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GROUNDWATER TRACING EXPERIMENTS

L.W. SINTON & M.E. CLOSE

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Hydrology Centre, Ministry of Works and Development, Christchurch

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Antibiotic-resistant bacteria, fluorescent dyes and salt were used to trace the movement of groundwater through well arrays at two sites. Part 1 describes an experiment at Burnham in which the relative performance as tracers of E. coli JC 3272 (streptomycin-resistant) and rhodamine WT dye was evaluated. Part 2 describes experiments at Templeton in which E. coli J6-2 (nalidixic acid-resistant) and fluorescein were used to confirm the horizontal direction and velocity of groundwater movement, and a sodium chloride solution was used to determine vertical water movement in selected wells.

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PREFACE

In 1975-76, the effects on groundwater quality of land disposal of sewage by border-dyke irrigation at Burnham and Templeton in the Central Canterbury Plains were investigated in a joint study by the Ministry of Works and Development and Lincoln College (Martin and Noonan, 1977). An array of 7 unpumped bores, one being located upstream as a control, was installed at each site, along a flow line derived from regional piezometric surveys by the North Canterbury Catchment Board. No direct evidence of chemical contamination of the underlying alluvial gravel aquifers was demonstrated at either site. At Burnham, however, after effluent application to specific border-dyked strips, micro-organisms indicative of faecal contamination were found in the wells downstream of the disposal area.

This publication consists of two reports describing some of the subsequent work at the Burnham and Templeton sites. The first report describes an experiment at Burnham in which the primary purpose was to evaluate the relative performance of two groundwater tracers. The second describes work at Templeton, where the relative performance of the tracers used was also assessed, but the primary aim was to indicate the direction and velocity of vertical and horizontal movement of groundwater at the site, as a precursor to a groundwater quality experimental programme. Neither study was designed to provide detailed hydrological information on groundwater characteristics at the respective sites.

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REPORT 1

TRACING SEWAGE-POLLUTED GROUNDWATER MOVEMENT AT BURNHAM WITH AN ANTIBIOTIC-RESISTANT BACTERIUM AND A FLUORESCENT DYE

L. W. Sinton

ABSTRACT

An antibiotic-resistant bacterium, Escherichia coli JC 3272 (lactose negative, streptomycin-resistant), was evaluated as a tracer of sewage movement in an alluvial gravel aquifer and its performance compared to that of a fluorescent dye, rhodamine WT. The E. coli JC 3272 cells were recovered from groundwater samples by membrane filtration and incubation on MacConkey Agar. The incorporation of 50 mg litre^{-1} streptomycin into the agar suppressed background sewage organisms without reducing E. coli JC 3272 counts. The bacterium performed satisfactorily as a tracer in the aquifer and the passage of both E. coli JC 3272 cells and rhodamine WT through two wells, 140 m and 570 m downstream of the injection well was recorded. In each well, the bacterium and dye arrived simultaneously, and the estimated first arrival velocity for both wells was 300 m day^{-1}. However, peak concentration velocities differed, being 215 and 265 m day^{-1} for E. coli and 180 and 230 m day^{-1} for rhodamine WT in the first and second wells, respectively. The bacterium suffered proportionally greater reductions in the aquifer, due primarily to the effects of die-off.

INTRODUCTION

In conjunction with the 1975-76 groundwater quality investigation at Burnham (Martin and Noonan, 1977), attempts were made to trace the movement of effluent into and through the groundwater system, using the radio-isotope Iodine-131 (McCabe and Rowse, 1976). Firstly, the tracer was added to effluent being irrigated onto the border-dyke strip that had previously been associated with pollution of the well array. However, the I-131 was apparently completely adsorbed onto the soil profile and none was detected in any of the downstream bores. Secondly, the isotope was injected into well 2 and scintillation detectors were suspended in wells 4, 7 and 6 (Figure 1). A small positive response, which reached a peak 14 hours after injection, was recorded in well 4, but the tracer was not detected in the other bores. The results from well 4 suggested a groundwater velocity to peak concentration of 257 m day^{-1}.

The Templeton-Burnham groundwater quality investigation was followed by experiments at the Burnham site with two bacterial tracers: the thermophile Bacillus stearothermophilus and a hydrogen sulphide positive strain of Escherichia coli (Sinton, 1980a). Although both species were sucessfully used to monitor groundwater movement from the injection well (well 2) to wells 4, 6 and 5 (a distance of 920 m), neither was considered suitable for use in sewage-polluted groundwater. B. stearothermophilus is consistently found in sewage and E. coli H_2S+ strains are present intermittently. To ensure success of the experi-

ment, it was therefore necessary to maintain low background concentrations of these organisms by witholding effluent from the border-dyke strips associated with contamination of the well array. To overcome these problems, further experiments were conducted at Burnham, using antibiotic-resistant bacteria. This work culminated in the successful use of E. coli J6-2 (nalidixic acid resistant) and E. coli PB 922 (rifampycin resistant) to trace the movement of sewage-polluted groundwater from well 2 to wells 6 and 5 (Sinton, 1980b). The incorporation of the appropriate antibiotic into the recovery media suppressed the background sewage-associated micro-organisms and allowed groundwater velocity, as indicated by peak tracer concentration, to be estimated at 224 m day $^{-1}$.

This report describes an experiment conducted at the Burnham site to evaluate a third antibiotic-resistant E. coli strain as a tracer of sewage movement in groundwater and to compare its performance with that of a fluorescent dye.

