Technical Memorandum 15

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A study of the Magela Creek system, March 1978

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ABSTRACT

Smith, D.I., Young, P.C. and Goldberg, R.J. (1985). Use of fluorometric dye tracing to simulate dispersion of discharge from a mine site. A study of the Magela Creek system, March, 1978. Technical Memorandum 15, Supervising Scientist for the Alligator Rivers Region.

The applicability of fluorometric dye tracing techniques to simulate the likely downstream dispersion of discharge from the Ranger mine site was investigated using Rhodamine WT as the tracer.

In the upper part of the system mixing was rapid and the velocity of the dye pulse, calculated from the centroid of the dye mass, was close to 1 km per hour. In the lower section of the Magela Creek system vertical and horizontal mixing was poor and velocities were much lower: the first arrival of the dye at a site 20 km downstream of the injection point was some 80 hours after injection.

It is concluded that fluorometric dye tracing is a viable method for obtaining information on the pattern of mixing and the speed of flow in systems of this kind. The variations of velocity in relation to discharge are such that, for management purposes, it is recommended that further dye traces are undertaken. These should be chosen to correspond to both high and low natural discharges in the Magela Creek system.

Rhodamine WT was found to be a conservative tracer, at least over a period of 24 h.

A summary of a similar experiment undertaken in February 1979 is given.

1 INTRODUCTION

Dye tracers have been used throughout this century to provide visual information on a range of hydrological problems. However, it is only since the early 1960's that improvements in dye technology and, more importantly, the development of sensitive fluorometers for field use have enabled dyes to be used for detailed field investigation with the possibility of quantitative application.

The fluorescent dye Rhodamine WT[1] was developed for the US Geological Survey (Water Supply Division) specifically to meet the needs of such hydrological applications. Tracer experiments using Rhodamine WT dye have been conducted in a wide variety of locations (Yotsukura et al. 1970; Smart & Smith 1976; Smith 1978) including river systems with a range of sediment and vegetation characteristics. These studies have indicated that Rhodamine WT has a low toxicity and a greater resistance to adsorption and photo-chemical decay over short term experiments than the majority of fluorescent dyes, and that background fluorescence in the appropriate wavebands is normally very small. Information on dye losses over longer periods is sparse. Smith (1978) suggested a loss of approximately 1% per day for experiments in wildlife ponds at Tidbinbilla, ACT; Smith and Warner (1979) estimated a rate of some 3% per day for estuarine sections of the Georges River in Sydney. Estimates of dye decay from other hydrological studies in Australia suggest a rate of between 1% and 3% per day (Smith et al. 1979). The extent to which Rhodamine WT can be considered a conservative tracer in the Magela Creek system is discussed.

The field fluorometers used to detect the dye in natural waters are easy to use, can be adapted for *in situ* field use, have a lower limit of detection of about 0.05 µg/L and are relatively inexpensive. Comprehensive accounts of instrument design and overall methodology are given in Wilson (1968) and Smart and Laidlaw (1977).

This report describes dye tracing work undertaken during March 1978 and also gives a summary (Appendix) of a similar experiment undertaken in February 1979 (Smith et al. 1979). The aims of the dispersion study were:

(a) to investigate the applicability of fluorometric dye tracing techniques to study dispersion in the Magela Creek system;

(b) to gain information on the overall pattern of dispersion of an instantaneous dye input, injected close to one of the projected outfall sites of the Ranger operation. The dye was used to simulate the dispersion of the solutes that would be included in the effluent from the Ranger operation.

(c) to investigate the nature of the dispersion in the stream channel section of the Magela Creek system, to see if the tracer would mix quickly across the various channels between the input site and the upstream end of Mudginberri Billabong;

(d) to evaluate mixing characteristics for a cross-section of Mudginberri Billabong;

(e) to determine the speed of flow in various sections of the system;

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[1] The sole manufacturer is now Crompton and Knowles Corporation, USA. The Australian agents are Orthochemicals of Melbourne.

(f) to consider the pattern and rate of dispersion, horizontally and vertically, in the system;

(g) to evaluate the persistence of the dye: for how long could it be detected and for what distance?

(h) to conduct a field comparison of the concentrations of Rhodamine WT with those of tritium, which is assumed to be a fully conservative tracer.

The data collected in these studies was used to develop hydrological and water quality models of the Magela Creek system. The use of these data for modelling is reviewed by Goldberg (1978).

2 METHODS

2.1 Dye dispersion

Fluorometers Two models of field fluorometer were used during the experiment, a Turner Model III and the more recent Turner Designs Model 10. With the latter, dye concentrations can be read directly from the instrument and the procedure for continuous monitoring of dye concentration is more satisfactory. The fluorometers were operated according to details given in the manufacturers' handbooks. The primary and secondary filter combinations were the same for both instruments: a primary filter which was a combination of 1-60 (Corning) and 61 (Wratten) and a secondary filter consisting of 4-97 (Corning) and 3-66 (Corning). The Turner Designs Model 10 has an additional reference filter, supplied by the manufacturer.

Background, or 'natural', fluorescence in the Rhodamine wavebands was 0.02 to 0.07 µg/L, in accord with the values obtained for natural waters elsewhere in Australia. These values are very small compared to the dye concentrations in most of the samples collected during the experiment. Attention is drawn in the text to the small number of cases where background fluorescence could cause difficulties in the interpretation of the results.

Dye injection Eighty litres of Rhodamine WT solution, corresponding to 16 kg dry weight of dye, was poured into the creek at the proposed outfall site for the Ranger operation. The dye was injected, at a single point, into the most western channel at the site (Fig. 1). Input took about ten minutes and can be considered as an instantaneous ('gulp') input. The dye was poured into the creek at approximately 0900 h on 13 March 1978.

Sampling methods Samples were collected at various sites downstream to assess the speed of flow and dispersion characteristics of the dye. The method of sampling was, to some extent, conditioned by the aims of the dispersion study and by available personnel and equipment. Three methods of sampling were used:

1) The majority of samples were collected, by hand from a small boat, directly into 30 ml scintillation phials. Most of these were collected from a depth of about 20 cm. Occasionally, manual samples were collected at greater depths using standard Nansen bottles.

2) Automatic samplers, which could collect a maximum of 26 samples at pre-set intervals, were used at some sites. The samplers were either positioned in anchored boats or attached to trees in flooded sections of the creek system. The depth of collection was again approximately

20 cm. When these instruments were visited, samples were transferred to glass scintillation phials.

3) On most occasions, including the air-boat traverses and the detailed observations at Site 3, the Turner Designs Model 10 fluorometer, in conjunction with a small boat-mounted peristaltic pump and generator, was set up for *in situ* sampling and direct measurement of dye concentration in both depth and surface samples. These *in situ* determinations of dye concentration gave a general picture of the spread of the dye pulse and a quick method of determining the position of the dye front so that manual sampling could be concentrated, on any given run, in the key areas at optimum times. Unless otherwise stated, the values for dye concentrations given in this report are for samples analysed either at the Research Institute's laboratory at Jabiru East or the Pancontinental laboratory at Ja Ja.

The samples were generally analysed within 24 h of collection. The fluorescence of Rhodamine WT varies with temperature, and samples were allowed to equilibrate before analysis. Laboratory temperatures were not constant, and if more detailed quantitative work is contemplated, temperature corrections should be applied. It should be noted that for the data presented in this report, the temperature effect may cause a difference, in extreme cases of up to 10%, between the concentrations determined in the laboratory and those obtained in the field.

Sampling sites The location of the sampling sites is given in Fig. 1 and details of the sampling strategy used at the various sites are given below.

Sites 1 and 2. The section of the Magela Creek upstream of Mudginberri (Fig. 1) is a complex system of anastomosing channels. It was not known whether a point release of dye, or effluent, at the proposed outfall site from the Ranger operations would quickly mix across all the channels or follow a more closely defined flow path. In the latter case, dilution would be more limited. To investigate the dispersion, samples were taken from three channels, designated West, East and Centre, at each of two sites (Sites 1 and 2, Fig. 1). It should be noted that the channel pattern is extremely complex and the West, Centre and East Channels distinguished in Figs 2 and 3 are not directly connected between sites. Similar dye concentrations and travel times in the three channels would indicate a high degree of mixing. Personnel located at Sites 1 and 2 collected samples, manually, from each channel at intervals of a few minutes. In addition, an automatic sampler, set up to take samples every hour, was installed at the West channel at Site 2. This extended information on the fall in dye concentration after the completion of the manual sampling.

Site 3 was located at the Manager's house at Mudginberri, where a rope traverse line across the billabong had been established by a team from the Australian Atomic Energy Commission (AAEC). Sampling points were marked along the traverse line by eleven equally spaced floats. Beyond the eastern end of the traverse, there was flowing water in a heavily wooded area. No samples were taken in this section of the creek, but observation established that the flow was limited compared to that in the open water. This site had previously been used as a gauging cross-section to measure stream discharge.

The aim was to collect samples during the passage of the dye pulse. Some sets of samples comprised only near surface samples, while others also included samples taken at 2 m, 4 m and close to the bottom of the channel.

Sites 4-16. The physical nature of the area limited the choice of sampling sites downstream of Site 3. At the northern end of Mudginberri Billabong the width of the flood plain increases and the flow is through a flooded forest of paperbarks. Access by boat is limited to a narrow, flagged navigable passage as far as Ja Ja Billabong. Where possible, this passage utilises the limited area of open water afforded by the billabongs shown in Fig. 1. A number of sampling sites were situated along the flagged passage, many of them in the areas of open water.

North of Ja Ja Billabong the density of trees in the flooded area is much lower, but the thick growth of aquatic vegetation makes the use of outboard motors impossible. Sampling was only possible by air boat.

Manual sampling was supplemented by automatic samplers at some of the sites. The number of such samplers was limited and they were progressively moved downstream during the course of the experiment.

Traverse lines 1-3. On the lower section of the system three traverse lines were established which, depending on the availability of air boats, were sampled once or twice per day. Samples were taken at a number of points spaced between the east and west banks of the flooded area. Again, the information was augmented by the use of automatic samplers. In this case the samplers were tied to trees, with the hoses immersed just below the surface.

2.2 Comparison of Rhodamine WT and tritium

Because of the peculiarities of the Magela Creek system, it was considered useful to check the conservativeness of Rhodamine WT under the conditions prevailing in the Magela Creek during the Wet season. This was done by comparing the results of a simultaneous release of tritium and Rhodamine WT. The assumption made was that losses of tritium by evapotranspiration effects would be negligible and that tritium could be considered conservative.

Midway through the release of dye, two curies of tritium were injected at the same site. Prior to the release of tritium, water samples to determine background counts had been taken at the injection point and at Mudginberri Billabong (Site 3). After the release, duplicates of water samples were taken for tritium analysis at all locations from Site 1 to Site 16.

Analysis was carried out at the Pancontinental laboratory at Ja Ja using a procedure recommended by the AAEC. As Rhodamine interferes with scintillation counting, each sample was distilled to dryness and a 10 ml aliquot of the distillate was mixed with 11 ml 'Instagel' scintillation solution. Tritium determinations were made with a Model 3255 Tri-carb Liquid Scintillation Spectrometer at 8°C; the counting time for each sample was 20 minutes, and counting efficiency was 18%.

3 RESULTS AND DISCUSSION

3.1 Dye Dispersion

The large number of figures and tables that accompany this report are presented to give as full a picture of the results as possible.

Sites 1 and 2 Samples were collected manually at these sites every few minutes. At both sites, the first appearance of the dye in each of the

channels, and the time to peak, are virtually identical (Figs 2 and 3). Time differences between the channels are of the order of a few minutes after a travel time from the injection point of three hours to Site 1 and five hours to Site 2. For both sites, the general form of the dye concentration curve is of the form found in simple, single channel rivers. For comparison, the dye concentration curve for a dye dilution experiment on the Murrumbidgee River near Canberra is illustrated in Fig. 4 (CRES 1978). At this stage of the experiment the dye was visible at Sites 1 and 2 and observations from a helicopter during the first few hours of the experiment confirmed that mixing across the channel complex was rapid and was complete by a distance of about 1 kilometre below the injection point.

The manual samples at Sites 1 and 2 were collected at a depth of about 20 cm. The stream velocity, about 30 cm/sec, was relatively high for natural streams and collection at a single depth is the normal procedure for dye dilution gauging under these circumstances. Thus it was assumed that at these sites the water was fully mixed. The internal consistency of the results supports this conclusion; however, results from sites downstream of Site 2, where depth samples were taken, showed that mixing was not complete, and any further experiments should include samples taken at depth to establish that mixing is indeed complete.

An automatic sampler on the West channel at Site 2 extended the observations on the recession limb of the dye concentration curve for approximately 20 hours after manual sampling ceased. At the end of 20 hours the dye concentration had fallen to 0.5 µg/L (Fig. 5).

Samples were also collected from a backwater area some 120 m east of the main channel complex at Site 1. The field workers involved considered that the water was stagnant, but the dye did in fact find its way into this backwater area. The observations were limited in number and the maximum dye concentration recorded was only 1.4 µg/L. These observations illustrate the ability of the dye method to detect low concentrations and its potential for application in areas where information on dye persistence may be of value, as in the Magela Creek system.

Tracer concentration can also be used to calculate river discharge. The tritium concentrations at Site 2 were used to calculate the river discharge at that point. The value obtained was 10.94 m^3/s; the details are given in section 3.2.

Site 3 Several hundred samples were collected at Site 3. Surface samples were taken from all stations on the traverse line on eighteen occasions between 1830 h 13 March and 1750 h 15 March (9 h 30 min and 56 h 50 min respectively after injection of the dye). On nine occasions, dye concentrations were also determined in depth samples.

