Application of Tracers in Arid Zone Hydrology (Proceedings of the Vienna Symposium, August 1994). IAHS Publ. no. 232, 1995.

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The use of fluorescent dyes as tracers in a study of artificial recharge in northern Qatar

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Abstract The State of Qatar Ministry for Municipal Affairs and Agriculture is considering artificially recharging two carbonate aquifers in northern Qatar. A feasibility study comprising the drilling and testing of boreholes and a programme of injection and re-abstraction tests has been carried out at four sites. At some of these sites the only water available for injection was of similar composition to the native groundwater at the test site and Rhodamine WT fluorescent dye has been used successfully to label the injected water. Analysis of data indicate different recoveries of injected water calculated from Rhodamine WT and electrical conductivity data and different behaviours of the two tested aquifers. Numerical simulation of tracer and hydraulic data using the SWIFT III finite difference model support a complex conceptual hydrogeological model with solute transport in a multi-layered, dual porosity aquifer. Regional models have examined the feasibility of large scale and long term artificial recharge.

INTRODUCTION

In northern Qatar, groundwater is abstracted for rural water supply and agricultural use from two fissured carbonate aquifers; the Rus and the underlying Umm er Radhuma (UER). For over 20 years, abstraction has exceeded that naturally replenished by rainfall and as a result groundwater levels are in decline and saline intrusion is occurring near the coast. The State of Qatar Ministry of Municipal Affairs and Agriculture is considering artificially recharging the two aquifers to ameliorate this situation.

In 1992 Entec Hydrotechnica was commissioned to undertake a two year feasibility study of artificial recharge in northern Qatar. Work was undertaken in collaboration with the Department of Agriculture and Water Resources (DAWR) of the Ministry of Municipal Affairs and Agriculture, State of Qatar, with United Nations co-ordination and overview. This investigation comprised collation of existing data, a detailed programme of field testing, and computer modelling to simulate the field test results and predict the effects of a large scale artificial recharge scheme.

As part of the field testing, injection and re-abstraction tests were carried out to determine travel times, dispersivity, effective porosity and recovery efficiency. At many of the test sites, the only water available for injection was groundwater of a similar

composition to that at the test site. In order to differentiate the injected and native groundwater on re-abstraction an artificial tracer was required to label the injected water. This paper discusses the selection and use of Rhodamine WT fluorescent dye as a tracer in this study.

SELECTION OF TRACER

A number of criteria were required for the tracer used in the tests.

Firstly, as the tracer was injected into a potable water resource, it had to be safe to use in concentrations high enough for accurate measurement. At low concentrations, Rhodamine WT is approved for use in potable water by the US Environmental Protection Agency and by the National Rivers Authority of England and Wales. However, there has been some suggestion that Rhodamine WT may react to produce diethylnitrosamine, a known carcinogen, in waters with high nitrite contents (Abidi, 1982) and may have undesirable by-products if injected into chlorinated water supplies (Aldous *et al.*, 1987). Neither high nitrite nor free chlorine were likely to be present in the groundwaters of northern Qatar.

Secondly, tracer/aquifer interaction such as adsorption had to be negligible. A major problem in the use of fluorescent dyes as groundwater tracers is the adsorption of the tracer onto the host rock or soil. In the past, laboratory and field tests have shown that Rhodamine WT is less susceptible to adsorption than many of the other commonly used dyes (Smart & Laidlaw 1977). However, more recent laboratory tests using granular and powdered materials such as soils have suggested that Rhodamine WT may be significantly adsorbed (Trudgill, 1987; Sabatini & Austin, 1991). Tracer adsorption increases with the ratio of rock surface area to water volume ratio and this ratio is high in soils, but small in highly fractured and fissured aquifer systems such as the Rus and UER aquifers. It was therefore considered that adsorption of Rhodamine WT would be negligible.

Thirdly, given proposed injection rates of up to 2500 m^3 day^{-1} for 14 days, the tracer had to be accurately quantifiable at very low concentrations and background concentrations had to be low to permit only small and cost effective quantities to be dosed to the injected water. Background fluorescence for Rhodamine WT is less than 0.2 μg l^{-1} and the detection limit is below 0.1 μg l^{-1}. Rhodamine WT costs about £30 sterling per kg and dosing at 50 μg l^{-1} would only cost about £1.50 per 1000 m^3 of injected water.

Finally, continuous and cost effective monitoring of the tracer concentration was required during injection and re-abstraction and this was achieved using a fluorometer with a data logger facility.