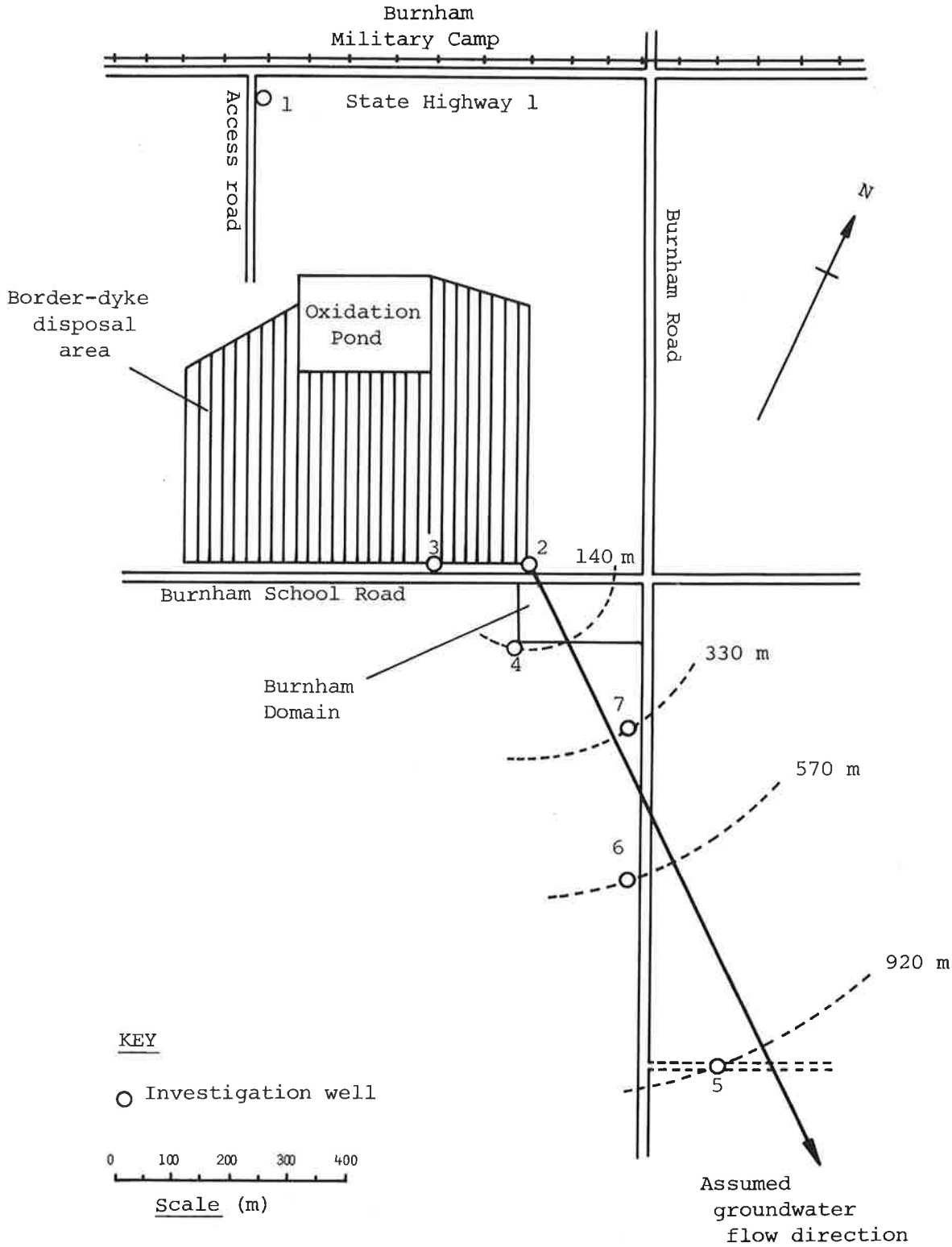

FIGURE 1: THE BURNHAM SEWAGE TREATMENT AND DISPOSAL SCHEME AND ASSOCIATED INVESTIGATION WELLS (SHOWING RADIAL DISTANCES OF WELLS 4, 7, 6 AND 5 FROM WELL 2)

SITE DESCRIPTION

The Burnham sewage treatment and disposal area (Figure 1) is situated approximately 25 km south of Christchurch and serves the Burnham military camp. The population of the camp fluctuates markedly, but an average of 1,300 m^3 of treated sewage is discharged daily from the single 4.16 ha oxidation pond onto a 23 ha border-dyked disposal area.

The plant is located on the Burnham geological formation which comprises fairly well sorted, little weathered, glacial outwash gravels. The soil type is a Lismore very stony silt loam (Kear et al., 1967).

The investigation wells are 76 mm PVC pipes, sunk to a depth of 22 m below ground level and screened over the bottom 6 m. Screen porosity is approximately 1%. Static well water level normally varies from between 7 and 10 m below ground level. However, at the time of the experiment described in this report, the level had risen to 5 m below ground level as a result of an abnormally wet winter.

MATERIALS AND METHODS

Tracers

The tracers selected for comparison were the fluorescent dye, rhodamine WT, and the bacterium E. coli JC 3272, a spontaneous streptomycin-resistant mutant which is also lactose negative, in contrast to normal E. coli. It is a derivative of E. coli K-12 (Bachmann, 1972). The strain, which was supplied by Mr W J Kelly, Biochemistry Department, Lincoln College, meets certain safety criteria for use as a tracer. The organism was tested by the New Zealand National Health Institute and confirmed as a non-pathogenic serotype (this was expected for an E. coli K-12 derivative). The strain is unlikely to have retained the competitive capacity necessary for colonisation of the human gastro-intestinal tract (Gorbach, 1978) and does not appear to possess plasmid-borne (transferable) antibiotic resistance characters ("R-factors"). The safety aspects of the use of E. coli K-12 derivatives and other bacteria as water tracers have been discussed in detail elsewhere (Sinton, 1980b).

Laboratory Procedure

Rhodamine WT concentration was measured in a Turner Model 111 fluorometer at excitation and emission wavelengths of 555 and 580 nm, respectively, using the procedures outlined by Wilson (1968).

The E. coli JC 3272 tracer was cultured in brain-heart infusion broth (BBL). The culture media was aerated and incubated for

36 hours at 37° C. The culture was centrifuged and the precipitated cells were washed twice and resuspended in sterile 0.85% w/v NaCl.

The bacterial cells were recovered from groundwater samples by membrane filtration using Gelman GN-6 0.45 um filters. Dilution series of 0.1% peptone water were prepared when required. The filters were incubated on inverted plates of MacConkey agar (BBL) at 30° C for 4 hours, followed by a further 14 hours at 44.5° C. Streptomycin was added to the agar prior to pouring to give a concentration of 50 mg antibiotic per litre of MacConkey agar. This concentration was found to totally suppress background sewage organisms, while causing minimum suppression of the tracer.

The survival rate of E. coli JC 3272 in laboratory-stored groundwater samples stored at 12.5° C (mean Canterbury groundwater temperature) was measured and compared to that of an E. coli neotype, using the procedures described in Sinton (1980b).