Figure 6 shows the dye concentration versus time plots for surface samples from stations 0 to 10. The form of the dye pulse is similar for all the stations but the time of first arrival, time to peak and the peak dye concentrations show significant variations.

These differences are also obvious in Fig. 7, which shows dye concentration vs. station number for 13 sets of samples taken between 1830 h on 13 March and 1100 h on 15 March.

It should be noted that at stations 0, 1, 2 and 3, the first samples were taken after the initial dye arrival, but extrapolation of the data enables a good estimate to be made of the time of first arrival.

The traverses that include depth samples are shown separately (Figs

8-24), with contour plots of the dye concentration. In Figs 8-16 there are five classes of dye concentration and the classes are in equal increments of concentration, but the increments vary from plot to plot. This method of portrayal gives maximum visual impact. In Figs 17-24 the dye concentration classes are constant throughout, in order to present comparative information. The locations of sampling sites used in the individual traverses are shown on the contour plots. It should be noted that samples were not taken below a depth of 6 m although the stations at the centre of the traverse exceed this depth.

These figures clearly demonstrate that the dye initially arrived, in a concentrated form, at sites located on the western section of the traverse, and that subsequently the peak moved towards the east bank. This is particularly evident in Figs 10 and 11, which show that the dye peak moved across the traverse between 2040 h and 2230 h on 13 March.

Figs 8-16 confirm the observation that maximum concentrations are greater at the sites with an early dye arrival.

At any given station on the traverse the variation of dye concentration with depth does not present a consistent pattern over time. The results clearly show that mixing, both laterally and vertically, is poor at the upstream end of Mudginberri Billabong.

Site 4 This site was located at the downstream end of Mudginberri Billabong, close to the west bank. The initial samples were taken by hand and the remainder by an automatic sampler, set to sample every hour at a depth of about 30 cm. The shape of the dye concentration versus time curve (Fig. 25) has a regular form and the time of first arrival and time to peak concentration can be readily discerned. However, bearing in mind the results from the eleven stations along the traverse at Site 3, it should not be assumed that the values obtained at Site 4 would hold throughout a cross-section of the billabong.

Sites 5-16 The dye concentrations in samples collected manually at the surface from Sites 5-16 are shown in Figs 26-28. Figures 26 and 27 show the variation in dye concentration with time at the various sampling sites and Fig. 28 shows the variation in dye concentration with distance at different times and dates. In some cases the frequency of sampling was insufficient to draw detailed conclusions, but the presentation of the data in this form allows the majority of the observations to be displayed.

A number of factors should be remembered in any consideration of these graphs:

- The samples are surface samples collected from a depth of about 20 cm.
- The boat route used to collect these samples was determined by a narrow path through thick vegetation. Thus in some cases samples were collected from shallow water close to the east and west banks and in other cases, from the central portion of the deep and open water of the billabongs (Fig. 1).
- Not all of the sites were marked with buoys and the exact location of the sampling point could, in some cases, be within a range of up to 50 m. This is particularly the case for samples collected in the larger billabongs, e.g. Sites 10 and 11.

Automatic sampler data Samples were also collected by automatic sampler at a number of sites between 5 and 16. The results for Sites 11 and 16 are presented below.

Site 11. Figure 29(a) shows the dye concentrations in samples taken by an automatic sampler attached to the structure housing the water level recorder at GS 023. This gauging station is located at the edge of Island Billabong, close to Site 11 which was in the central, open water section of the billabong. The samples were collected at 2-hourly intervals between 1445 h on 15 March and 1045 h on 17 March (53 h 45 min and 97 h 45 min respectively after injection of the dye). The figure shows a consistent fall in dye concentration at that site after the passage of the dye peak. The first arrival of the dye at Site 11 had been established, using the continuous flow fluorometer, to be close to 1400 h on 14 March (29 h after injection of the dye).

Site 16. The dye concentrations in samples collected hourly between 1055 h on 19 March and 0840 h on 21 March, by an automatic sampler at Site 16, are given in Fig. 29(b). The two main features of this figure are:

- a pattern of minima and maxima, not shown by previously described sites, and
- possible superimposition of minor irregularities on this broad pattern.

It is difficult to suggest firm reasons for the major variations. It could be that the main dye peak had split into several distinct streams prior to its arrival at this site; or, as Site 16 (like its neighbouring sites) is located close to the edge of the main flooded area, that the various peaks represent some form of eddy.

High frequency sampling During the course of the sampling at Sites 5 and 16, it became apparent that local variations occurred in dye concentration both with time and with depth.

To further investigate variations over a short time interval, surface samples were collected manually at 2-minute intervals at Site 16. Fifteen samples were collected starting at 1705 h on 19 March (152 h 5 min after the dye injection), the results are shown in Fig. 30. These can be compared to results shown in Fig. 27, which shows the dye concentration in samples (both manual and automatic) taken at Site 16 between 1000 h 17 March and 0800 h 21 March (97 h and 193 h respectively after injection of the dye).

The dye concentrations at Site 16 for this first experiment varied from a minimum of 0.28 to a maximum of 0.45 µg/L. Interpretation of these results should, therefore, take into account the very low, near background, concentrations.

Temperature and dye concentration in surface and depth samples A second high frequency sampling was undertaken at Site 16 on 20 March. On this occasion, surface and depth (2 m) samples were collected at 2-minute intervals. The surface and depth samples are out of phase by one minute. The temperature of the samples was measured using a mercury in glass thermometer. The results are given in Figs 31(a) and 31(b). It can be seen that the surface and depth concentrations are very different: the mean for the surface is 0.61 µg/L while that for the depth samples is 0.16 µg/L, omitting the 0.59 µg/L value discussed below. The range of the surface samples is from 0.53 to 0.68 µg/L. Once again, it should be noted that concentrations are low.

There was a consistent difference in temperature of about 0.6°C between surface and depth. It is of interest to note that one of the depth values gave a dye concentration of 0.59 µg/L which is comparable to the

surface values, and that this depth sample has a temperature that corresponded to the surface range.

It is almost impossible to draw any conclusions from one sample but, if representative, it would suggest some form of convectional overturning of the water column.

Variation of concentration with depth Depth samples were collected routinely from a number of the sampling sites and Fig. 32 gives the results for three of these sites, Site 11 and Sites 13a and 13b (the latter two were located in open water close to the centre of Hidden Billabong). These results, and others not presented, suggest that the dye concentration tends to decline with depth, but that numerous exceptions occur.

Conclusions from measurements at Sites 5–16:

1) A broad dye pulse can be distinguished moving downstream through this part of the Magela Creek system (Figs 26–28).

2) In the section downstream of Site 14, the pattern becomes more confused and the dye distribution tends to become multimodal, see for example Fig. 30.

3) Downstream of Site 14 (where concentrations were quite low) the measured dye concentration in surface samples becomes more irregular on a short time scale (measured in minutes rather than hours). The vertical mixing also seems relatively poor, with a tendency for the surface layers to have a higher concentration of dye than those at depth.

4) At Sites 1 and 2 the dye is well mixed, but at all sites downstream of these both vertical and horizontal mixing is much less complete. This raises important questions for sampling design, especially if the aim is to establish the mixing pattern for effluent moving through the lower part of the system. For the downstream part of the system, in contrast to the river channels sampled at Sites 1 and 2, it is impossible to give specific advice on locations of single sites which could be used to give an overall impression of the dispersion of effluent through the system.

Traverse lines 1–3 The lower section of the Magela Creek system, downstream of Ja Ja Billabong, is relatively open (i.e. the density of trees projecting through the flood water is low) but the abundant growth of aquatic vegetation severely limits the use of small boats for sampling. On 18, 19 and 20 March an air boat was used to collect samples. Three traverses were made across this section of the system and each one was repeated on each of the three days. The location of the traverse lines is shown in Fig. 1.

Between ten and fifteen surface samples were collected on each air boat traverse. The results are given in Fig. 33. In this figure, individual sampling sites are presented as equi-spaced stations across each traverse line. However, there was not time to establish site markers and the spacing of the samples was gauged by eye; the errors involved are unlikely to affect the general pattern of the results.

Figure 33(a) shows that the dye had reached traverse line 1 by 1100 h on 18 March, and that the dye was divided into two main streams, with very little dye present in the central portions of the traverse. The dye concentration in samples taken at 1700 h on 20 March was higher, but the two broad peaks of concentration were still apparent.

The dye concentation in samples collected at 1100 h on 18 March on traverse line 2, (Fig. 33(b)), suggests that the dye front had reached some of the centre and east bank sites. The values for 1745 h on 19 March support this observation and, with the data for 1740 h 20 March, confirm the bifurcate nature of the dye stream observed on traverse line 1.

Figure 33(c) presents the data for traverse line 3. The dye front seems not to have reached this section by the time of the runs of 19 March and 20 March. However, it should be stressed that the detection of the first arrival of a diffuse dye front with concentration values so close to background values makes any interpretation tentative.

Some of these surface samples were taken where the water was relatively deep (4 or 5 m) and where there was only sparse growth of aquatic vegetation at the surface, others were from water of about 2 m depth but with prolific vegetation. There was no discernible variation in dye concentration between adjacent sites with these differing characteristics.

Automatic sampling on traverse line 2. An automatic sampler was positioned on traverse line 2; its approximate position is shown in Fig. 33(b). Figure 34 shows the dye concentration in samples collected hourly from 1800 h on 19 March until 1600 h on 20 March. These results confirm that the first arrival of the dye was prior to 19 March, and that the peak concentration had not yet arrived at traverse line 2 when collection of samples ceased. The quantity of dye used would be sufficient to obtain a significant pulse of dye concentration at traverse line 2.

The curve for dye concentration does show some irregularity but certainly less than that observed from the automatic sampler observations at Site 16.

Depth samples. Only a limited number of depth samples were collected from sites on traverse lines 1-3. Generally, vertical mixing was relatively poor and broadly comparable with the results illustrated in Fig. 32. For example, at the site of automatic sampler on traverse line 2, the dye concentrations in samples taken at a depth of 2 m (close to the bottom) were less than half those in surface samples. Only occasional measurements were made on water temperature and it was found that surface temperatures were frequently 3-5°C above those at depths of one or two metres. The prolific weed growth in the lower section of the Magela system may also have had important effects on the vertical mixing of the dye.

Samples collected from Jabiluka Billabong on 20, 30 and 31 March The CRES field sampling ended on 21 March, but arrangements had been made for a limited number of samples to be collected by Mr R. Rous of the Water Resources Branch. These were collected from three sites on a traverse through Jabiluka Billabong, which is some 2 km downstream of traverse line 3 (Fig. 1), i.e. about 27 km from the original injection point. The samples were sent to Canberra for analysis and the results are given in Table 1.

Direct comparison of these values with those obtained for samples analysed in Jabiru within 24 h of collection, is dangerous owing to problems of dye decay and to calibration problems between different fluorometers. However, some useful comments can be made from the values obtained. The increase in dye concentration between samples collected on 20 March and those collected on 30/31 March is considered to be significant, as the dye reached Jabiluka Billabong at concentration levels that were still usable for dispersion studies. The time of arrival at this

site cannot be determined from the data. There is an indication that the dye was more concentrated away from the open water of the billabong, but the dye peak could have passed through the open water section prior to 30 March.

Conclusions for the samples from the lower section of the Magela Creek system:

1) Under the discharge conditions prevailing at the time of the experiment, the quantity of dye injected was sufficient for its dispersion to be studied for at least 25 km below the injection point.

2) The dye concentrations in samples taken on the traverse lines suggests that lateral mixing across the flooded section of the creek was not very good. The limited evidence suggests that vertical mixing was also relatively poor.

3) The air boat provides an excellent method of collecting samples and it can also be used for the collection of continuous flow fluorometric data.

Time of travel and velocity Times of travel and velocities based on them are given in Table 2. These are sub-divided into data for the first arrival of the dye at a given site and the time to attain the centroid of the dye mass. It is assumed that there were no changes in the discharge during time necessary for the dye pulse to pass an individual site.

Table 2 lists only those sites for which precise time information is available. For Site 3, the traverse across Mudginberri Billabong, data is given for Stations 0 and 10, which were the stations with the first and last dye arrival at this site.

First arrival of dye. The time of travel from the injection point to Site 4, a distance of 12.5 km, gives a mean velocity of 1.25 km/hr. There are only small variations for intermediate velocities upstream of this point and 1.3 km/hr can be taken as the approximate velocity throughout the upper section of Magela Creek system, at the discharge conditions prevailing at the time of the experiment. The discharge was approximately 11 m^3/s at Site 2 (see Section 3.2). The velocity shows a marked decrease in the lower sections of the system, e.g. from Site 11 to traverse line 2 the velocity is close to 0.06 km/h (0.017 cm/s).

Arrival of centroid of dye concentration. The times and velocities for the centroid of dye concentration are also given in Table 2. Generalisation is difficult but it should be noted that for Station 10, on the traverse at Site 3, the velocity was considerably lower than for the other stations. There are insufficient data for sites downstream of Site 4 to calculate velocities from centroid time, but the differences in velocity calculated from first dye arrival and from the centroid will continue to increase. This is a basic feature of channel flow dispersion.

3.2 Comparison of Rhodamine WT and tritium

Background samples Tritium analysis was repeated 23 times on the background sample from the injection point and 15 times on the background sample from Mudginberri Billabong. The results are given in Table 3.

There was no significant difference in tritium levels between these two sites, and a background tritium level of 104 counts/20 min (SD = 18 counts/20 min) was obtained by averaging the results of the total 38 analyses.