TEST DETAILS

Following construction of pumping wells and observation boreholes in the Rus and UER, each aquifer was tested by carrying out step discharge tests and seven day constant rate tests. During these tests borehole water levels and the water quality of the pumped discharge were monitored. Subsequent to these tests, a 14 day injection test, a 28 day re-abstraction test and a final step discharge test were carried out at each site. A break

of one day occurred between the injection and re-abstraction tests to permit installation of the submersible pump. The final step discharge test was carried out one day after the end of the re-abstraction test.

For the injection tests, the water to be injected was sourced from nearby well fields or purpose constructed supply wells and piped on site. Here, a steady dosing rate of Rhodamine WT concentrate was achieved using a LMI P155SM pump, although fluctuations in the flow rate of the supplied water led to small concentration variations in the injected water. Mixing of Rhodamine WT and the supplied water was aided by passage through a flow meter prior to injection at the well head.

For the re-abstraction and step discharge tests, water was pumped from the test borehole using a submersible pump and discharged over 800 m away from the test site. Flow rates were measured using a flow meter and a 90° V-notch weir.

Throughout the injection and re-abstraction tests, a bleed line was used to sample the water at the well head. Tracer concentrations were monitored every two seconds, then averaged and logged at 30 min intervals using the continuous flow cell facility of a Turner Designs 10-AU-005 Fluorometer fed by the bleed line. The automatic temperature compensation facility of the fluorometer was used to correct fluorescence for large diurnal fluctuations in temperature. Depth samples were collected from observation wells using a teflon 350 ml bailer during the injection and re-abstraction tests. These samples, together with samples of pumped discharge collected during the final step discharge test were analysed using the discrete sample facility of the fluorometer. Water quality was monitored using a Grant Instruments quality logger measuring temperature, pH, conductivity (EC), dissolved oxygen and turbidity at 30 min intervals.

RESULTS

Two examples of tracer concentrations in the pumped water during injection, re-abstraction and the final step discharge test are shown in Fig. 1.

Tracer recovery during re-abstraction tests

Between tests, there were differences in the rates of injection and re-abstraction, in the dosed levels of Rhodamine WT and in the EC of the injected and native water. Native water is defined as all water present in the aquifer which has not been artificially injected. To permit a direct comparison of results from all sites the percentage of injected water in the re-abstracted water has been calculated based on Rhodamine WT concentrations or EC and compared to the volume of re-abstracted water as a percentage of the total volume injected. To calculate the percentage of injected water in the re-abstracted water the following formulae have been employed:

$$\% \, Injected \, water \ = \ \frac{T_R - T_N}{T_I - T_N} \times 100\%$$

where subscripts R, I and N denote the tracer concentration (or EC), T, in the re-abstracted, injected and native waters respectively. For Rhodamine WT, where background levels in the native groundwater were close to zero, this equation may be re-written as:
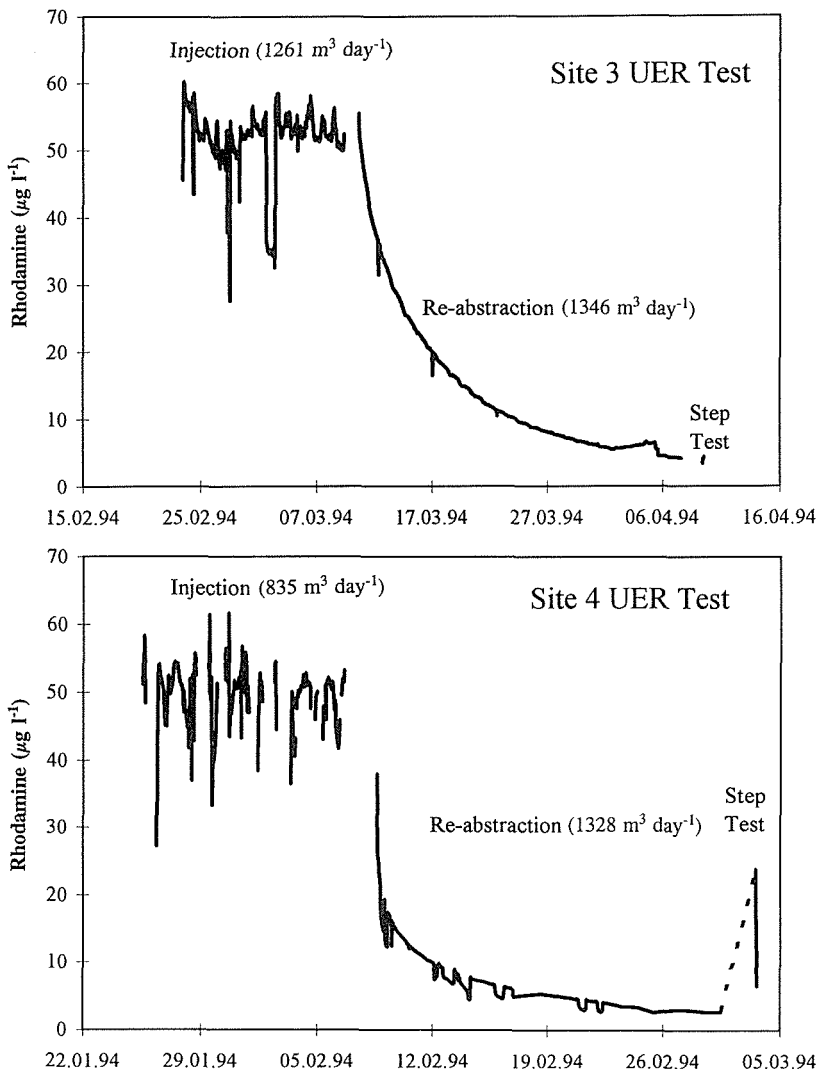
Fig. 1 Examples of Rhodamine WT concentrations during injection, re-abstraction and the final step discharge test. Injection and re-abstraction rates are noted.