Field Work

A 10 litre NaCl solution containing approximately 5.72×10^{11} E. coli JC 3272 cells, and 10 litres of 20% Rhodamine WT dye were simultaneously injected into well 2 (Figure 1). Samples were collected from two downstream wells, using a Manning automatic water sampler. The sampler, set to collect one sample every half hour, was first set up on well 4 and operated for

22.5 hours, starting at the time of injection of the tracer (46 samples). The instrument was then transferred to well 6, set to collect one sample/hour (first sample collected 23 hours after injection) and operated for 41 hours (42 samples).

The sampler bottle chamber was packed in ice to minimise bacterial die-off. Samples were removed from the instrument every 6 hours for processing in the laboratory and sampler bottles were sterilised between samples by autoclaving.

RESULTS AND DISCUSSION

Figure 2 and table 1 show that both the bacterium and dye were first detected in well 4 11 hours after injection into well 2, giving a first arrival velocity of 300 m day^{-1}. However, times to peak concentrations of the tracers differed, with the bacterium reaching maximum concentration approximately 4 hours before the dye, giving peak concentration velocities of 215 and 180 m day^{-1}, respectively (the rhodamine WT peak was indistinct but was taken to have occurred 19 hours after injection). This pattern was repeated in well 6, where both tracers were first detected 45.5 hours after injection into well 2, giving a first arrival velocity of 300 m day^{-1}. Times to peak concentrations again differed, but by a greater amount, with the peak bacterial concentration preceding that of the dye by 7 hours (265 and 230 m day^{-1}, respectively).

Differences in peak arrival times between chemical and microbial tracers have been noted by previous workers, including Wood and Ehrlich (1978) and Pyle and Thorpe (1979). No conclusive explanation of this phenomenon appears to be available. Possibilities include different adsorption characteristics of the chemical and particulate tracers, and electrostatic repulsion effects causing preferential movement of the bacterial cells into larger pores within the aquifer.

As with the two antibiotic-resistant *E.coli* strains tested previously at the site (Sinton, 1980b), *E. coli* JC 3272 performed satisfactorily in the sewage-polluted groundwater. The

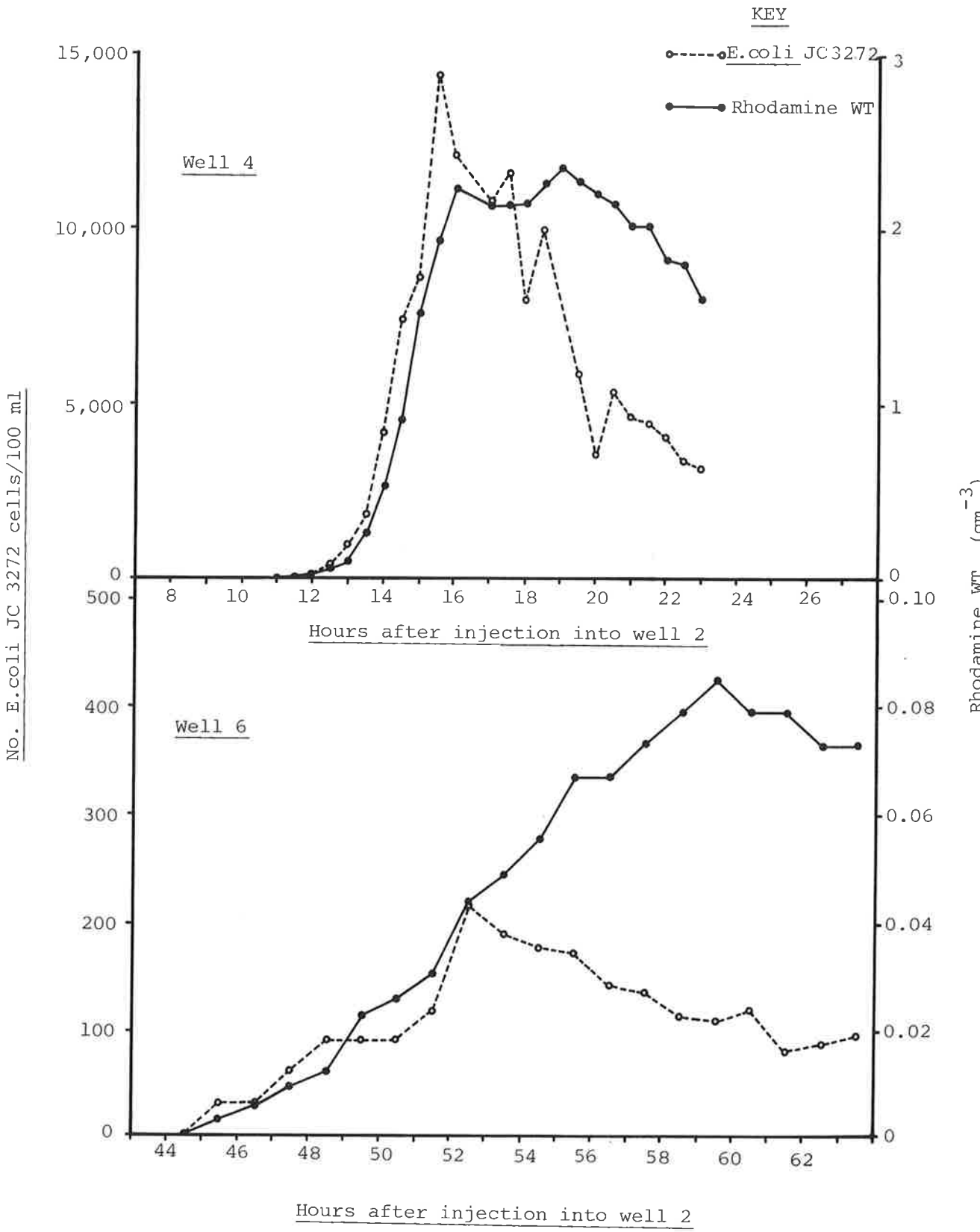

FIGURE 2: CONCENTRATIONS OF E. COLI JC 3272 CELLS AND RHODAMINE WT IN WELLS 4 AND 6 FOLLOWING INJECTION INTO WELL 2

		Radial distance from well 2 (m)	Estimated time to first arrival (hr)	Estimated time to peak concentration	Estimated Velocity			
					To first arrival		To peak concentration	
					m/hr	m/day	m/hr	m/day
Well 4	E. coli / JC 3272	...140...	11	15.5	12.5	300	9	215
Well 4	Rhodamine WT		11	19	12.5	300	7.5	180
Well 6	E. coli / J6 3272	...570...	45.5	52.5	12.5	300	11	265
Well 6	Rhodamine WT		45.5	59.5	12.5	300	9.5	230

TABLE 1: ESTIMATED FIRST AND PEAK ARRIVAL TIMES OF THE TRACERS AND CALCULATED VELOCITIES FROM WELL 2 TO WELLS 4 AND 6

border-dyke strips associated with pollution of the well array were deliberately irrigated for 6-8 hours on each of the two days before the experiment, giving background faecal coliform concentrations in wells 4 and 6 of approximately 10,000 and 1,000/100 ml, respectively, immediately before installation of the Manning sampler. Therefore, the E. coli JC 3272 cells were being recovered against background faecal coliform levels that exceeded tracer concentrations in each well.

