of 10^{-7} can be detected with the naked eye[8]). Hence the fluorescein must have been decomposed, decolourized or adsorbed during its movement through the sandstone aquifer.

The fluorescence of fluorescein is destroyed by strong oxidizing agents and fades with decreasing *p*H and on exposure to light; it is adsorbed in clayey and organic soils and in peat[9]). The most likely cause of the loss of fluorescence observed in the present experiments is the acid nature of the groundwater found in the Brithdir Series. The *p*H of the water issuing from four springs which contribute to the flow of the Nant-y-Maen to the north of the Tip Complex lay between 4.8 and 5.4 on 30th November, 1966 and the *p*H of the discharges from Sampling Points A, B, H, J and K fell between 6.0 and 7.0 over the period 25th October to the end of December, 1966.

Fluorescein was detected in the third experiment largely because much greater quantities were employed in relation to the distance travelled than in any of the other experiments. However, in this experiment sodium hydroxide was added to the fluorescein during the tracer injection to make it more readily soluble and it seems probable that this alkaline slug partially counteracted the decolouring effect of the acid groundwater.

In the first experiment neither the salt nor the fluorescein were detected after injection. If a similar dilution of the tracer had occurred as that experienced during Experiment 2, and if the decreased distance of travel between injection and sampling points and the smaller quantity of tracer used in this experiment are taken into account, a concentration of approximately 20 mg/l Cl^- in excess of the background would have been expected at Sampling Point A. A further factor to be considered in this first experiment is the greater flow from the Culvert at the site of Tip No. 7 as compared to the flow during Experiment 2. The total flow was approximately three times greater during the first experiment and it is estimated that groundwater discharge was between two and three times as high as in the second experiment. Thus the concentration of tracer to be expected at Sampling Point A would be between 7 and 10 mg/l above the background value and such an increase would have been readily detected by the titration method used for chloride determination. However, there was no increase in the background chloride ion concentration which remained constant at about 13 mg/l and it is concluded that the negative results of this first experiment are significant in terms of the groundwater conditions existing at the time. This implies that there was no movement of groundwater from Injection Borehole 1 to Sampling Point A or to the other sampling points during the course of the experiment, under the given hydraulic conditions.

After injections 2, 3 and 4 recoveries of tracer were made from the sampling points within the Central Complex but not from the North and South Streams. In the third experiment, first arrival and peak concentration times only were recorded but in the other two experiments the variation of tracer concentration with time was monitored and plots are shown in Fig. 6.

A comprehensive definition of the time of travel of a tracer cloud should include the following parameters [10],

1. The time of travel of the leading edge of the tracer cloud
2. The time of travel of the maximum concentration of tracer
3. The time of travel of half the tracer in the tracer cloud (mean travel time)
4. The time required for the tracer cloud to pass the sampling point
5. The total amount of tracer recovered at the sampling point, which is proportional to the area under the concentration/time curve.

TABLE 4

Results for tracer experiments 2 and 4.

Expt. No.	Injection Borehole	Sampling Point	I (hours)	II (ft per min)	III (hours)	IV (ft per min)	V (lbs)	VI
2	2	A	2.5	3.8	7.5	1.3	130	1 in 28.5
		C	4.5	7.1	–	–	500	1 in 6.
4	3	A	29	0.7	93.5	0.2	312	1 in 9.1

I – approximate time of travel of leading edge of tracer cloud in hours measured from the start of the salt injection.

II – velocity of leading edge of tracer cloud in feet per minute.

III – approximate time of travel of maximum concentration of tracer in hours, measured from the time at which half of the salt injection was completed. In Experiment 2, the arrival curve at Sampling Point C contains more than one maximum and is discussed later.

IV – velocity of maximum concentration of tracer in feet per minute.

V – approximate total quantity of tracer recovered at sampling point during the course of the experiment in pounds.

VI – hydraulic gradient at start of experiment.

The first two of these parameters can be measured directly from the curves obtained in experiments 2 and 4. However, the significance of the values of groundwater velocity obtained from these parameters is not clearly defined. There are two reasons for this, firstly the tracer took a considerable time to inject and secondly, groundwater flow conditions were changing throughout the experiments. The length of time taken over tracer injection is particularly important in the second experiment, when it took 59 min and the tracer was first detected $2\frac{1}{2}$ h after the injection started. These limitations must be taken into account when considering the times of travel and the calculated groundwater velocities which are presented in Table 4.

Only those parameters which can be directly measured from the arrival curves are given in Table 4. Although estimates of the other parameters could be obtained by extrapolation, the significance of the values of groundwater velocity obtained would be questionable because of the changes in groundwater flow which occur in the periods following the tracer injections.

The calculated velocities indicate that there was a rapid movement of the tracer cloud from Injection Borehole 2 to Sampling Point A in the second experiment. The leading edge and maximum concentrations of the tracer cloud travelled at 3.8 ft/min and 1.3 ft/min respectively. Under the prevailing hydraulic gradient a velocity of 1.3 ft/min could be interpreted, for a granular medium, as representing a permeability of 3.2×10^5 gal/day/ft^2. However, the intergranular permeability of the Brithdir Sandstone determined in the laboratory by the variable head method averages 2.5×10^{-4} gal/day/ft^2 (data from National Coal Board, Scientific Department). Thus the calculated permeability, based on a granular medium, exceeds the intergranular permeability determined in the laboratory by a factor of 10^9. The calculations suggest that groundwater moves between Injection Borehole 2 and Sampling Point A in a well-developed fissure system. The small dispersion of the tracer cloud suggests the presence of large open fissures. The injection and sampling points lie at either end of the tensional corridor which underlies Tip No. 7 and the evidence can be taken to indicate that this well-developed fissure system is coincident with the tensional corridor.