$$\% \, Injected \, water \;=\; \frac{T_R}{T_I} \times 100\%$$

These results are presented in Fig. 2 for the Rus tests and in Fig. 3 for the UER tests and show that there are differences in the estimated recoveries for a given test calculated from the Rhodamine and EC data. These differences are most pronounced for the UER, particularly at Sites 2 and 4. Percentage recoveries of injected water after 100% of the volume injected had been re-abstracted and at the end of the test are summarized in Table 1.

Given that the two methods of calculation should produce the same result, it is important to consider what mechanism might explain the difference. For EC, the calcu-
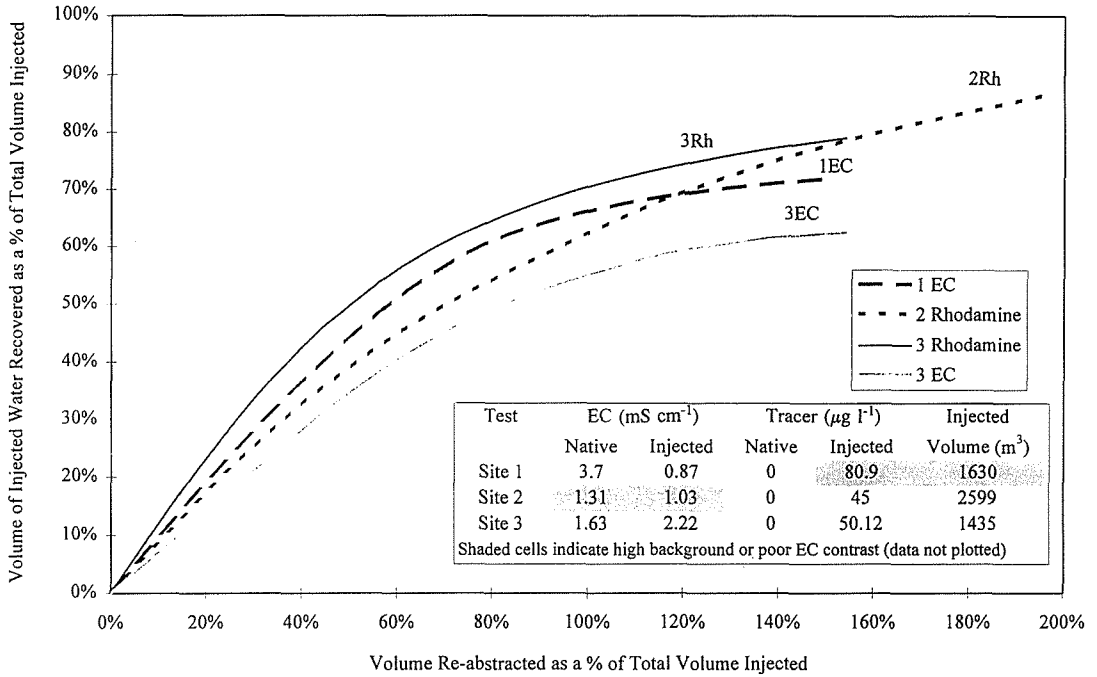
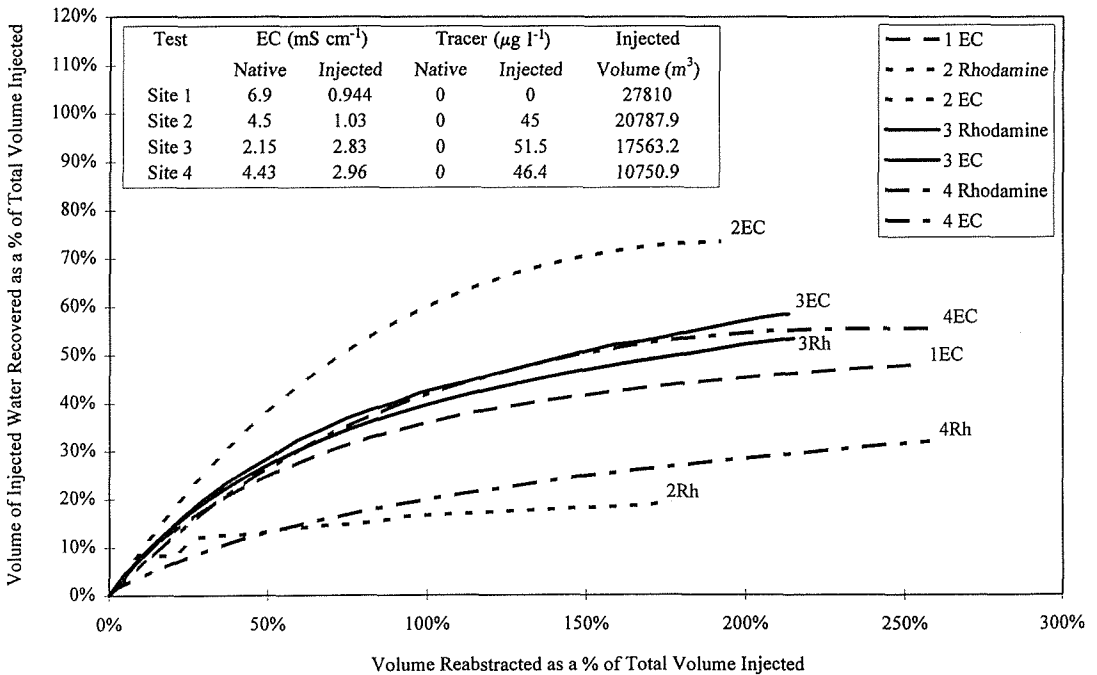**Fig. 2** Comparison of recovery of injected water for the Rus tests.