Some crude estimates of the relative performance of the two tracers in the aquifer may be made. The rhodamine WT:E. coli ratio in the injection mixture (g dye:number of cells) was 1:286,000,000. In well 4, the peak rhodamine WT:peak E. coli ratio (g m^{-3}:cells m^{-3}) was 1:61,300,000, indicating a 4.6-fold decrease in bacteria numbers relative to the dye concentration. In well 6, the ratio was 1:25,600,000, indicating an 11.2-fold relative decrease in bacteria numbers from the injection solution concentration. It was assumed that the bacterium and the dye were subject to similar dilution and dispersion effects in the Burnham aquifer. Reduction in rhodamine WT concentrations are also likely to have occurred due to adsorption (it is assumed that no chemical denaturing of the dye occurred in the absence of sunlight). In addition to the probable reductions of E. coli JC 3272 cells due to adsorption, the bacterium would also have been subject to the effects die-off.

The relative importance of adsorption and die-off in reducing concentrations of the bacterial tracer in the groundwater

strata may be assessed. In the laboratory experiment, the E. coli JC 3272 strain conformed to a $\log_{10}$ "die-off" curve (r=0.92) with a T90 value (time taken for 90% of the cells to die-off) of 2.9 days. It can therefore be estimated that, had no die-off occurred, the peak number of E. coli JC 3272 cells would have been 24,000/100 ml in well 4 and 1,240/100 ml in well 6, giving corrected dye:bacteria ratios of 1:102,000,000 and 1:146,000,000, respectively. These figures now show a 2.8-fold decrease in E. coli numbers relative to dye concentrations between wells 2 and 4 and a 2-fold relative decrease between wells 2 and 6. When compared to the measured concentrations, these figures suggest that, at least over the longer distance (520 m) from well 2 to well 6, die-off was the more significant factor reducing the tracer bacteria numbers. However, no quantitative relationships between die-off and adsorption can be drawn from the results because the low levels of rhodamine WT (well 6) would result in up to 20% error in the fluorometer readings, and conversely, the measurement of high bacteria numbers by membrane filtration (injection solution) involved considerable potential error because of the need for repeated dilutions. In addition, the peak concentrations (which were difficult to determine accurately) do not necessarily provide the best relative measure of tracer reductions.

The T90 value of 2.9 days for the E. coli JC 3272 tracer is similar to the 3.2 days for the E. coli neotype (Sinton, 1980b). The tracer should, therefore, adequately represent the behaviour of "typical" E. coli in alluvial aquifer systems.

SUMMARY AND CONCLUSIONS

The antibiotic-resistant bacterium *E. coli* JC 3272 was found to be a suitable tracer for use in sewage-polluted groundwater. The organism was recovered from groundwater samples by membrane filtration and enumerated on MacConkey agar containing streptomycin at a concentration (50 mg/litre) which totally suppressed background bacteria. The strain exhibited a similar survival rate in laboratory-stored groundwater samples to an *E. coli* neotype. The fluorescent dye, rhodamine WT, also performed satisfactorily in the polluted aquifer. The bacterium suffered proportionally greater reduction in the aquifer, due primarily to the effects of die-off.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the co-operation of Messrs D.G. and D.J. Scott in providing access to the wells on their property, and Miss D.L. Hartley for assistance with the field and laboratory work. Dr H.R. Thorpe provided valuable comments on the presentation of this material.

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REPORT 2

TRACING THE HORIZONTAL AND VERTICAL MOVEMENT OF GROUNDWATER AT TEMPLETON

L.W. Sinton and M.E. Close

ABSTRACT

Estimates of horizontal groundwater flow direction and velocity adjacent to a border-dyked sewage disposal area at Templeton, in Central Canterbury, were obtained from an existing well array using fluorescein and an Escherichia coli strain as tracers. No differences in first arrival times of the dye and bacteria in two downstream wells were recorded, but times to peak concentration differed. Groundwater velocity was estimated at 235 m day^{-1} based on first arrival of the tracers, and between 111 and 196 m day^{-1} based on peak concentrations.

The vertical movement of a NaCl tracer solution in each of four new wells was monitored using conductivity probes. Downward movement of groundwater in all four wells was detected with peak concentration velocities ranging from Ø.2 to 1.9 m $minute^{-1}$. This movement was confirmed using rhodamine WT dye. The results indicated that uniform chemical and microbial composition could be expected over the top 1Ø m of well water, but would tend to be more representative of water quality in the upper layers of the surrounding groundwater strata. They also suggested that pollutants reaching the groundwater table in the Templeton area would tend to migrate into deeper aquifers through any discontinuities in the local confining layers.

INTRODUCTION

Although Martin and Noonan (1977) found indicator micro-organisms in the downstream array of monitoring bores at Templeton, levels of pollution could not be related to the irrigation of specific areas in the disposal scheme, as they could at Burnham. This may have resulted from the misalignment of the original well array and/or from the effects of filtration by the deeper soils in the south-eastern sector of the disposal area. In a subsequent study at the Templeton site, Quin (1978) found evidence to suggest that increases in NO_3, Cl, Na and Ca in the groundwater were occurring as a result of effluent irrigation. Anomalous results between downstream wells were noted, and the possibility of "preferred pathways" in the local aquifer system was suggested. However, as in the earlier investigation by Martin and Noonan (1977), levels of groundwater contamination could not be related to the irrigation of specific areas in the disposal scheme.

To re-examine the effects of the Templeton scheme on groundwater quality, four new wells downstream of the shallower soils in the south-western sector of the disposal area were proposed. So that these wells could be correctly positioned, it was necessary to confirm the original estimate of groundwater flow direction, or establish a new flow line.