A comparison of the tracer arrival curves obtained at Sampling Point A in the second and fourth experiments indicates that there has been a much greater dispersion of the tracer cloud in the latter experiment (Fig. 6). Compared with the arrival curve from Experiment 4, that of Experiment 2 closely resembles those obtained in many streamflow experiments where the flow is confined to one channel[11]). The much greater dispersion of the tracer cloud in the fourth experiment suggests that the tracer may have taken a more circuitous route and that the fissure system between Injection Point 3 and Sampling Point A may be neither as open nor as direct as that between Injection Point 2 and Sampling Point A. Of greater significance is the fact that Injection Point 3 is just outside the surface-water catchment of the stream draining the Central Complex, which implies that in this area the groundwater has moved from one surface-water catchment to another in an area subject to tension.

The data obtained at Sampling Point C in the second experiment are shown in Table 4 and Fig. 6. The leading edge of the tracer cloud was detected at Sampling Point C, which is linked by a surface channel to Sampling Point A, two hours after its detection at Sampling Point A. The arrival curve has a number of distinct maxima which were detected after $7\frac{1}{2}$ h, 21 h, 25 h and 29 h respectively. The peak after $7\frac{1}{2}$ h is probably caused by groundwater reaching Sampling Point C from Sampling Point A and from the other springs discharging into the Culvert, but the other peaks must be the result of water reaching Sampling Point C from springs downstream of A. This is confirmed by the quantities of tracer recovered at sampling points A and C during Experiment 2. A total of 500 lbs of salt passed through Sampling Point C whereas only 130 lbs passed through Sampling Point A. The balance must emerge from springs downstream of Sampling Point A and the results of the third tracer injection enable the relevant springs to be located.

The times of travel and resultant groundwater velocities calculated from the data collected in the third experiment are given in Table 5.

The velocity of groundwater flow between Injection Point 2 and Sampling Point A is slightly less than that in the second experiment because of the greater head differences between these two points in Experiment 2. The dispersion of the tracer cloud at sampling points H and J is much greater than at Sampling Point A which can again be taken to imply that groundwater takes a more circuitious route when it leaves the tensional corridor underlying Tip No. 7.

In Experiment 3 fluorescein was detected at the springs which constitute

TABLE 5

Results for tracer experiment 3*

Sampling Point	1 (h)	11 (ft per min)	11 (h)	1V (ft per min)
A	3.5	2.7	9	1.0
H	7	1.8	24	0.5
J	12	1.5	36	0.5

* The figures given in Table 5 are only approximations as first arrival times and maximum concentrations were estimated purely by visual methods.
I–IV as for Table 4.

sampling points H and J but not at those which constitute sampling points K and L. However, the chemistry of the groundwater issuing from the springs at sampling points K and L, together with their behaviour after rainfall, suggests that their flow is derived from groundwater. Part of the flow of the North Stream was seen to be sinking midway between G and E (Fig. 5). A few lbs of dissolved fluorescein was injected at the sink-holes and soon afterwards dye was detected at Sampling Point L. The stream-flow was then piped across the sink-holes and the test was repeated. On this occasion no trace of dye appeared at Sampling Point L and the flow from the spring decreased slightly. Thus, at least some of the flow of this spring is derived from the North Stream and it seems probable that the springs which constitute sampling points K and L are fed from groundwater which is derived in part from outside the surface catchment of the Central Complex.

Conclusions

The groundwater tracing experiments undertaken at Aberfan underline the importance of mining subsidence in controlling the movement of groundwater in thick massive Pennant Sandstones which overlie areas from which coal has been extracted at depth. Calculations of subsidence in the area beneath the tip-complex show that Tip No. 7 is underlain by a narrow "tensional corridor". Tracers injected at the north-western end of this corridor moved rapidly to the artesian borehole at the head of the Culvert constructed beneath the toe of Tip No. 7. Tracer velocity and dispersion were such that the groundwater carrying the tracer must have moved through an open fissure system. Tracer movement in other tensional areas was also rapid, but less so than through the tensional corridor beneath Tip No. 7. Tracers injected into an area subject to compressional strain were not recovered and it is suggested that boundaries between zones of tensile and compressional strains should be regarded as hydraulic discontinuities.

The tracer experiments show that, in at least two distinct areas, groundwater can move across surface catchment boundaries into the Central Complex. It seems possible that the groundwater catchment of the Central Complex has been enlarged at the expense of the North Stream Catchment, and perhaps even at the expense of the Nant-y-Maen Catchment, as a result of mining subsidence. This enlargement accounts for the high groundwater component of the stream draining the Central Complex and bears directly upon the large volume of water discharged immediately subsequent to the flow-side.

Of the two tracers used in the experiments, sodium chloride, in the form of a saturated brine solution made from rock salt, proved to be more successful than fluorescein probably because of the acid nature of the groundwater involved.

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