Table 1. Dye concentrations (µg/L) in Jabiluka Billabong

Site	Date		
	20 March	30 March	31 March
Open water	0.05	0.12	0.11
Centre of traverse	0.09	0.14	0.14
West side of traverse	0.06	0.22	0.17

Table 2. Velocities calculated from first arrival and centroid times

These figures are based upon estimates of arrival times which are uncertain for various reasons. Sufficient information was not available, however, to specify the resulting uncertainty in the velocity estimates. Asterisk indicates that data were inadequate for calculation.

	Site						
	1	2	3(0)[a]	3(10)[b]	4	11	14
Distance from injection point (km)	3.8	7.1	11.5	11.5	12.5	17.7	19.4
Time to first arrival (h)	3.0	5.0	8.5	10.0	10.0	31.0	80.0
Mean velocity calculated from first arrival time (km/h)	1.26	1.42	1.35	1.15	1.25	0.57	0.28
Time to centroid dye concentration (h)	4.4	6.7	14.3	20.4	17.3	*	*
Mean velocity calculated from centroid time (km/h)	0.86	1.06	0.80	0.56	0.72	*	*

[a]Site 3, Station 0
[b]Site 3, Station 10

Other velocities, based on first arrival time

Site 4 to Site 11	0.25 km/hr
Site 11 to Site 14	0.035 km/hr
Traverse line 1 to traverse line 2	0.06 km/hr

Samples taken after injection Eighty-one samples were analysed for tritium and concentrations in μCi/L were calculated from the net tritium counts (sample count minus average background count).

Of the 81 samples, only 29 had tritium concentrations more than 3 standard deviations above the mean of the background tritium concentration (i.e. greater than 158 counts/20 min). On the advice of the AAEC, only those results with tritium levels in this range were considered significant. With this criterion, no samples collected after 0555 h on 14 March (21 h after injection) from Site 4 had a tritium level significantly above background.

Calculation of dye loss There are two ways in which a measure of the conservativeness of Rhodamine WT can be obtained from the data. The first is to compare the changes in the ratio of tritium to dye concentration (T/D) over time, assuming that tritium is conservative. Any increase in this ratio with time would provide a measure of dye loss. The T/D ratios for the 29 samples which had significant tritium concentrations are listed in Table 4. The second approach is to calculate the mass budget for the dye from concentration versus time curves at various sites along the river system.

Tritium/dye ratios. To determine if there was any significant change in the T/D ratio over time, a linear regression of T/D ratio against time after injection was calculated using the values listed in Table 4, together with the initial tritium/dye ratio of 12.5×10^{-5} Ci/g at the injection point. (Note: the T/D ratio of 17.3×10^{-5} Ci/g at 17 hours was considered an outlier and not included in the regression analysis.)

The resulting regression equation was:

$$y = 13.04 + 0.06x$$

where y = tritium/dye ratio (Ci/g x 10^{-5}) and x = time (h)

For this relationship, the coefficient of x, 0.06, is not significantly different from zero at the 5% level. This indicates that over the 21 h period for which reliable tritium results were available, and under the particular conditions which existed in the Magela system from the injection point to Site 4, the dye could be considered conservative.

Dye budget. It is of interest to compare the result of the analysis of the T/D ratios with that obtained by calculation of the mass budget for the dye. If river discharge is constant during the sampling period and the dye concentration is constant at all points of the sampling cross-section, the mass of dye is given by:

$$M = Q \int (C_s - C_o)\, dt \qquad (1)$$

where M = mass of dry weight dye
Q = discharge
C_s = dye concentration in sample
C_o = background dye concentration

Although extensive sampling was carried out at Site 1 (Fig. 2), no samples were collected after 1345 h on 13 March, and so the tail of the concentration curve is not defined well enough to allow calculation of $\int (C_s - C_o)\, dt$ (the area under the concentration curve).

The data for Site 3 showed extreme variation in dye concentration over the cross-section and are not suitable for calculating a dye budget.

Table 3. Background tritium analysis

Site	No. of analyses	Range counts/20 min	Average counts/20 min	SD counts/20 min
Injection point	23	82-146	104	19
Mudginberri Billabong	15	75-128	104	17
Combined	38	75-146	104	18

Table 4. Tritium to dye ratios for different sites and times

Site	Time (h after injection)	Tritium/dye ratio Ci/g x 10^{-5}
1	3.3	12.0
1	3.8	13.9
1	4.8	14.0
2	5.3	13.8; 12.4; 13.7
2	5.8	12.5; 13.9; 13.0
2	6.4	15.3; 15.6; 12.5
2	6.9	13.1; 13.0; 12.5
2	7	13.4
2	8	14.6
2	9	13.0
2	10	13.7
2	11	15.4
4	13	12.6
4	14	13.6
4	15	12.6
4	16	13.7
4	17	17.3
4	18	14.2
4	19	14.0
4	20	14.6
4	21	14.8

Data at other sites further downstream also showed poor mixing characteristics.

As a result, only Site 2 has sufficient data and uniform enough dye concentration on the cross-section (Fig. 5) to enable the dye budget to be calculated. The gauge height at gauging station GS 009 (Site 1) was constant at 2.28 m during the sampling period (1030 h - 1345 h 13 March), and so the condition of constant discharge, a requirement for dye budget calculations, is satisfied.

The dye input was 80 litres of Rhodamine WT as supplied by the manufacturers, and this is the equivalent of 16 kg dry weight of dye.

A calculation based on the area under the tritium concentration curve for Site 2 (Fig. 35) gives a discharge at that site of 10.94 m^3/s. Using this discharge figure in Equation 1, the dye recovered at Site 2 was 15.29 kg. This appears to indicate a dye loss of 0.71 kg or 4.4% over some eleven hours. However, the level of noise on the data, together with the imperfect assumption of constant concentration over the sampling cross-section, could produce errors of at least ± 5% in the dye budget calculation, and so this apparent dye loss cannot be considered significant.

Final comments These results agree with other dye tracing studies which indicate that no significant loss of Rhodamine WT occurs over a 24 h period. Considerably more than 2 Ci of tritium would need to be injected if a sensible comparison were to be made between dye and tritium quantities over periods greater than 24 hours.

The use of tritium to determine dye loss in a tracer study is not necessary if the discharge during the sampling period is constant. Dye loss under constant discharge conditions can be determined equally well by the dye budgeting method, provided an independent estimate of discharge is available. However, the nature of the section of Magela Creek under consideration is not ideal for determinations of discharge based on present metering techniques.

If, however, discharge varies during the sampling period, and the temporal variation of the discharge is unknown, dye budgeting is not appropriate, and a simultaneous tritium and dye release would provide a useful method of assessing dye loss under these conditions.

We conclude that Rhodamine WT is conservative over approximately 24 hours, the period for which reliable tritium samples were obtained. It is likely that the dye is conservative for a much longer period, and any further evaluation should use a much larger input of tritium.

4 SUMMARY

Applicability of fluorometric tracing techniques It is clear that fluorometric dye tracing techniques can be successfully applied to the waters of the Magela Creek system. It is not possible to give a detailed assessment of the decay rate of Rhodamine WT in the Magela Creek system but, qualitatively, there is no reason to suspect that it is greater than in other regions. Certainly for the limited period during which a direct comparison with tritium was possible (some 24 h), the dye can be regarded as conservative.

Information on dispersion It is helpful to summarise the salient features of different sections of the system.

The upper system extends from the input site to immediately upstream of Mudginberri Billabong. This section is a fast-flowing series of anastomosing channels. The mixing of the dye from an instantaneous point injection is rapid, both laterally and vertically. The upper system thus has similar dispersion characteritics to a simple, single channel river.

Mudginberri Billabong to Site 11 represents a category intermediate between the fast-flowing upper section and the slower moving waters of the lower section (see below). The velocity is initially rapid, but both lateral and vertical mixing are less complete than in the upstream channel section.

Conclusions about dispersion in this section of the system rely heavily on the detailed information from Site 3. This site showed very much poorer mixing than Sites 1 or 2, but this could in part be due to the location of Site 3, close to the point where the river water first encounters the deeper waters of the billabong. It could be argued that Site 3 is not particularly representative of the middle sections of the system, and it is recommended that in any future tracer studies the traverse be situated further downstream, i.e. closer to Site 4 (Fig. 1).

The lower section of Magela Creek is from Site 11 to traverse line 2. The velocity of flow is very much reduced and mixing, both vertically and laterally, is much poorer than at the upstream sites. In general, dye concentrations decline with depth in any individual profile and the concentration values in the lower portions of a profile are frequently only half of those at the surface.

Lateral mixing is poor and the information from Site 16, for example, exhibits a multimodal distribution of dye concentration against time (Fig. 29b). The dye concentrations in surface samples taken across the flooded section at traverse lines 1 and 2 show considerable lateral variations. Superimposed upon these major lateral and vertical variations are quite marked variations in samples collected at short time intervals. The reasons for both major and minor variations are not fully clear but may, in part, be due to factors such as the marked temperature stratification in the water column (which is of greater significance when the flow rates are small) and differences in the density and form of aquatic vegetation.

Hydrological and water quality modelling Initial analysis of the data has yielded promising results; Fig. 36, for example, shows a comparison of model output and the observed data for the concentration of the dye at Site 2. This modelling work is being carried out in parallel with initial modelling of rainfall/flow data in the Magela Creek area as exemplified in Fig. 37, which compares modelled flow with measured flow at gauging station GS 019. The model is based on measured flow GS 017.

5 ACKNOWLEDGMENTS

The Magela Creek dye tracer experiment was very much a team effort. We would like to record our thanks to the many individuals and institutions who helped us both in Darwin and in the field. Particularly, we would like to thank Des Davy and Neil Conway of the AAEC for their help in planning the exercise. Neil Conway also took a major part in the field work and we would like to thank him for his tireless effort on our behalf. Tim Walker, of the University of Tasmania, while not an official member of the CRES team, worked with us throughout. John Gilmour and Chris Wood of the Water Resources Branch gave generously of their time, particularly in obtaining

the wide range of equipment essential to the study. Without the help of Rob Rous of the Water Resources Board, we would have been unable to collect samples in the air-boat. Dr Geoff Pickup of the North Australian Research Unit of the Australian National University kindly agreed to help and was a valuable member of the team, although in no way funded by CRES or the Office of the Supervising Scientist.

All employees of Ranger and Pancontinental with whom we came in contact assisted in every way possible and helped make the study a success.

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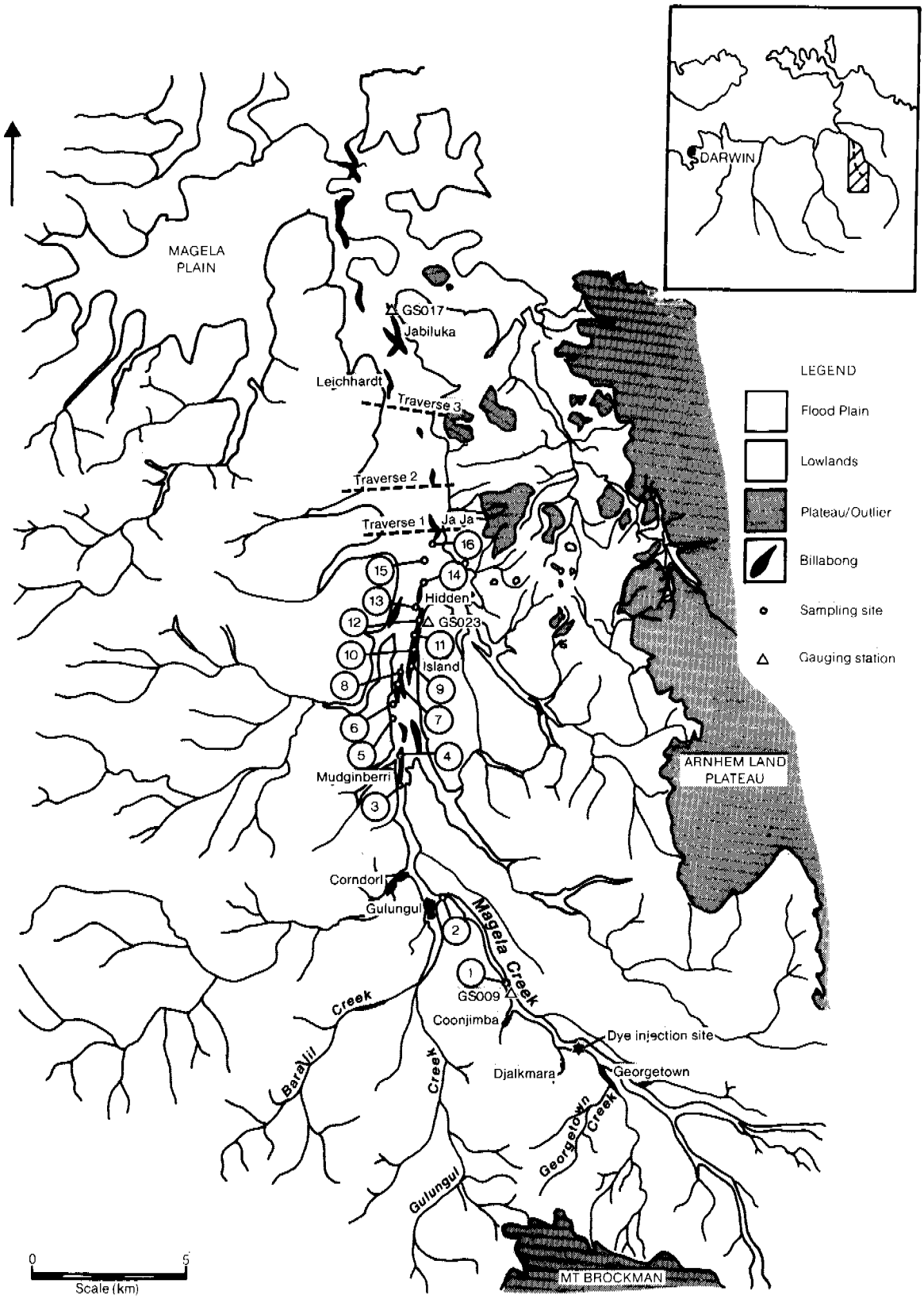