Secondly, to establish an appropriate sampling depth, an examination of the new wells for vertical water movement was required. Quin (1978) recorded uniform chemical composition of

the water in several of the Templeton wells over at least the top 4 m and suggested that "a large degree of vertical mixing" in the surrounding permeable gravels was responsible. However, the alluvial gravel strata underlying the Canterbury Plains are often separated by impermeable clay-bound gravel layers and tend to form discrete or semi-discrete aquifers of varying thicknesses and permeabilities. These bands are frequently under different hydrostatic pressures and, in any screened well that connects two or more aquifers, vertical well water movement may occur.

This report describes experiments carried out at the Templeton site to determine:

(1) the horizontal direction and velocity of groundwater movement using fluorescent and microbial tracers in the original well array;

(2) the vertical direction and velocity of well water currents, using salt tracing techniques in four newly installed monitoring wells.

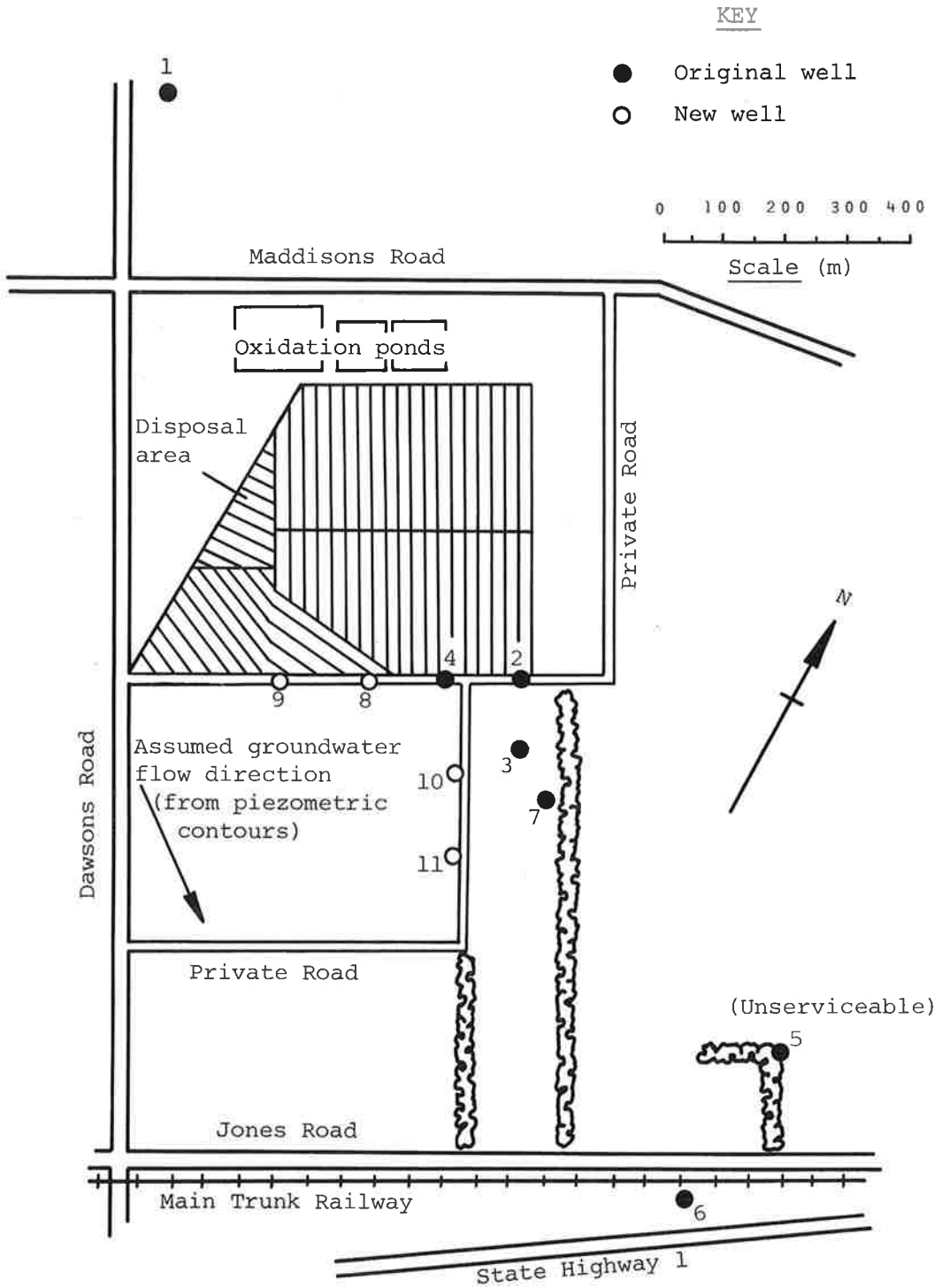

FIGURE 3: TEMPLETON SEWAGE DISPOSAL SCHEME AND ASSOCIATED INVESTIGATION WELLS

SITE DESCRIPTION

The Templeton sewage treatment and disposal scheme (Figure 3) is situated approximately 5 km south of Christchurch and consists of three oxidation ponds and a 25 ha border-dyked effluent disposal area. The soils in the disposal area are largely a mixture of Templeton silt loams and sandy loams from Ø.2 to 2.Ø m thick. The underlying profile is composed of coarse to very coarse silty gravels interspersed with layers of sand and clay.

The investigation wells are of two types: (1) wells 1 to 7 (installed in 1975) are 75 mm diameter unpumped PVC pipes, sunk to a depth of 18 m and screened over the lower 6 m. Screen porosity is approximately 1%; (2) wells 8 to 11 (installed in 1979-8Ø, after the horizontal tracing experiments described in this paper) are 1ØØ mm diameter unpumped PVC pipes, sunk to a depth of 24 m and screened over the lower 12 m. Screen porosity is approximately 2Ø %. The static well water level in all wells is approximately 12 m below ground level.

MATERIALS AND METHODS

Horizontal Tracing Experiment

The fluorescent tracers selected were the dyes fluorescein and rhodamine WT. Samples were analysed by irradiation at the respective peak excitation wavelengths (555.8 nm for rhodamine WT and 480 nm for fluorescein) using a Varian Techtron 635 spectrophotometer (a fault in the laboratory fluorometer precluded the use of fluorometric techniques). Sample absorbance was compared to that of a blank groundwater sample.