Fig. 3 Comparison of recovery of injected water for the UER tests.

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Table 1 Calculated percentage overall recovery of injected water from Rhodamine WT and EC data.

Site	Overall recovery efficiency[1]		Recovery at end of test[2]		
	Rhodamine	EC	Rhodamine	EC	Total[3]
Rus tests					
1	-	66	-	72	150
2	63	37	87	45	198
3	70	55	79	63	154
UER tests					
1	-	36	-	48	255
2	17	60	21	74	192
3	40	43	53	59	215
4	20	42	32	56	258

[1]Overall recovery efficiency is defined as that volume of injected water recovered when the volume of re-abstracted water is equal to that injected and expressed as a percentage of the volume injected.
[2]Recovery at end of test is defined as that volume of injected water recovered at the end of the test and expressed as a percentage of the volume injected.
[3]Total is the total volume reabstracted as a percentage of the volume injected.

lations of apparent recovery presented on Figs 2 and 3 use a native EC equal to that at the end of the constant rate test. Variations in the EC of the native groundwater during the re-abstraction test will clearly affect these estimates and it is known that, the EC of the pumped native water increased during the pre-injection step discharge and constant rate tests. At Site 2 the EC of the pumped native water increased from about 2500 to 4500 μS cm^{-1} and at Site 4 an increase from about 2600 to 4300 μS cm^{-1} was observed. Furthermore, during these tests the EC fell after short breaks in pumping and then rose again implying that this increase in EC with pumping is repeatable. A much smaller increase in EC of 1950 to 2150 μS cm^{-1} was seen during pumping at Site 3 and little change occurred following periods without abstraction. The large changes in EC with pumping cast some doubt on the validity of the recoveries calculated assuming a constant EC for the native water.

To examine the compatibility of the Rhodamine and EC results during re-abstraction, it has been assumed that the percentages of injected water calculated from Rhodamine data are correct. The EC of the native UER groundwater has then been estimated using the formula:

$$EC_{Native} = \frac{(EC_{Re-abstracted} \times 100) - (EC_{Injected} \times \%_{Injected})}{(100 - \%_{Injected})}$$

where:

EC_{Native} = calculated EC of background groundwater at each time during re-abstraction;

$EC_{Re-abstracted}$ = measured EC of pumped groundwater at each time during re-abstraction;

$EC_{Injected}$ = measured EC of injected groundwater; and

$\%_{Injected}$ = percentage of injected water in re-abstracted water calculated from Rhodamine data.