Fig. 1 Magela Creek showing the sampling sites

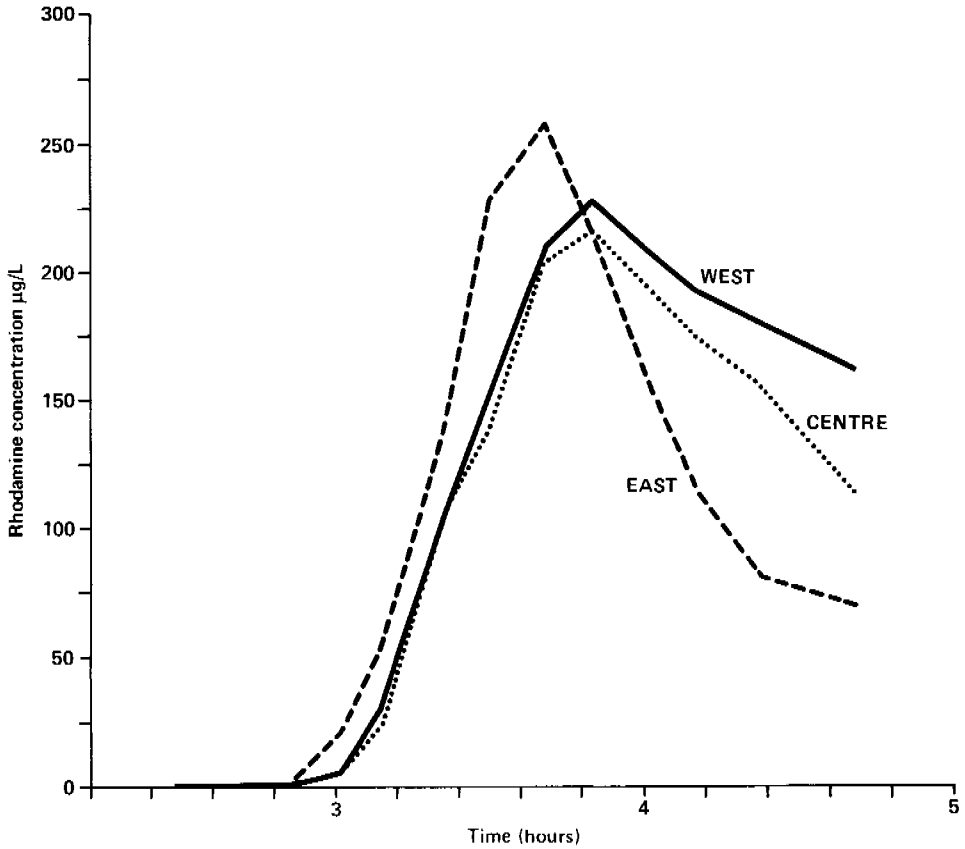


Fig. 2 Dye concentrations at Site 1

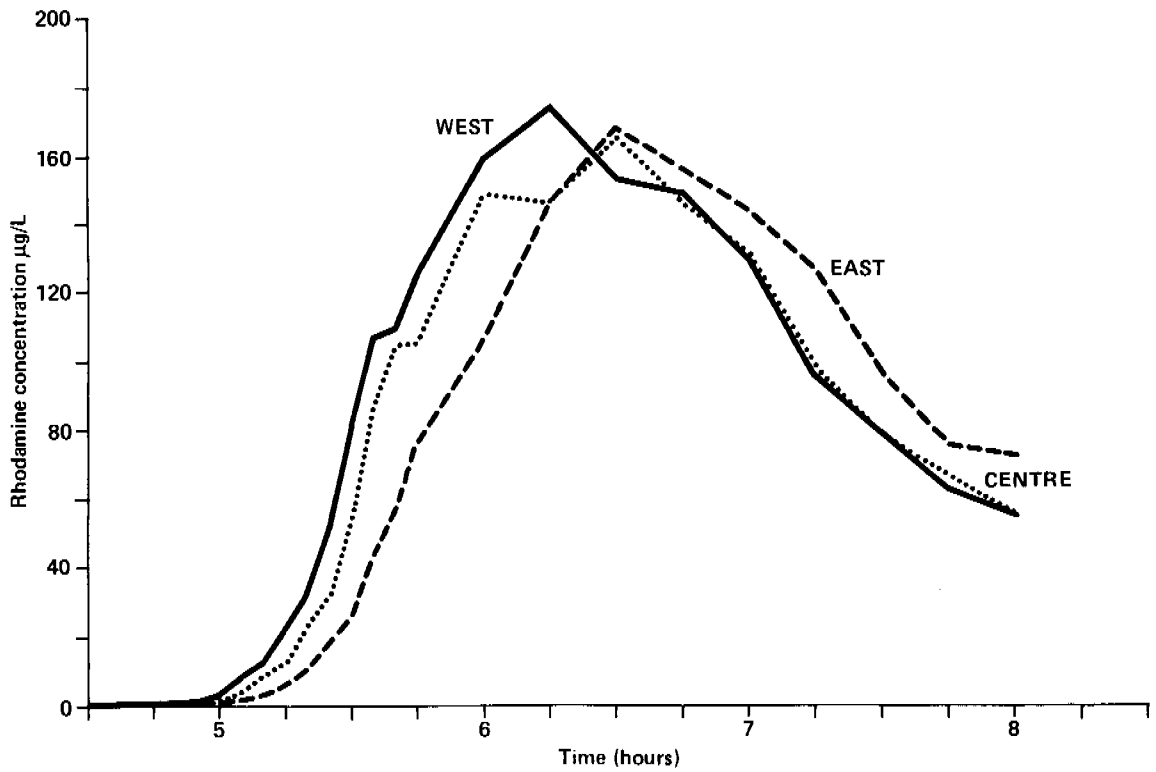


Fig. 3 Dye concentrations at Site 2

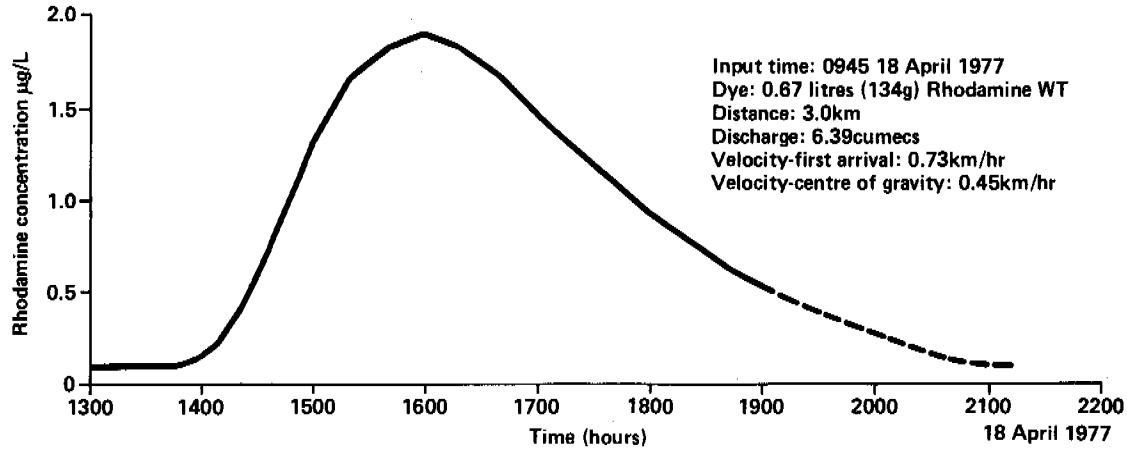


Fig. 4 Dye concentration curve obtained in a dispersion experiment on the Murrumbidgee River, A.C.T. (from CRES 1978)