The microbial tracers were two antibiotic-resistant strains of the bacterium Escherichia coli: E. coli J6-2 (nalidixic acid-resistant) and E. coli PB 922 (rifampycin-resistant). The strains were recovered from groundwater samples by membrane filtration and incubated on MacConkey agar. To suppress background organisms in the sewage-polluted groundwater, the agar was impregnated with the appropriate antibiotic. Details of culture and enumeration procedures for these strains and an evaluation of their potential as tracers in sewage-polluted water have been given elsewhere (Sinton, 1980).

Approximately 10 litres of 20% w/v rhodamine WT and 1.4×10^{14} E. coli PB 922 cells suspended in 20 litres of 0.85% w/v NaCl solution were injected into well 2 (Figure 3). Simultaneously, 10 litres of 20% w/v fluorescein and 20 litres of 0.85% w/v NaCl solution containing approximately 1.6×10^{14} E. coli J6-2 cells were injected into well 4. Injection was through separate

lengths of sterile rubber tubing lowered to a depth of 17 m below ground level (about 5 m below static well water level and approximately in the middle of the screened section of the well).

Over the next nine days, groundwater samples were collected from the well array, using "vacuum chamber" samplers (Martin, 1976) which were suspended in the wells for the duration of the sampling programme. Each sampler was flushed five times prior to sample collection. Samples for spectrophotometric analysis were collected in acid-washed plastic bottles, and those for microbial analysis in sterile glass bottles. Samples were stored in the dark and packed in ice for transport to the laboratory.

Vertical Tracing Experiment

Vertical well water movements were measured by salt tracing and confirmed using a fluorescent dye. Before the field work, the specific densities of the injection solutions (Ø.5% NaCl and Ø.2% rhodamine WT) were measured using specific density bottles. The movement of a Ø.5% NaCl solution down a static 6 m x 1ØØ mm diameter water column was also measured, using conductivity probes located at 1.5 m intervals down the column.

The tracer tests were conducted on four new wells (numbers 8 to 11) installed on flow lines derived from the results of the horizontal tracing experiment. Three injection depths (12.5 m, 17.Ø m and 22.Ø m) were used in separate experiments in each well. In each experiment, 4 litres of tracer solution were

injected through a length of rubber tubing, which was perforated over the lower 8 cm and stoppered at the lower end to ensure that the injected solution had no residual vertical velocity. Care was also taken to ensure that the tracer solution was at groundwater temperature (approximately 12.5^{o} C) immediately prior to injection.

The movement of the NaCl solution was monitored using five *in situ* conductivity probes, positioned at 13.Ø m, 15.Ø m, 17.Ø m, 19.Ø m and 21.Ø m below ground level. The probes were multiplexed into a Triac conductivity meter which enabled rapid sequential reading of the conductivity values. The confirmation of the flow patterns, using rhodamine WT, was undertaken in separate experiments. Samples were collected for visual assessment of dye concentrations, using jerk samplers positioned at the above depths, and opened at pre-determined time intervals.

RESULTS AND DISCUSSION

Horizontal Tracing Experiment

Most of the rhodamine WT dye and E. coli PB 922 cells were removed from injection well 2 in 3-4 days, although both tracers were present at the end of the sampling programme (Figure 4). No major differences in the relative rates of removal of the two tracers from the well were noted, although the dye appeared to be slightly more persistent than the bacterial cells. This was probably largely attributable to natural die-off of the bacterium in the well water. Neither rhodamine WT dye nor E. coli PB 922 were recorded in wells 3 or 7.

Most of the E. coli J6-2 cells were removed from injection well 4 in 5-6 days, but concentrations of between 10 and 100 cells/100 ml remained at the end of the sampling programme (Figure 4). In well 4, the fluorescein dye appeared to be considerably more persistent than the E. coli J6-2 cells. This was attributed to high levels of adsorption of the dye to the interior surfaces of the sampler chamber and hoses. Desorption of the dye in subsequent samples meant that, even after five cleansing flushes, fluorescein levels in the collected sample were probably considerably greater than concentrations in the well water; this was subsequently confirmed in laboratory experiments. The actual rate of removal of the fluorescein from well 4 would probably have been similar to that of the E. coli J6-2 cells.