Estimated native UER groundwater EC during re-abstraction calculated by this formula can be compared, at times of equal cumulative abstraction, to those observed during the initial step discharge and constant rate test. Fig. 4 shows that there is good agreement between the measured and predicted variation in EC with pumping for Sites 3 and 4. That is, the EC of native UER groundwater appears to have increased the same way in both constant rate tests and re-abstraction tests. This suggests that the disparities in estimated recovery rates calculated from Rhodamine and EC data shown on Figs 2 and 3 are largely due to the changing EC of native groundwater not allowed for in the calculations. At Site 2, there is still some difference between measured and predicted EC. This may be due to a pumping rate control on upward flow of more saline water at this site (the constant rate discharge rate was significantly greater than that used during the injection/re-abstraction test) affecting the native EC or, less probably, some extraneous effect on the Rhodamine data. If the EC of the native groundwater had increased in the same way as in the constant rate tests, then the change in EC of the total volume re-abstracted indicates a recovery rate between that of Sites 3 and 4.

It should be noted that at Site 1 where no tracer data are available the EC of the pumped water increased during the step discharge and constant rate test. Thus, although there was a large contrast in EC between the injected water and native groundwater, an increase in the EC of the native groundwater during re-abstraction is probable: this implies that the recovery estimates for this site will be slightly high.

The above discussion leads to the conclusion that the recovery characteristics calculated from Rhodamine data are more reliable than those calculated from EC data.
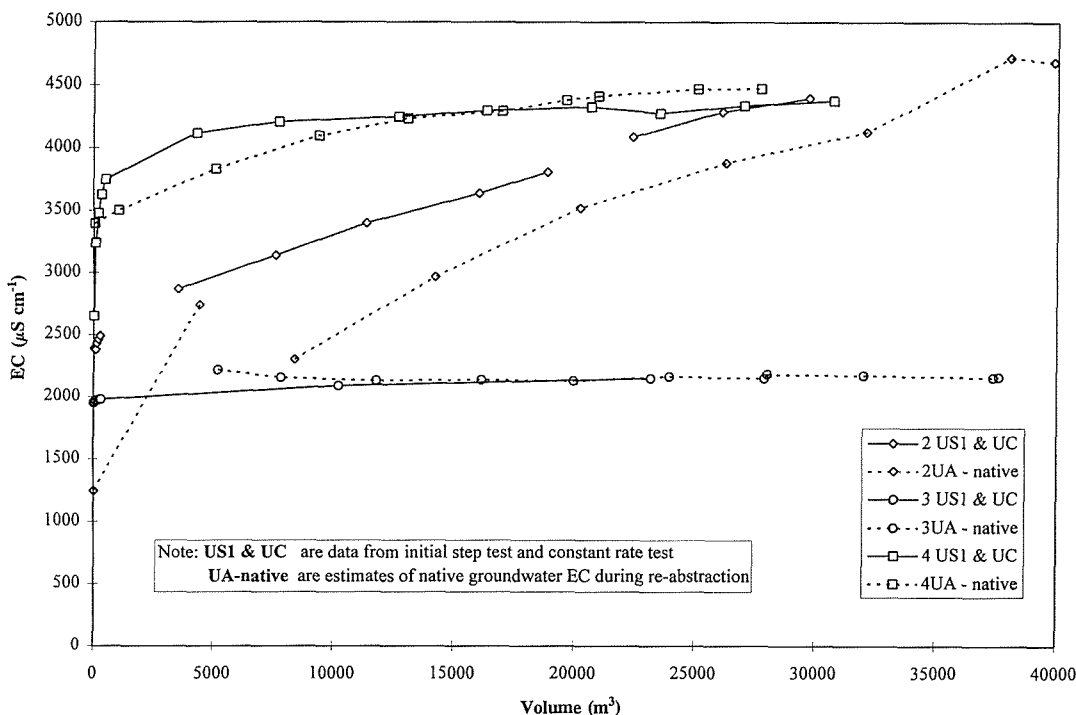

Fig. 4 Comparison of changes in electrical conductivity (EC) with pumping for UER constant rate tests and native groundwater component during UER re-abstraction tests.

Final step discharge test

At Sites 3 and 4 Rhodamine concentrations were measured in discrete samples of pumped discharge during the final step discharge test. These tests were carried out one day after the end of the re-abstraction test (see Fig. 1). At Site 3, Rhodamine levels were similar in the step discharge test to those at the end of re-abstraction. However, at Site 4, Rhodamine levels were much higher during the step discharge test than during the last 14 days of the re-abstraction test. This indicates that up to 50% of injection water was available to the pumped well, despite the continued decrease in the proportion of injected water during the re-abstraction test. This in turn may suggest that the hydrogeological system exhibits dual porosity behaviour with rapid flushing of injected water from the fissures and slower release from the matrix.