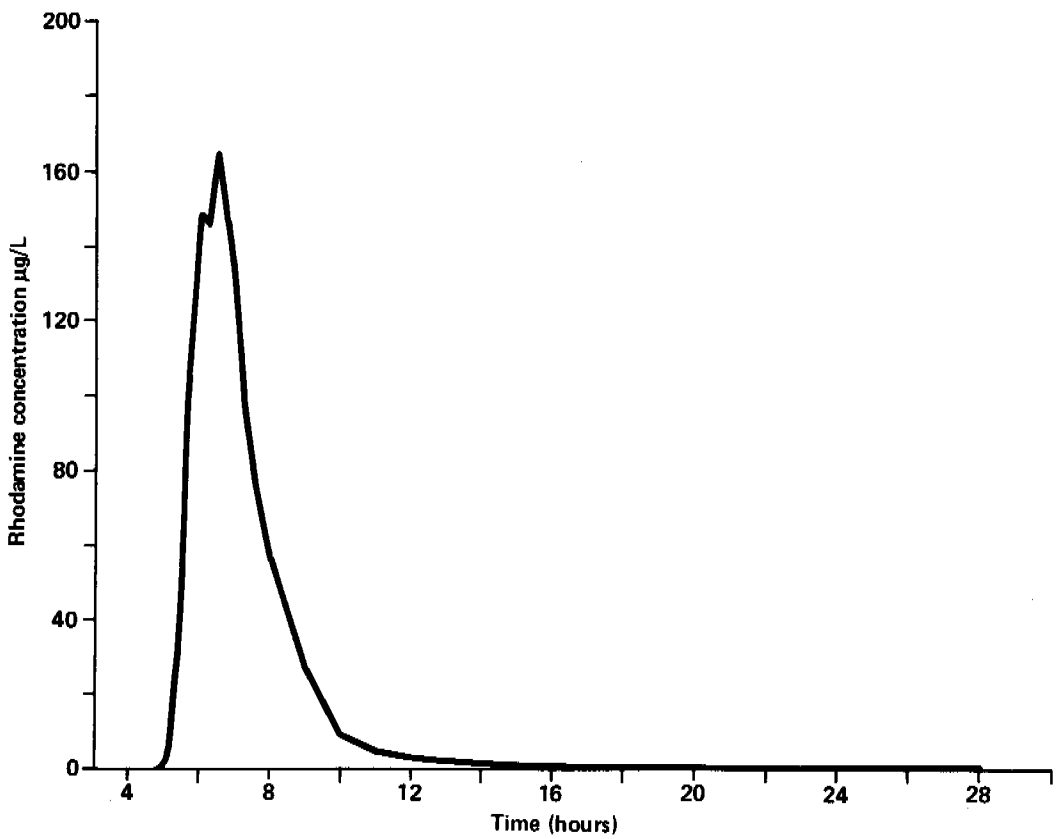


Fig. 5 Dye concentrations in samples taken by automatic sampler at Site 2

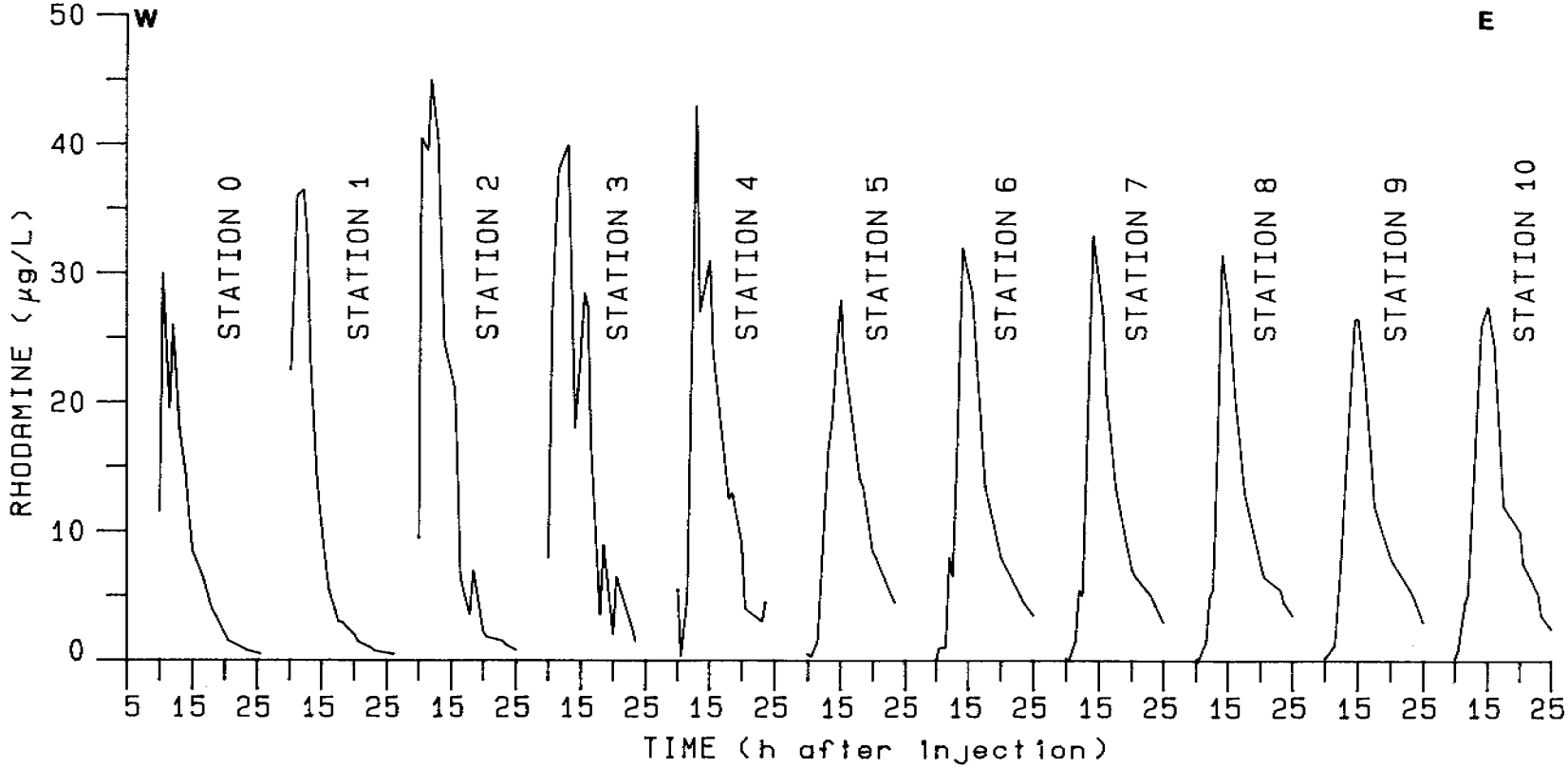


Fig. 6 Peak dye concentrations in surface samples from Site 3

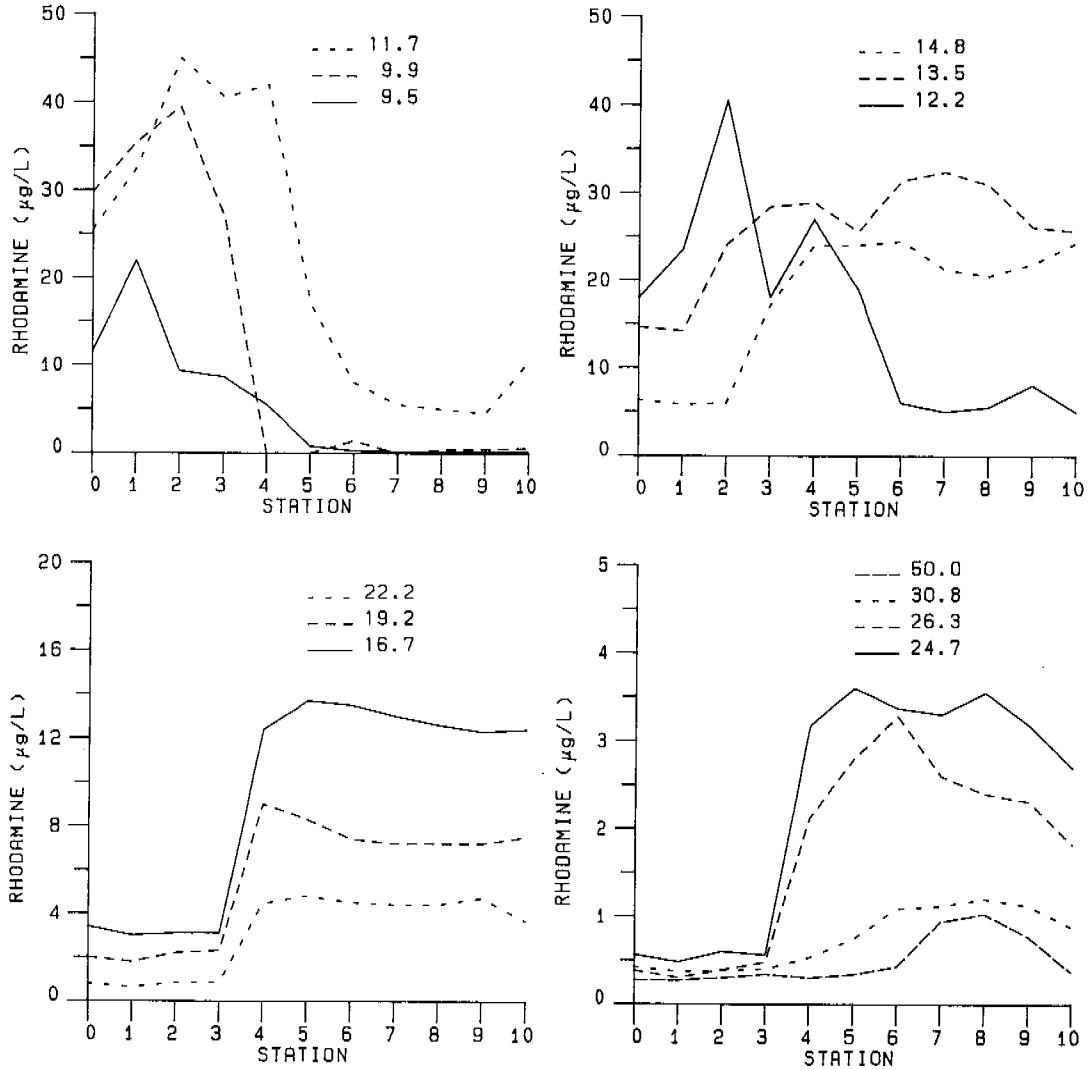


Fig. 7 Dye concentrations in surface samples taken on the traverse at Site 3. Numbers in the legends represent hours after injection of the dye. (Note variation in the scale of the vertical axis.)

Figures 8–16 are contour plots of dye concentrations on the traverse at Site 3 at various times after injection of the dye. In these figures the dye concentration has been divided into five classes so that the percentage of observations falling into each class is approximately equal; thus the dye concentration classes vary from figure to figure. Station 10 is the easternmost station.

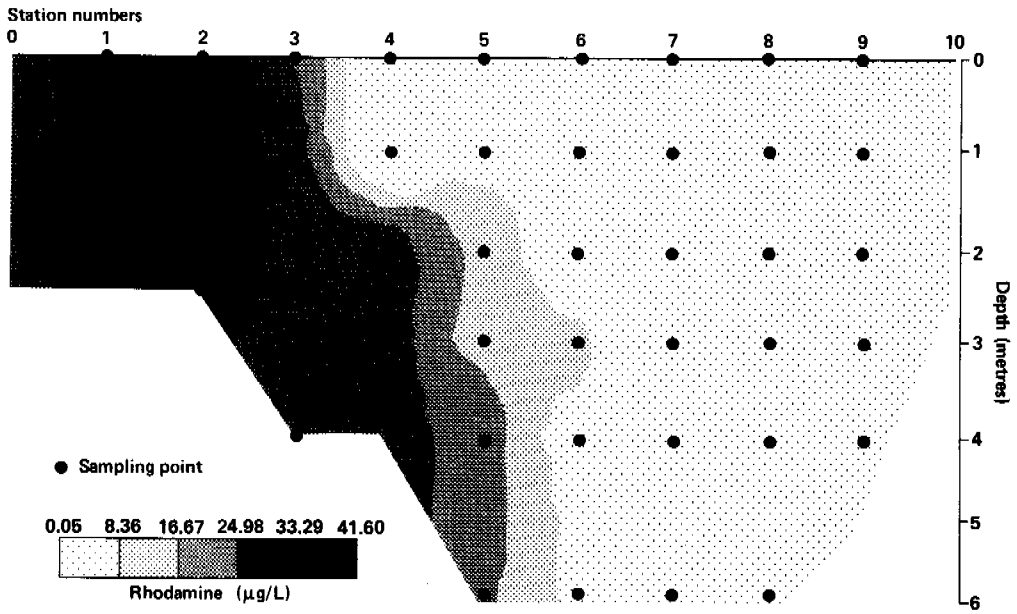


Fig. 8: 9 h 25 min after injection of the dye.

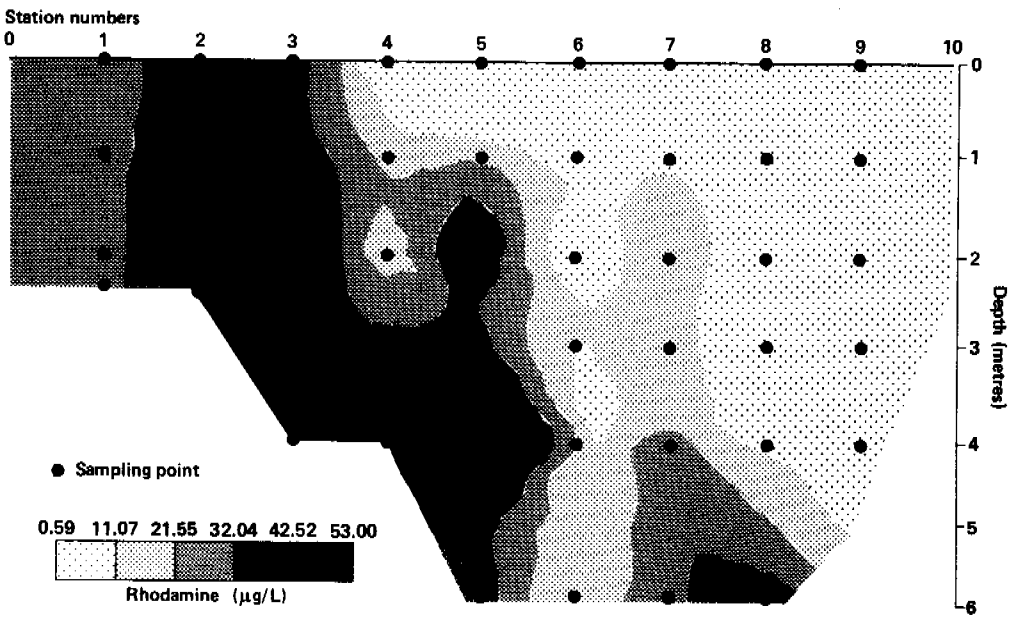
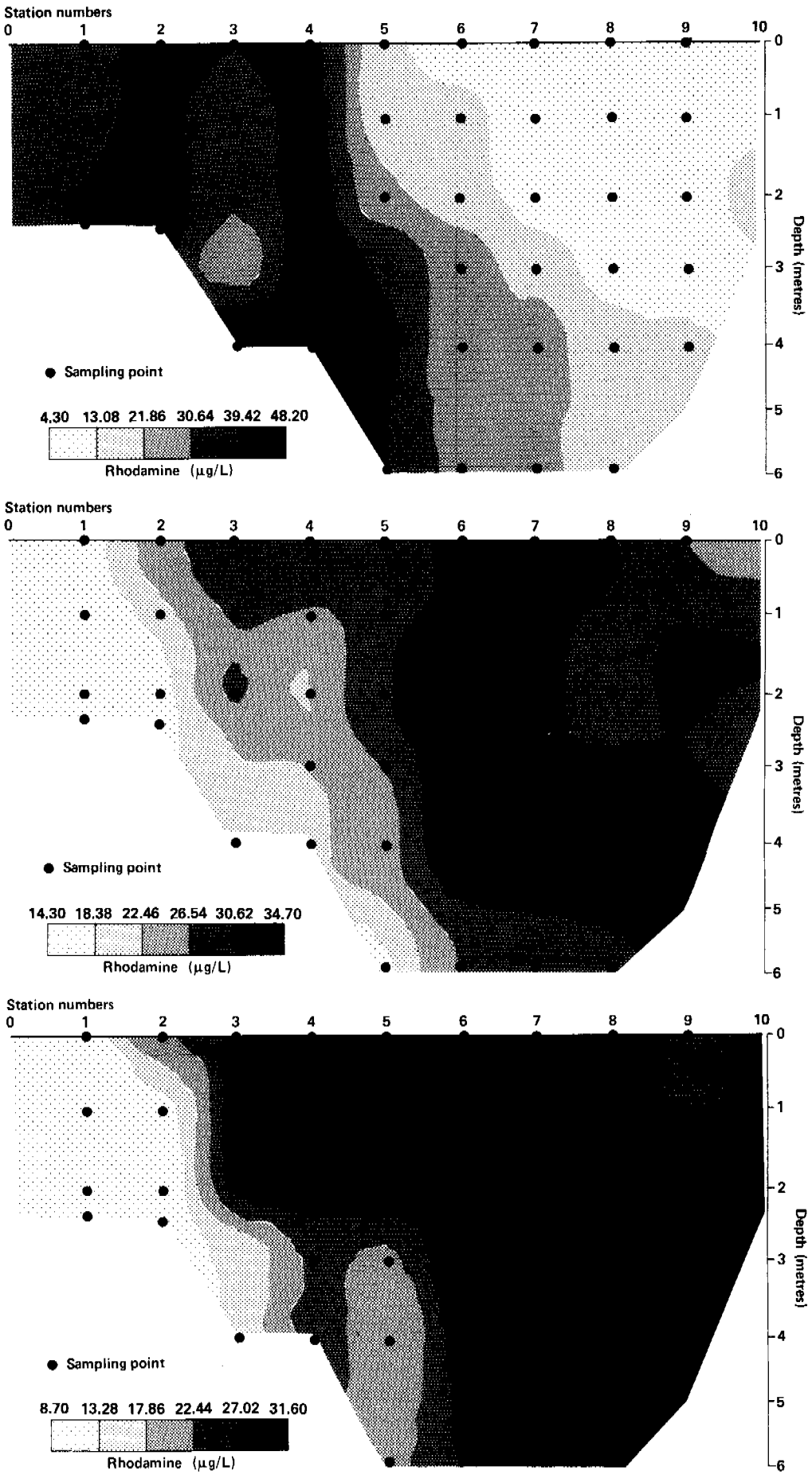