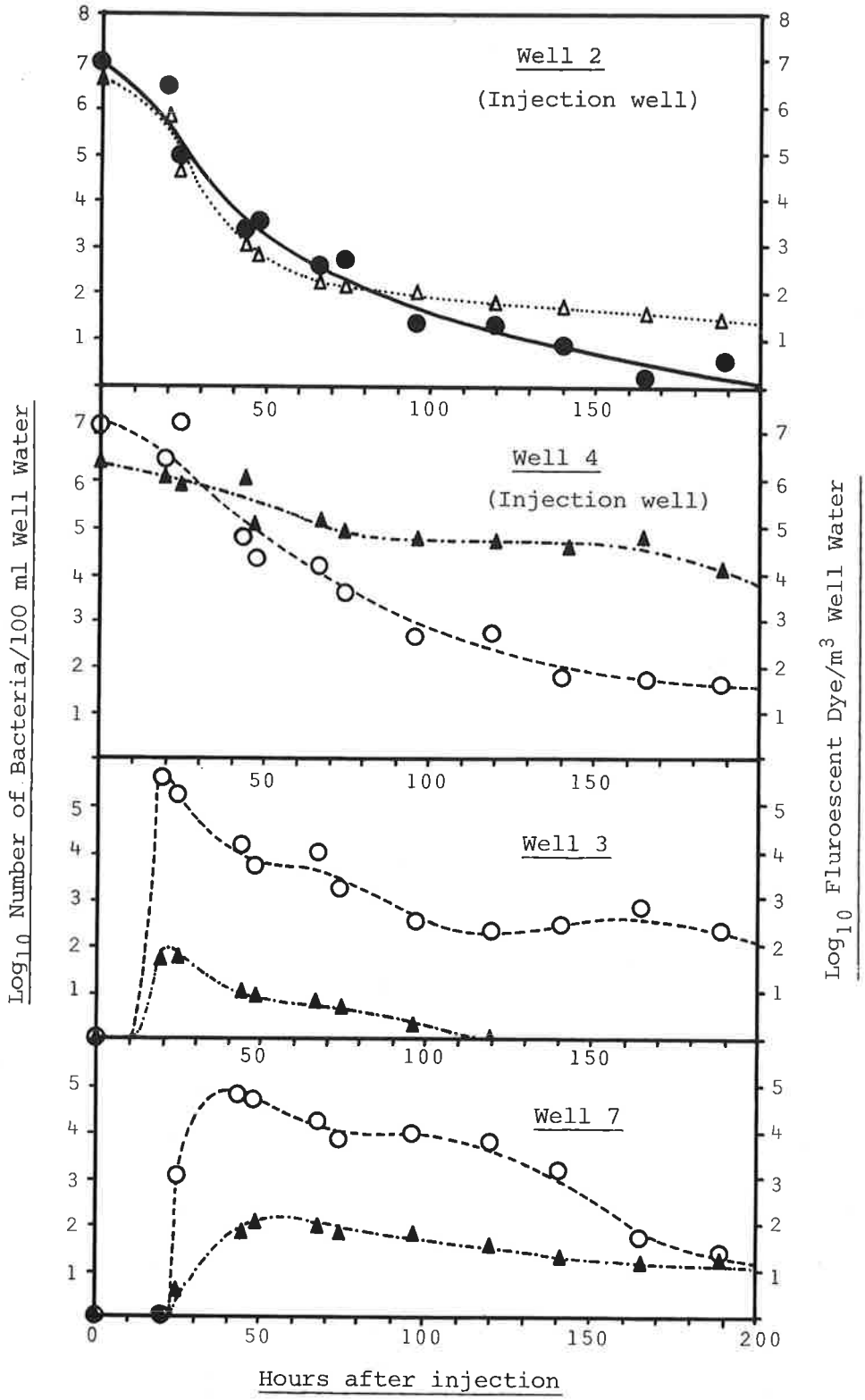

FIGURE 4: CONCENTRATIONS OF E. COLI J6-2, E. COLI PB 922, RHODAMINE WT AND FLUORESCEIN IN WELLS 2, 3, 4 AND 7 AFTER INJECTION INTO WELLS 2 AND 4.

Figure 4 shows that both fluorescein dye and E. coli J6-2 cells were recorded passing through wells 3 and 7. Although no conclusions on the shape and extent of the tracer plumes could be drawn from the results, they indicate that the wells are situated on, or close to the existing Templeton flow line (ie, through a line from well 4 to wells 3 or 7). Therefore, the axis of the tracer plume of rhodamine WT and E. coli PB 922 cells from well 2 was probably around 60 m due north of wells 3 and 7. This plume was apparently of insufficient width for the well 2 tracers to appear in wells 3 and 7.

For each of the estimated first and peak arrival times and calculated velocities presented in Table 2, the tracer was assumed to have arrived mid-way between the time of first detection and the previous sampling occasion. The interval between these two samples was approximately 22 hours for well 3, whereas it was less than 5 hours for well 7. The estimate of 235 m day^{-1} for well 7 is therefore considered to more accurately represent first arrival velocity than the corresponding estimate (338 m day^{-1}) for well 3. No differences between the first arrival times of the bacteria and dye were recorded. However, as noted in the Burnham experiment (see page 9) the bacteria appeared to reach peak concentrations first, in this case approximately 3 hours before the dye in well 3 and approximately 15 hours before the dye in well 7.

The decrease in concentration of fluorescein between the injection well and wells 3 and 7 was proportionally more rapid than

		Radial distance from well 4 (m)	Estimated time to first arrival (hr)	Estimated time to peak concentration (hr)	Estimated Velocity			
					To first arrival		To peak concentration	
					m/hr	m/day	m/hr	m/day
Well 3	*E. coli* J6-2	...155...	11	19	14	335	8	190
	Fluorescein		11	22	14	335	7	170
Well 7	*E. coli* J6-2	...240...	24.5	37	10	240	6.5	155
	Fluorescein		24.5	52	10	240	4.5	110

TABLE 2: ESTIMATED FIRST AND PEAK ARRIVAL TIMES OF THE TRACERS AND CALCULATED VELOCITIES FROM WELL 4 TO WELLS 3 AND 7

the decrease in concentration of the micro-organisms. This was in contrast to the results of the Burnham experiment, where rhodamine WT showed marginally less reduction in the groundwater, but confirms the observations of Rahe et al. (1978) who found that, compared to fluorescein, E. coli cells were considerably less prone to adsorbtion in groundwater tracing experiments.

Simultaneous injection of distinguishable tracers into two wells, as outlined in this study, permitted two possible flow lines to be investigated for the cost of one field sampling exercise. Laboratory analysis time was also reduced. This approach also eliminated the possibility of minor variations in groundwater velocity and/or direction resulting from temporal fluctuations in groundwater level or hydrostatic pressure.

Vertical Tracing Experiment

The specific densities of the Ø.5% NaCl and the Ø.2% rhodamine dye solutions were 1.ØØ3 and 1.ØØØ9, respectively. The figure for the rhodamine WT was considered to be too low to cause a measurable effect in the field experiments. However, the specific density of the NaCl solution was high enough for the results of the salt solution/static water column experiment to be subsequently used to adjust the field study data. Injection of the Ø.5% NaCl solution into the top of the 6 m static water column gave downward velocities for the top, middle and lower sections of the column of Ø.3 m minute^{-1}, Ø.1 m minute^{-1} and Ø.Ø5 m minute^{-1}, respectively. This observed decrease in

velocity was attributed to progressive dilution as the NaCl solution moved down the column. Therefore, the maximum downward velocity that would be expected in the wells due to density differences would be Ø.3 m minute^{-1}, and the mean velocity for a 6 x Ø.1 m water column would be around Ø.15m minute^{-1}.

In each of the four new wells (numbers 8 to 11), injection of NaCl and rhodamine WT at 12.5 m and 17.Ø m indicated only downward water movement. Injection at 22 m (at the bottom of the well) showed no upward movement. Therefore, only the 12.5 m injection results are presented.

Figure 5 clearly shows the passage of the NaCl tracer down the wells. Wells 8, 1Ø and 11 appeared to exhibit constant downward velocities over the full 13 to 21 m depth range. The first arrival and peak velocities (adjusted for a mean specific density effect of Ø.15 m minute^{-1}) were similar at 2.4 and 1.5 m minute^{-1}, respectively, in well 8, and 2.5 and 1.9 m minute^{-1}, respectively, in well 11. Well 1Ø exhibited lower first arrival and peak velocities at Ø.7 and Ø.5 m minute^{-1}, respectively. Although the first arrival and peak velocities in well 9 were similar to those in the other three bores over the top sections of the well, a marked decrease in velocity occurred between 19 and 21 m. Overall, first arrival and peak velocities in well 9 (measured between 15 and 21 m) were Ø.4 and Ø.2 m minute^{-1}, respectively.