Tracer breakthrough at observation wells

There was a marked difference in Rhodamine breakthrough in the observation wells between the Rus and UER. This was most apparent at Site 2, where, for the Rus, Rhodamine concentrations increased rapidly and uniformly with direction and depth to 100% of the injected concentration, whereas for the UER, less than 1.5% breakthrough was observed erratically and with significant depth variations (see Fig. 5). The observation borehole data indicate that in the Rus at Site 2, flow is distributed evenly through the aquifer thickness and borehole length. Conversely, the majority of the flow in the UER at this site is probably by a few discrete fissures which influence only a small part of the observation borehole length; a likely feature of a dual porosity aquifer.

MODELLING

The analysis of data collected from the four sites indicated that the hydrogeological behaviour of the groundwater system was highly complex with solute transport in a multi-layered, dual porosity aquifer. Available analytical solutions were inadequate to allow validation of the conceptual model developed and it was therefore necessary to apply numerical techniques to model the injection/re-abstraction tests at each site. Many of the simpler solute transport models available were also inadequate, but the SWIFT III finite difference code (Reeves *et al.*, 1986), proved suitable. Radial coordinates were adopted to allow incorporation of geological changes with depth and had the added benefit of faster computational time.

   Model input parameters were adjusted until agreement was achieved between measured results and model output. In this way the SWIFT site models were used to refine estimates of the hydraulic and dispersive characteristics of the aquifers. As noted above, the natural variation in EC of groundwater at most of the sites complicated the analysis of recovery using EC data. As a result, the model output of most interest was the comparison of simulated and measured Rhodamine concentrations during re-abstraction.

   Figure 6 presents best fit simulated and measured Rhodamine levels for the Rus at Site 3. There is a good fit for the Rhodamine concentration in both the pumped discharge
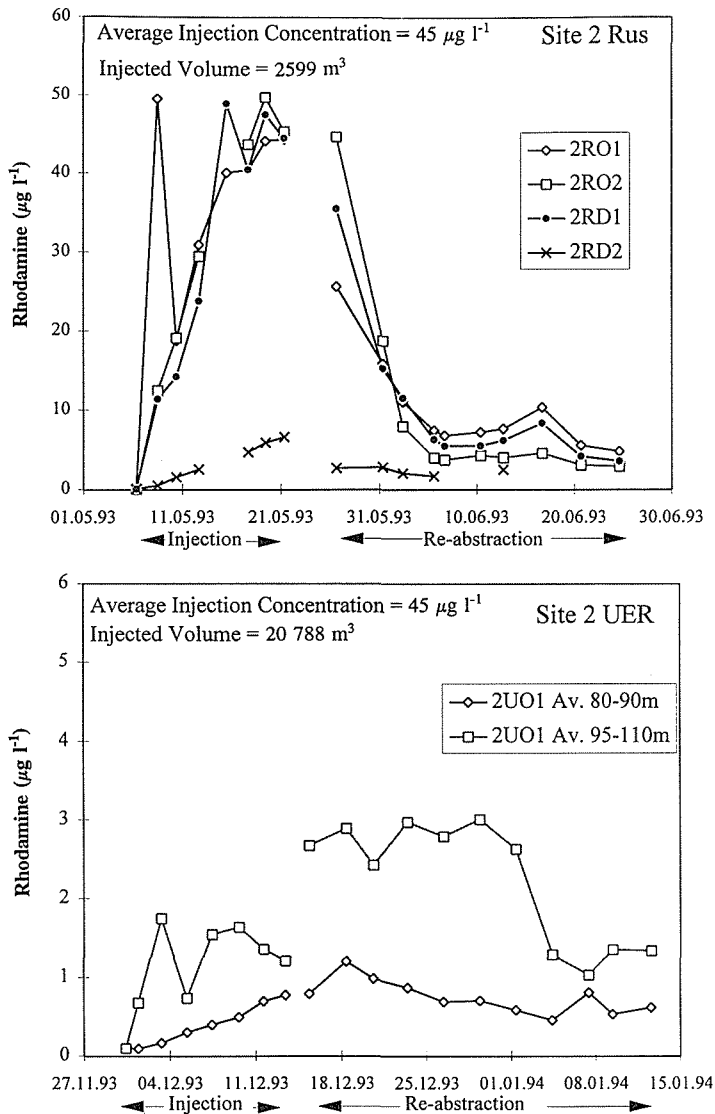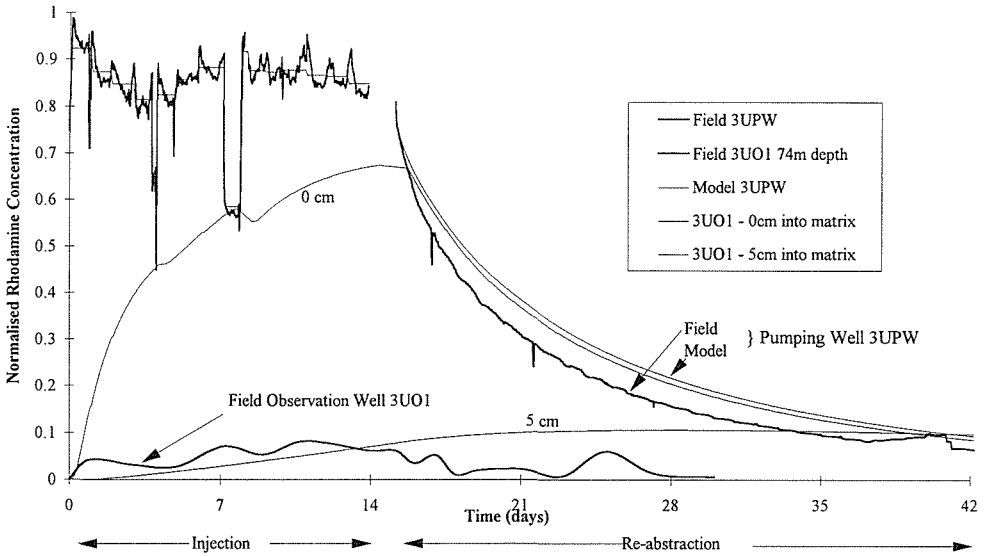
Fig. 5 Examples of Rhodamine WT concentrations in observation wells during injection and re-abstraction for the Rus and UER tests at Site 2.