Fig. 9: 10 h 50 min after injection of dye

Opposite (top): *Fig. 10: 11 h 10 min after injection of dye*
Opposite (middle): *Fig. 11: 13 h after injection of dye*
Opposite (bottom): *Fig. 12: 13 h 40 min after injection of dye*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Depth (metres)
0 1 2 3 4 5 6
Sampling point
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Rhodamine (µg/L)
Station numbers
0 1 2 3 4 5 6 7 8 9 10
Depth (metres)
0 1 2 3 4 5 6
Sampling point
14.30 18.38 22.46 26.54 30.62 34.70
Rhodamine (µg/L)
Station numbers
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Sampling point
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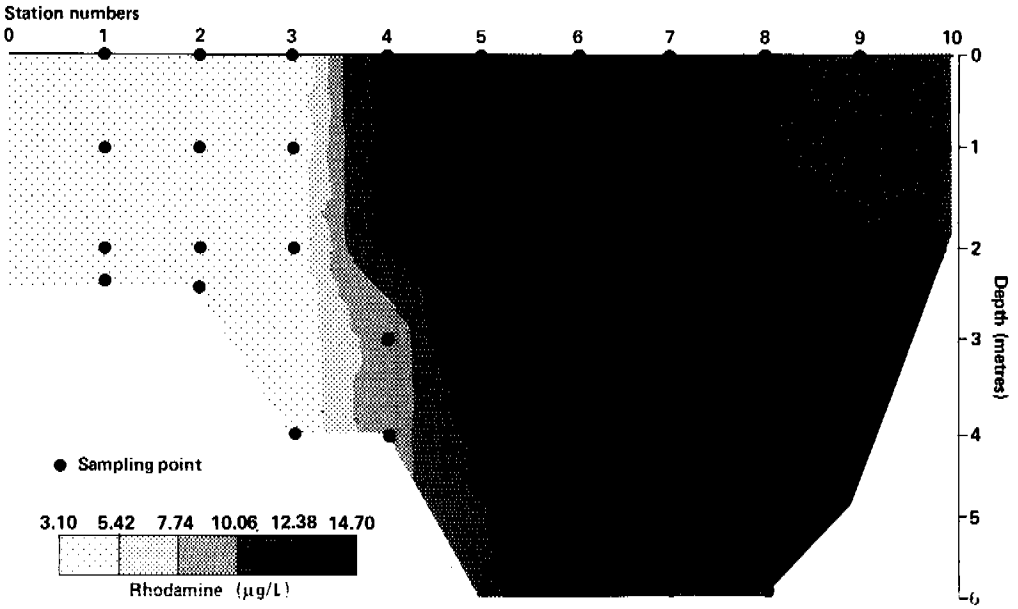
Rhodamine (µg/L)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Sampling point
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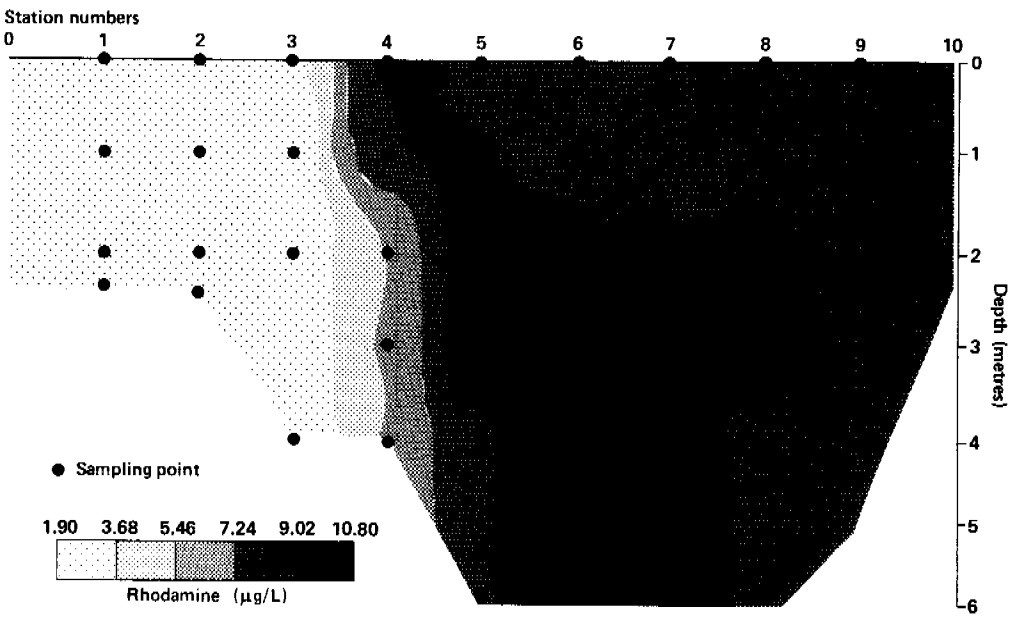
Rhodamine (µg/L)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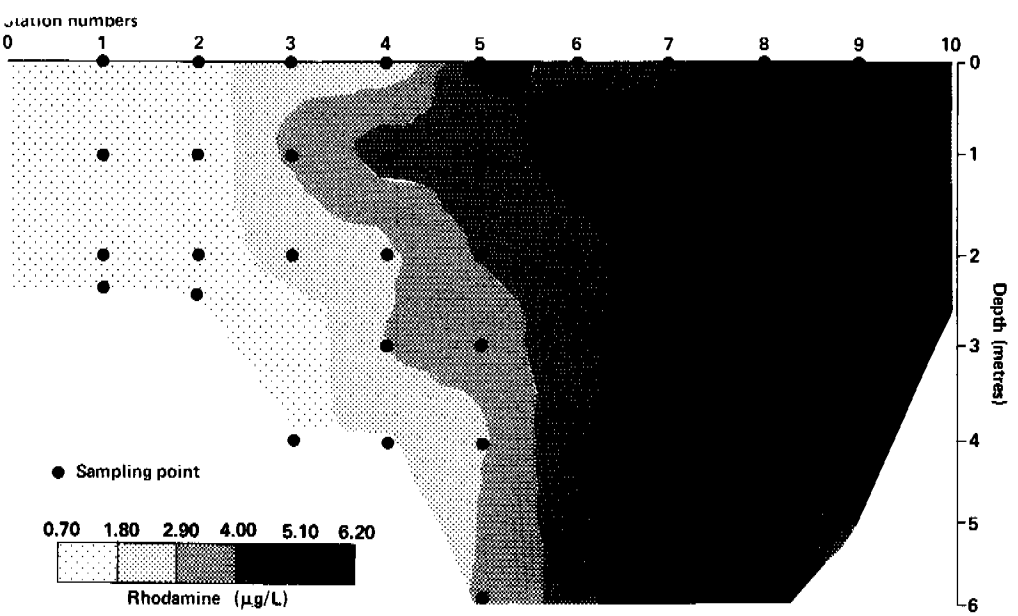
Rhodamine (µg/L)


Station numbers
0 1 2 3 4 5 6 7 8 9 10
Depth (metres)
0 1 2 3 4 5 6
Sampling point
0.70 1.80 2.90 4.00 5.10 6.20
Rhodamine (µg/L)

Opposite (top): *Fig. 13: 16 h 10 min after injection of dye*
Opposite (middle): *Fig. 14: 18 h 40 min after injection of dye*
Opposite (bottom): *Fig. 15: 21 h 20 min after injection of dye*

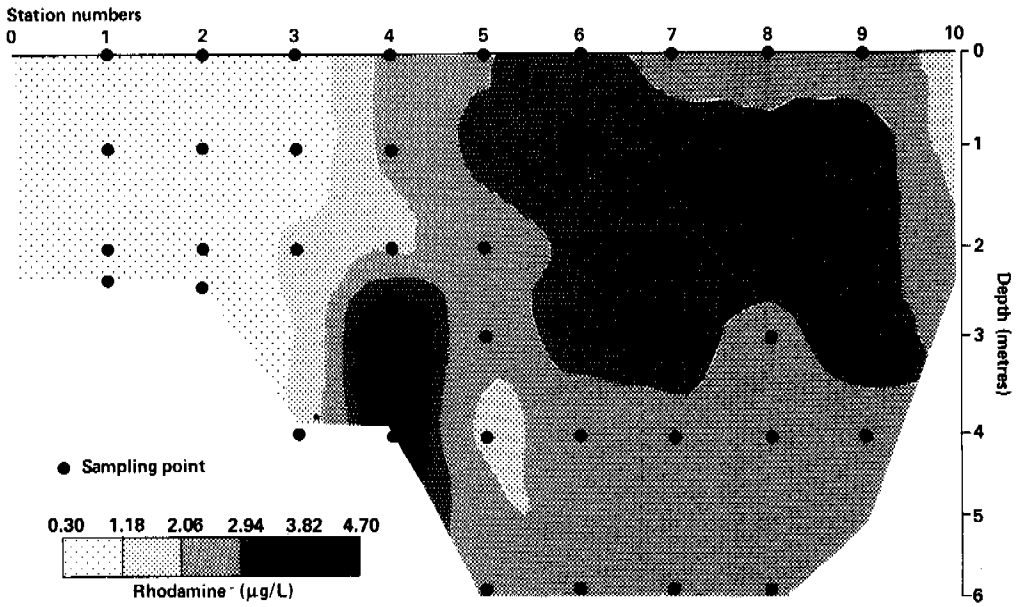


Fig. 16: 25 h 50 min after injection of dye

Figures 17–24 are contour plots of dye concentrations on the traverse at Site 3. In these figures the class intervals for dye concentrations are constant throughout. Station 10 is the easternmost station.