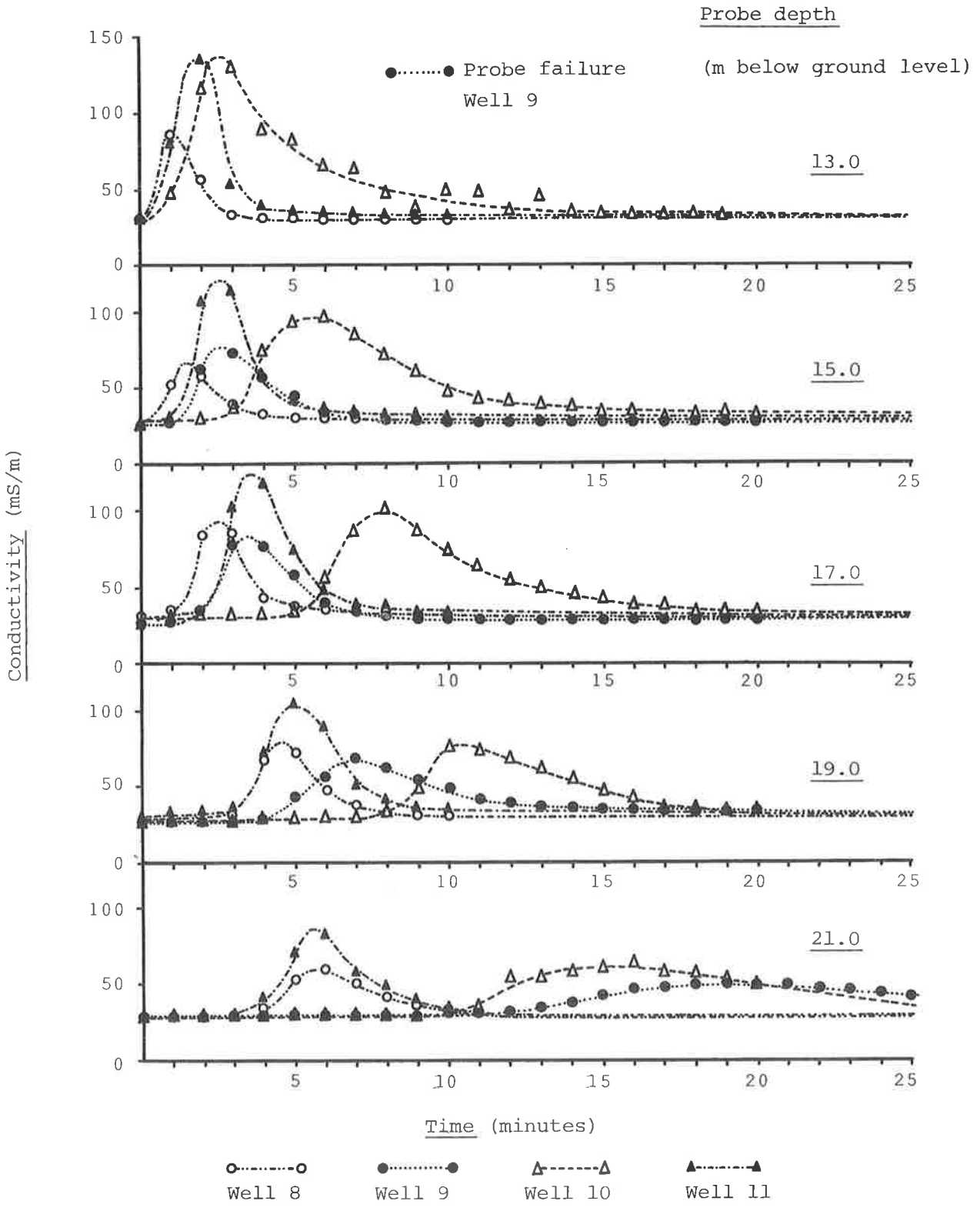

FIGURE 5: CONDUCTIVITY LEVELS RECORDED AT FIVE DEPTHS IN WELLS 8, 9,10 AND 11 FOLLOWING INJECTION OF Ø.5% SODIUM CHLORIDE SOLUTION AT 12.5 M.

The velocity patterns in the wells may be partially explained from the borelogs, which included the results of bailing tests conducted at 1.Ø m intervals. The logs show that wells 8, 1Ø and 11 pass through similar strata with very little groundwater infiltration between 14 and 21 m. Below 21 m, there is a slow-medium infiltration layer in well 1Ø and a fast infiltration layer in both wells 8 and 11. This would explain the constant downward velocities, although of different magnitudes, recorded in these wells. In contrast, well 9 traverses medium-fast infiltration layers at 16-18 m and 2Ø m. Some removal of the tracer in these zones may have occurred, thereby delaying the first and peak arrival times at the bottom probe.

SUMMARY AND CONCLUSIONS

The estimates of groundwater flow direction derived from the horizontal tracing experiment (along a line from well 4 to wells 3 or 7) differ only slightly from the original estimate (along a line through wells 1, 4 and 6) calculated from piezometric contour data (Martin and Noonan, 1977). The first arrival and time to peak estimates of velocity for *E. coli* J6-2 in well 7 (235 m day^{-1} and 156 m day^{-1}, respectively) also support the previous estimates by Martin and Noonan (1977) of the rate of movement of microbial contaminants (150-200 m day^{-1}) downstream of the Templeton site.

The results of the vertical tracing experiments indicate that the hydrostatic pressures in the 12.5 - 14 m aquifer layers at the Templeton site exceed the pressures in the 20-21 m groundwater bearing strata, resulting in a downward movement of the well water. The implications of these results are twofold. Firstly, the observed downward velocities would tend to create a uniform chemical and microbial composition throughout the well, and thus sampling at any depth in the upper 10 m of the water table would provide similar results. However, the sample would be more representative of water quality in the upper groundwater strata surrounding the well than in the lower layers. This is the probable explanation for the observed uniformity in well water composition in previous studies at the site (Quin, 1978). Secondly, pollutants entering the groundwater system via drainage at the Templeton site would tend to move into the deeper

groundwater strata through any discontinuities in the confining layers.

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