and observation wells. For the UER at this site (Fig. 7), there is a good fit for the pumped discharge, but a relatively poor fit for the observation well data. However, it is interesting to note that the levels of Rhodamine detected in the observation wells during the UER injection test are between those simulated for the fractures and those for the matrix of the dual porosity system.

Effective porosities and dispersivities determined by simulating the Rhodamine concentrations in the site models were incorporated into regional models. The regional models were then used to examine the feasibility of a number of large scale and longer duration injection (artificial recharge) and re-abstraction scenarios with different well
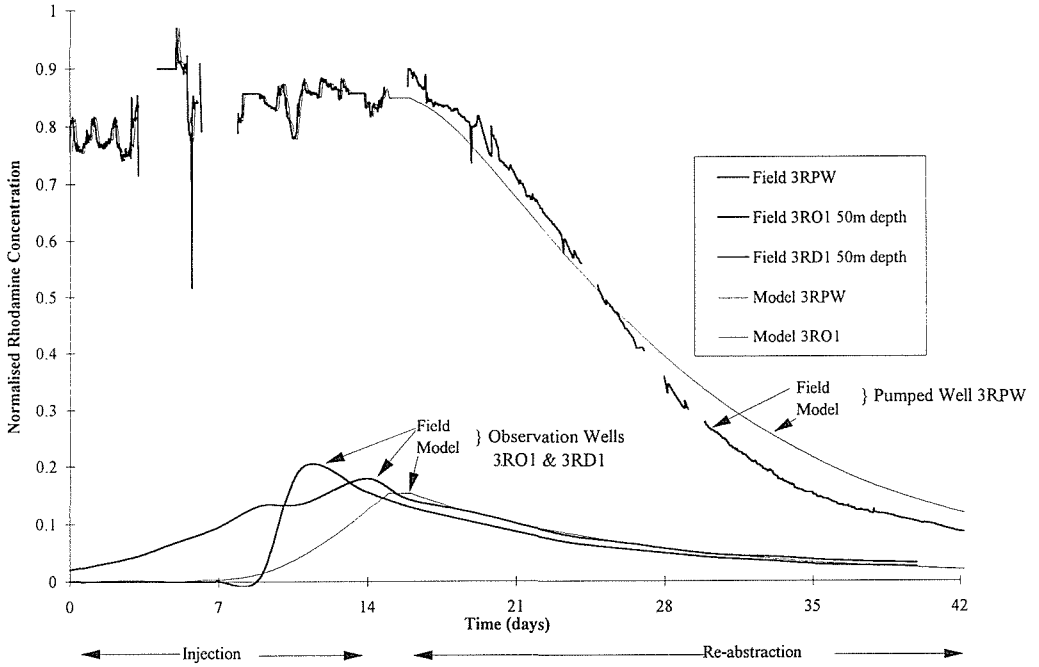
Fig. 6 Comparison of field and modelled Rhodamine WT concentrations for the Rus injection and re-abstraction tests at Site 3. Observation wells 3RD1 and 3RO1 are 10 m from the pump well.