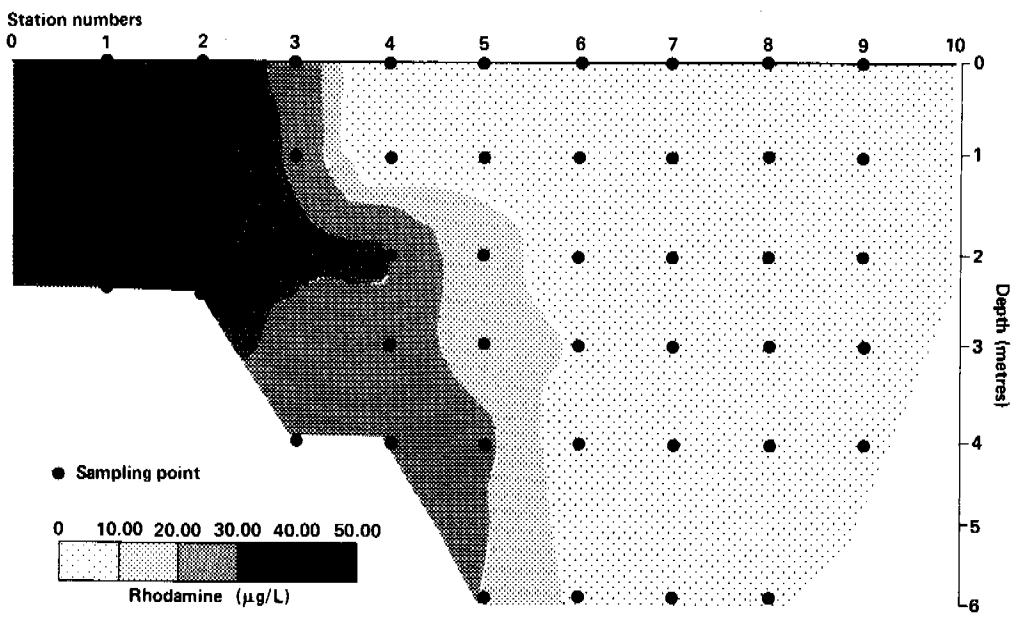


Fig. 17: 9 h 25 min after injection of dye

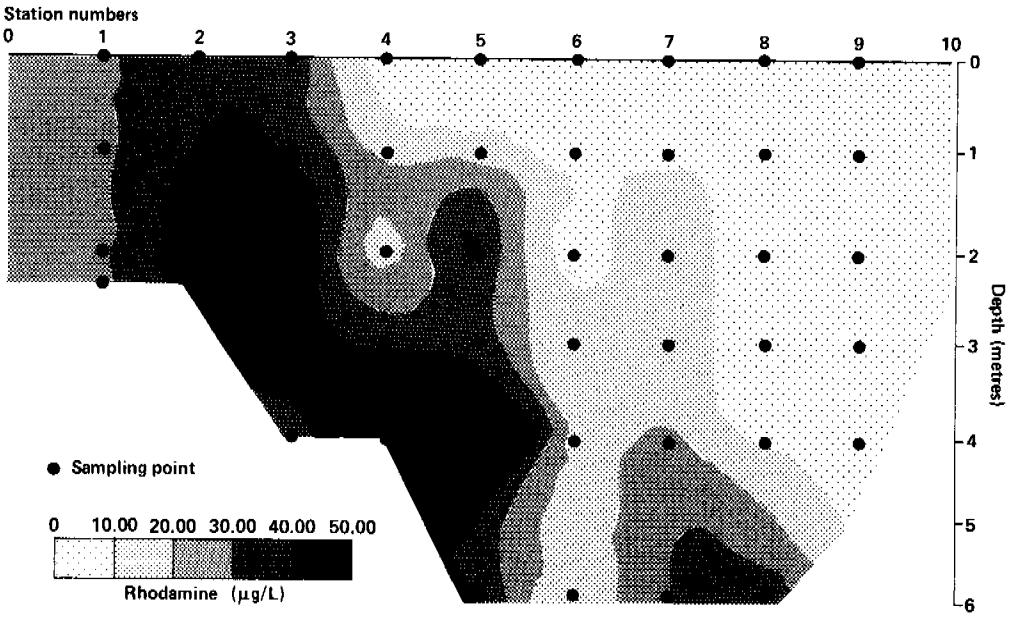


Fig. 18: 10 h 50 min after injection of dye

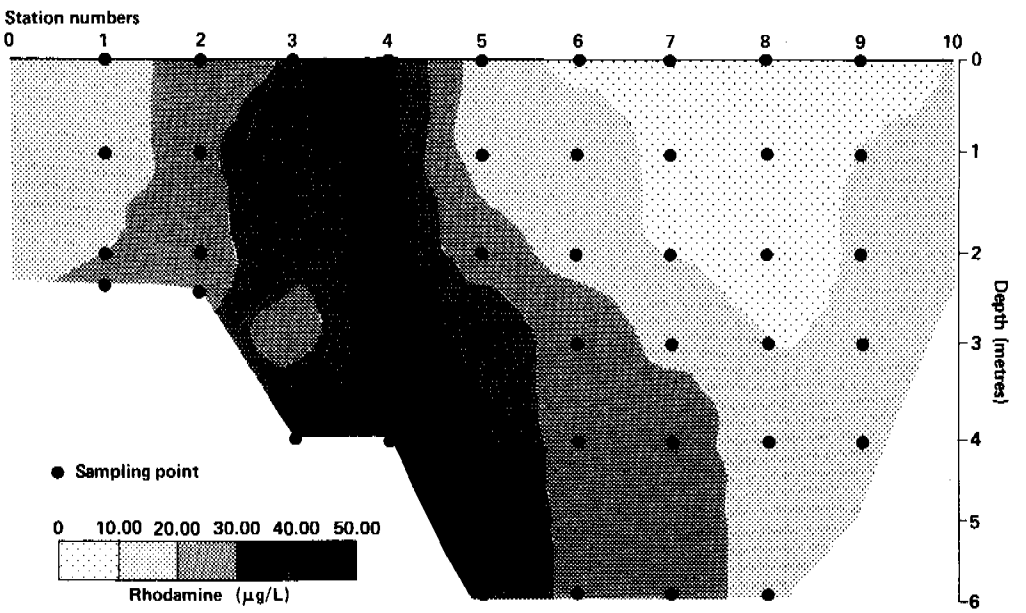
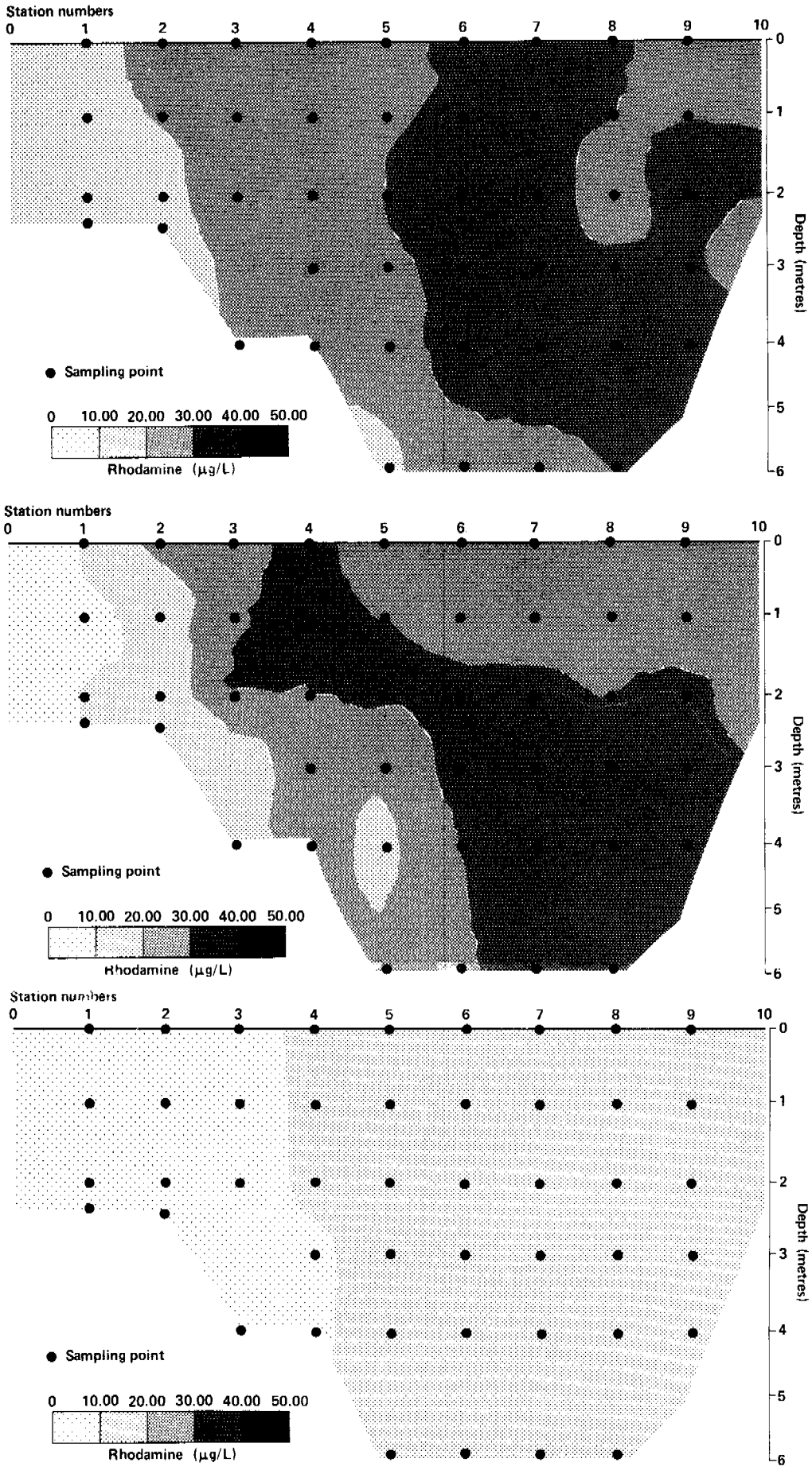


Fig. 19: 11 h 30 min after injection of dye

Opposite (top): *Fig. 20: 13 h after injection of dye*

Opposite (middle): *Fig. 21: 13 h 40 min after injection of dye*

Opposite (bottom): *Fig. 22: 16 h 10 min after injection of dye*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Sampling point
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Rhodamine (µg/L)
Station numbers
0 1 2 3 4 5 6 7 8 9 10
Depth (metres)
0 1 2 3 4 5 6
Sampling point
0 10.00 20.00 30.00 40.00 50.00
Rhodamine (µg/L)
Station numbers
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Depth (metres)
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Sampling point
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Rhodamine (µg/L)

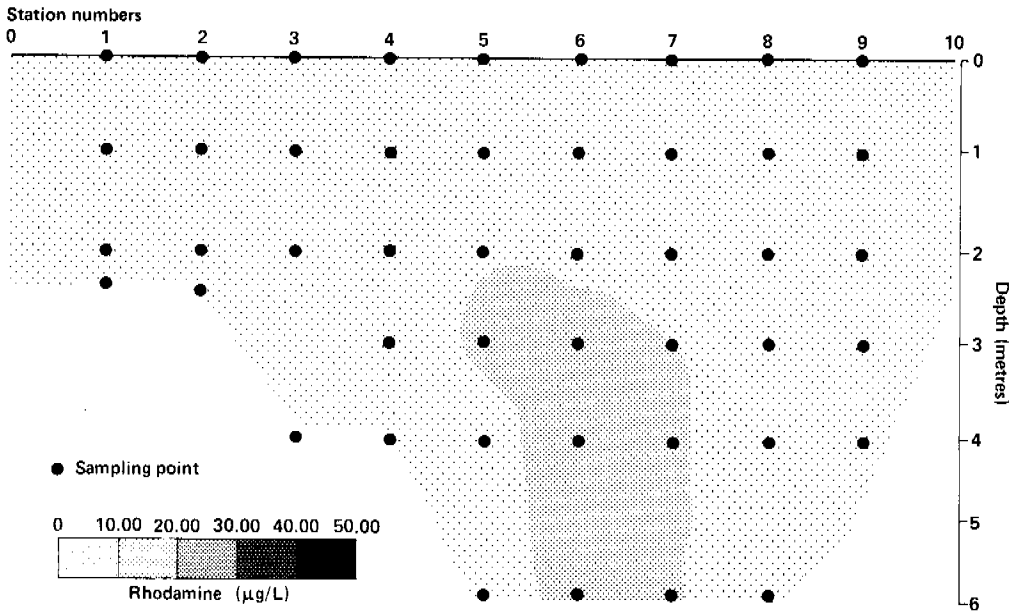

Fig. 23: 10 h 40 min after injection of dye

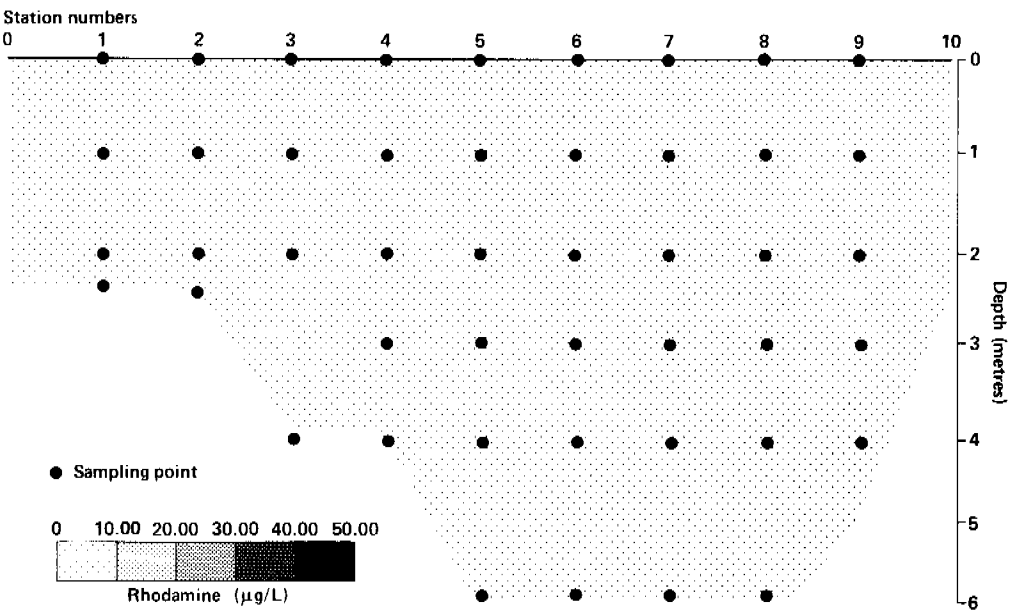

Fig. 24: 25 h 50 min after injection of dye

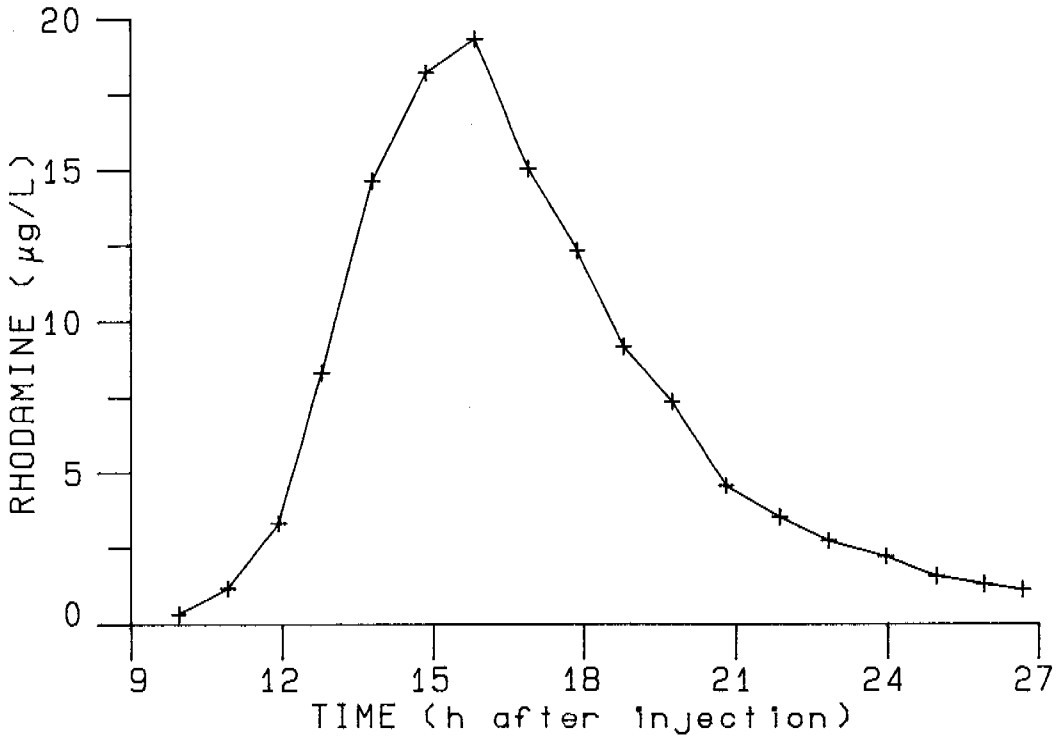

Fig. 25 Dye concentrations in samples collected by an automatic sampler located at Site 4 (the northern end of Mudginberri Billabong)