Fig. 7 Comparison of field and modelled Rhodamine WT concentrations for the UER injection and re-abstraction tests at Site 3. Note that a dual porosity configuration is used and that the concentrations of Rhodamine WT approximate to the modelled concentrations 5-10 cm into the matrix blocks.
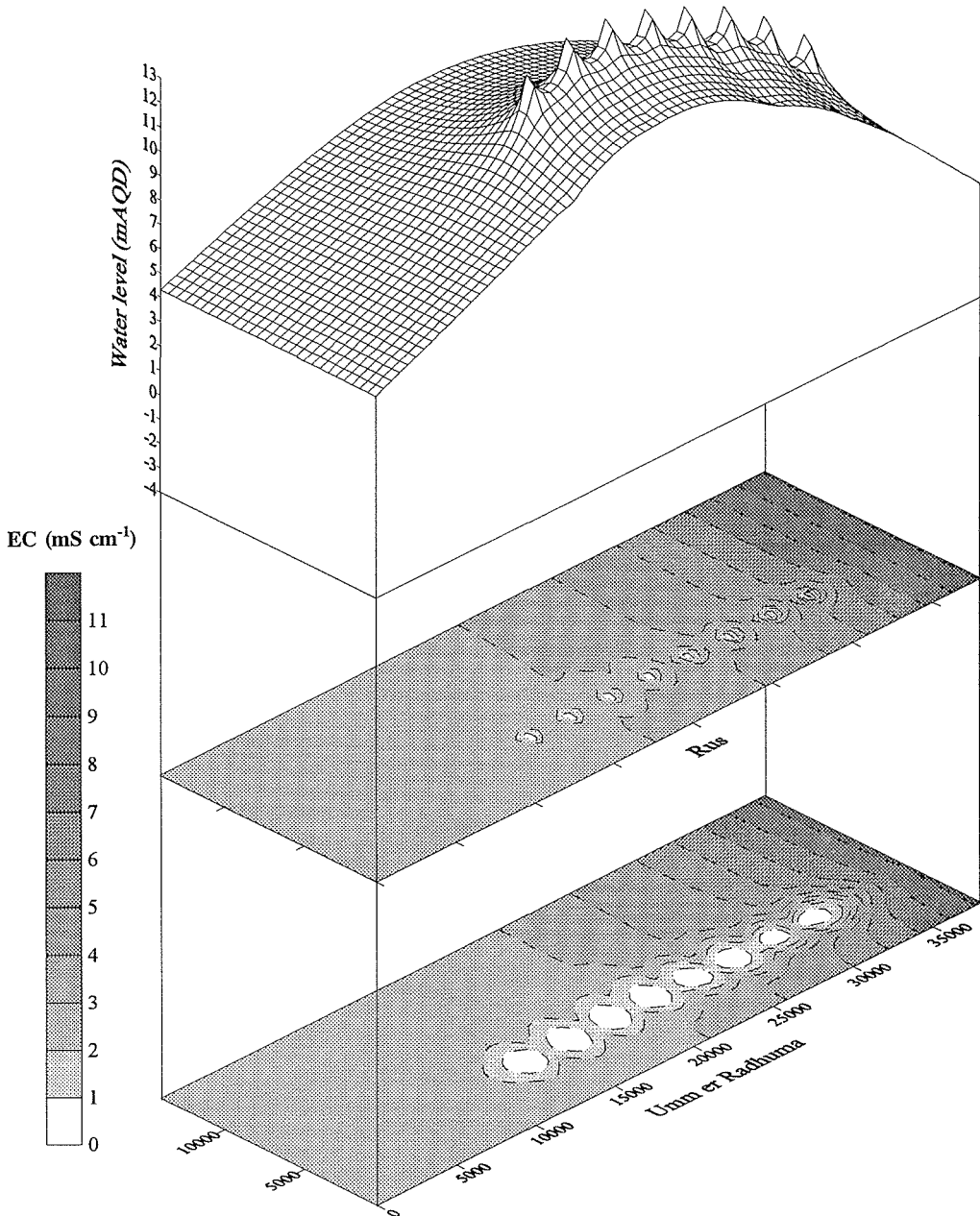
Fig. 8 Example of output from a large scale model. The grid is 15 km by 40 km and changes are shown in water level and electrical conductivity (EC) resulting from 10 years continuous injection at eight well fields. Note EC gradient from west to east simulating the natural deterioration in water quality towards the coast. Tracers were used to determine dispersivity and effective porosity which were then incorporated into large scale models to test the feasibility of artificial recharge.

field configurations. An example of the model output is presented in Fig. 8.

In summary, Rhodamine tracer has been used successfully to quantify the effective porosity and dispersivity of the two main aquifers in Qatar. Without this information, the likely recovery efficiencies of any artificial recharge scheme would not have been adequately assessed. EC data could not have been used to provide this information and the Rhodamine results have also highlighted dual porosity behaviour in one of the tested aquifers.

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