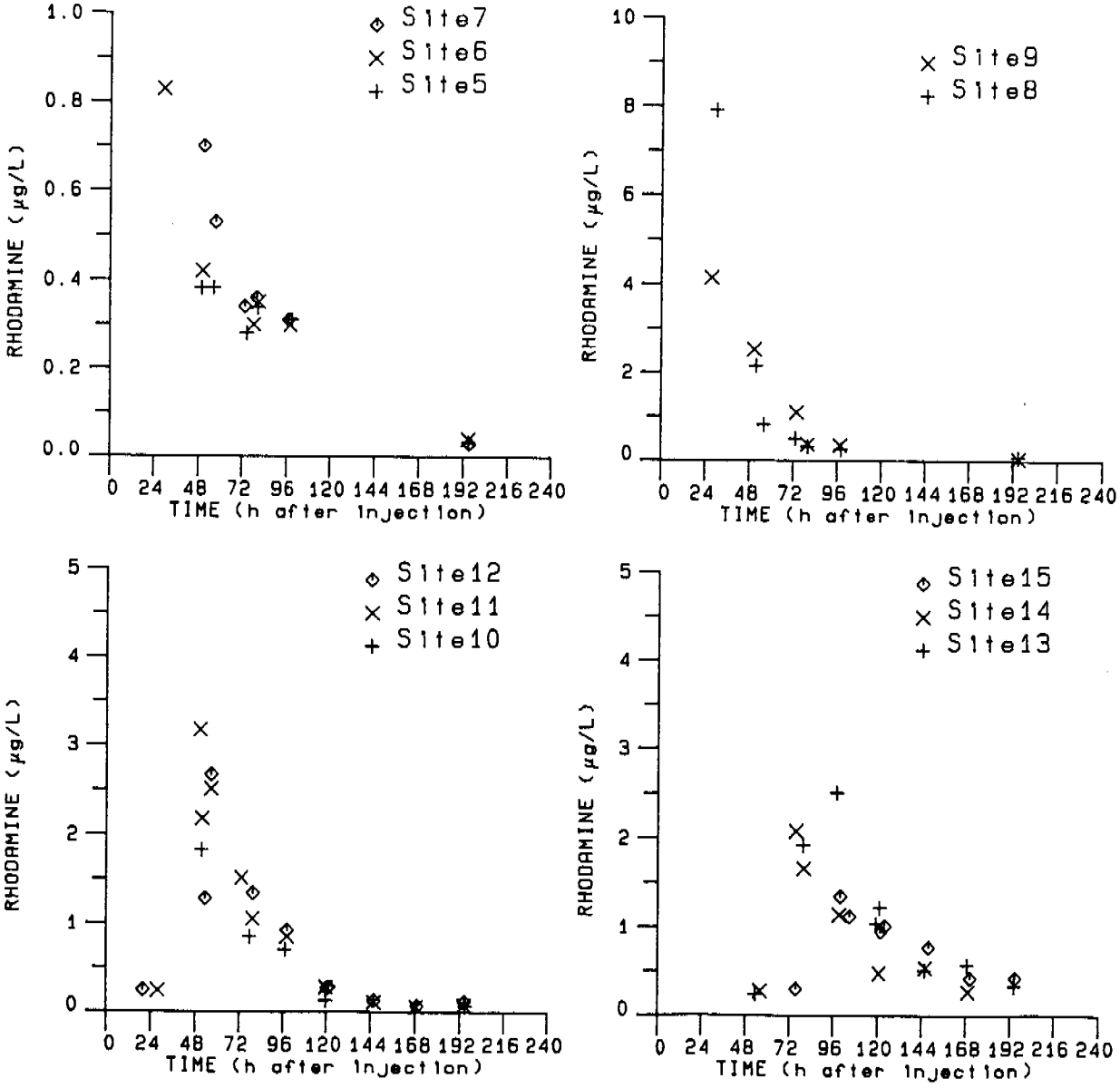

Fig. 26 Dye concentrations in surface samples from Sites 5-15

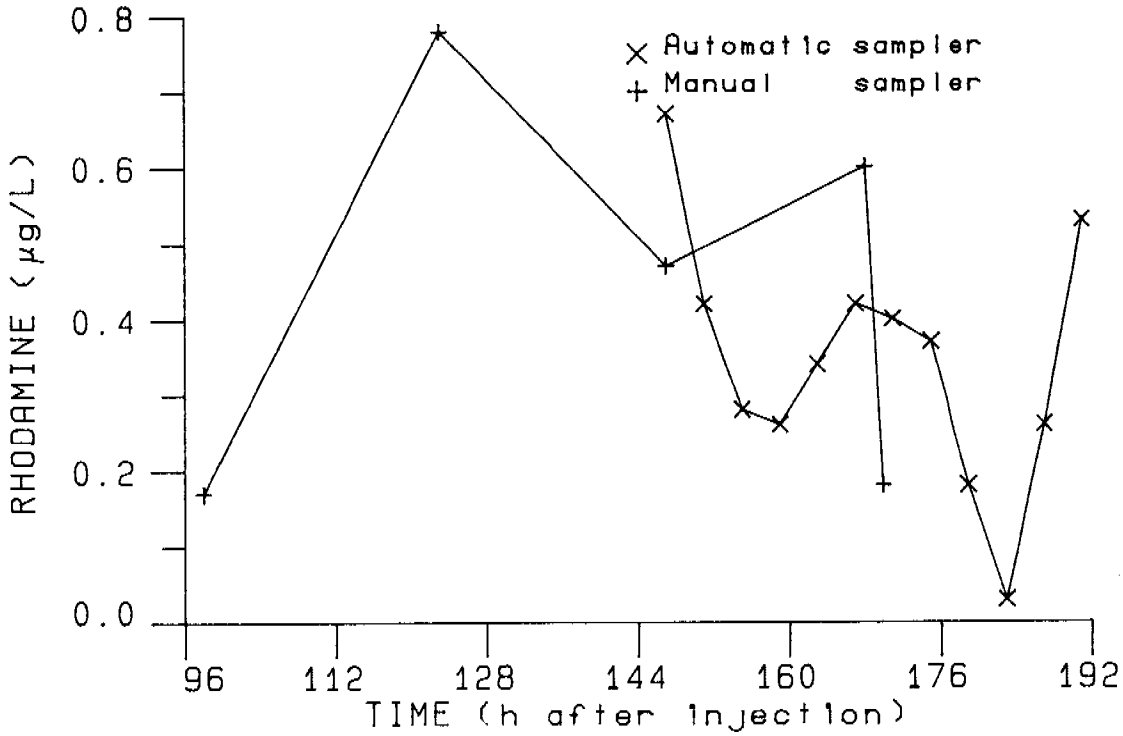

Fig. 27 Comparison of dye concentrations in samples collected manually and by automatic sampler at Site 16

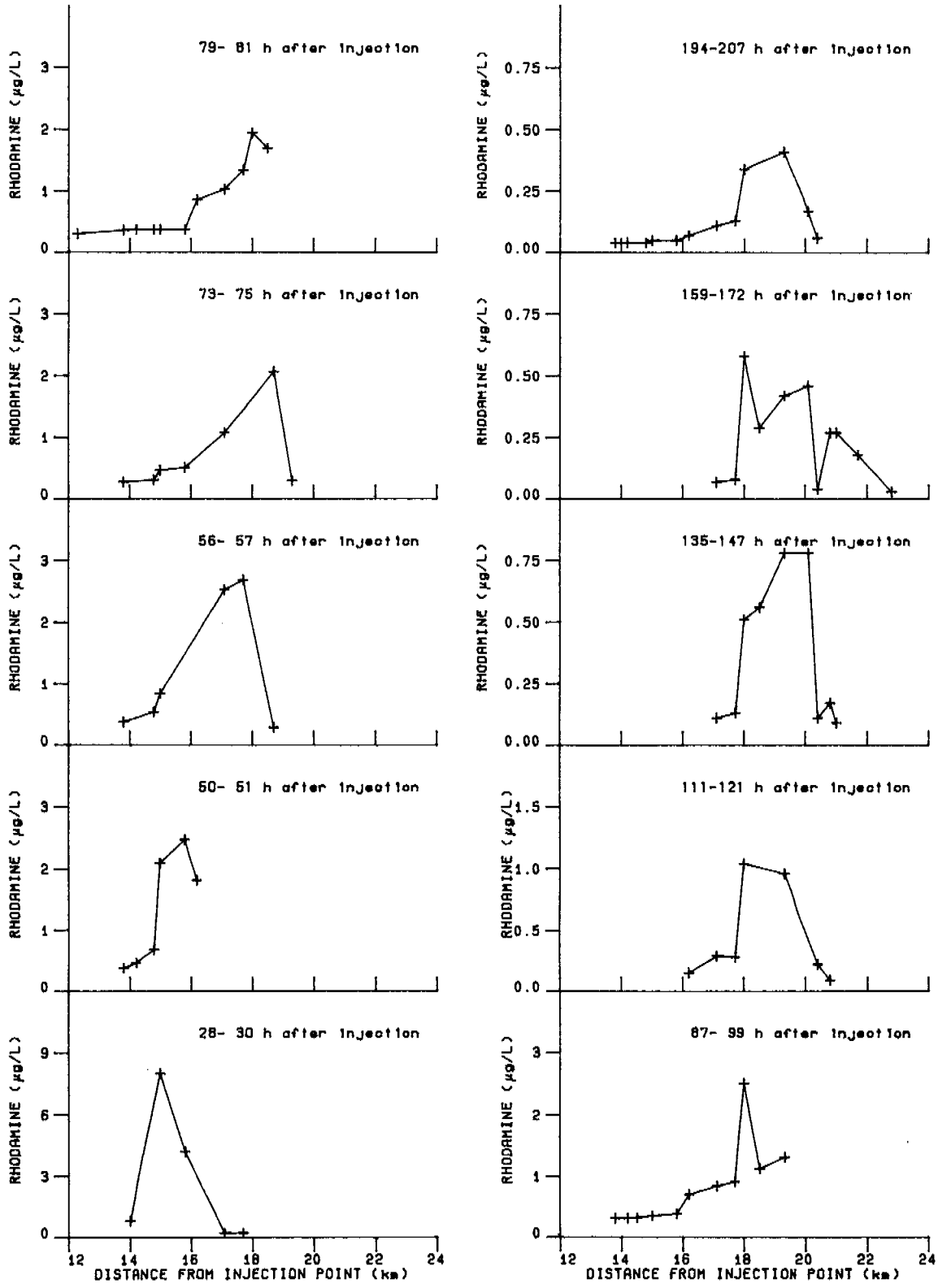

Fig. 28 Dye concentrations at various times plotted against distance. (Note variation in the scale of the vertical axis.)

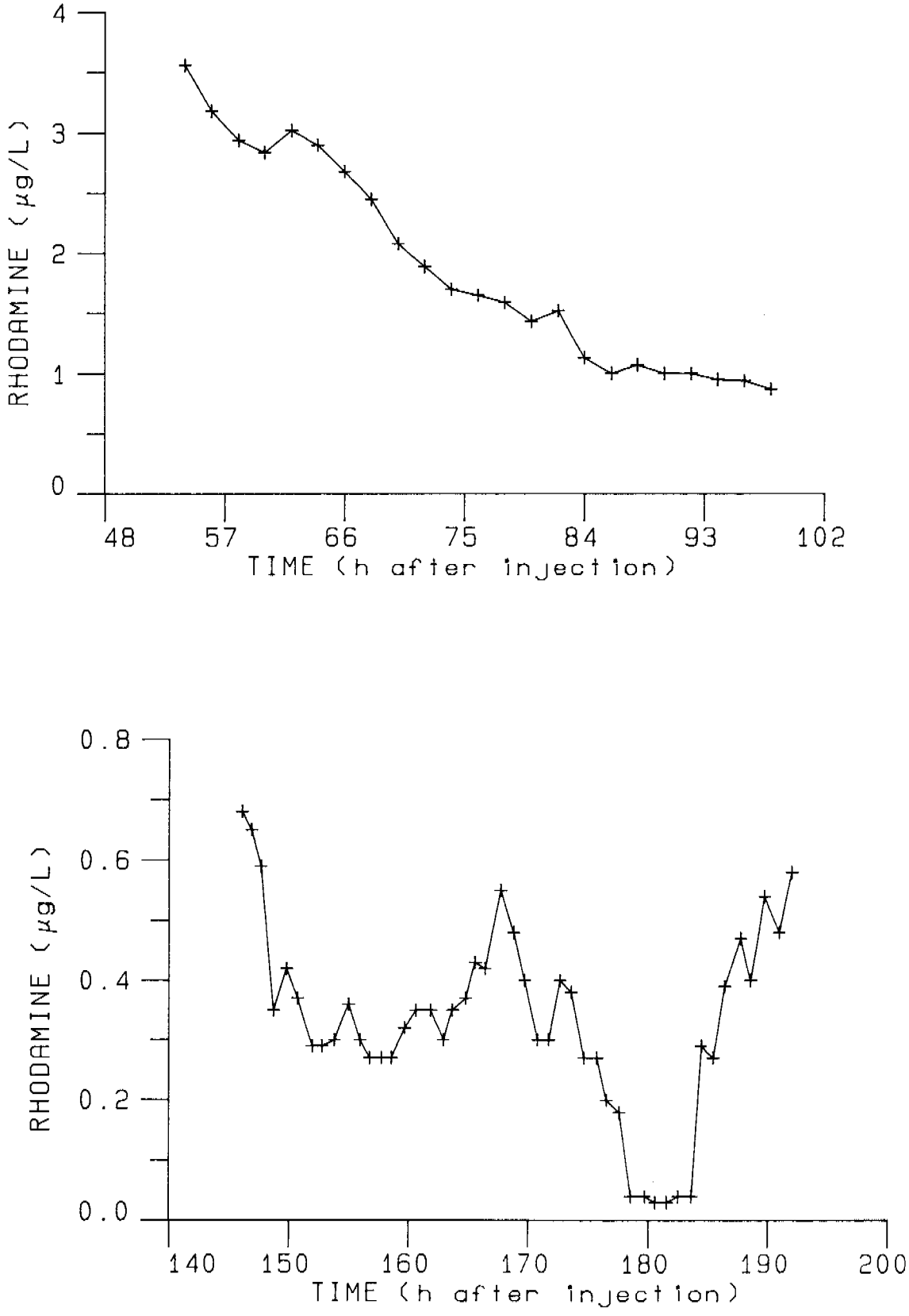

Fig. 29 Dye concentrations in samples collected by automatic sampler at (A) Site 11 and (B) Site 16

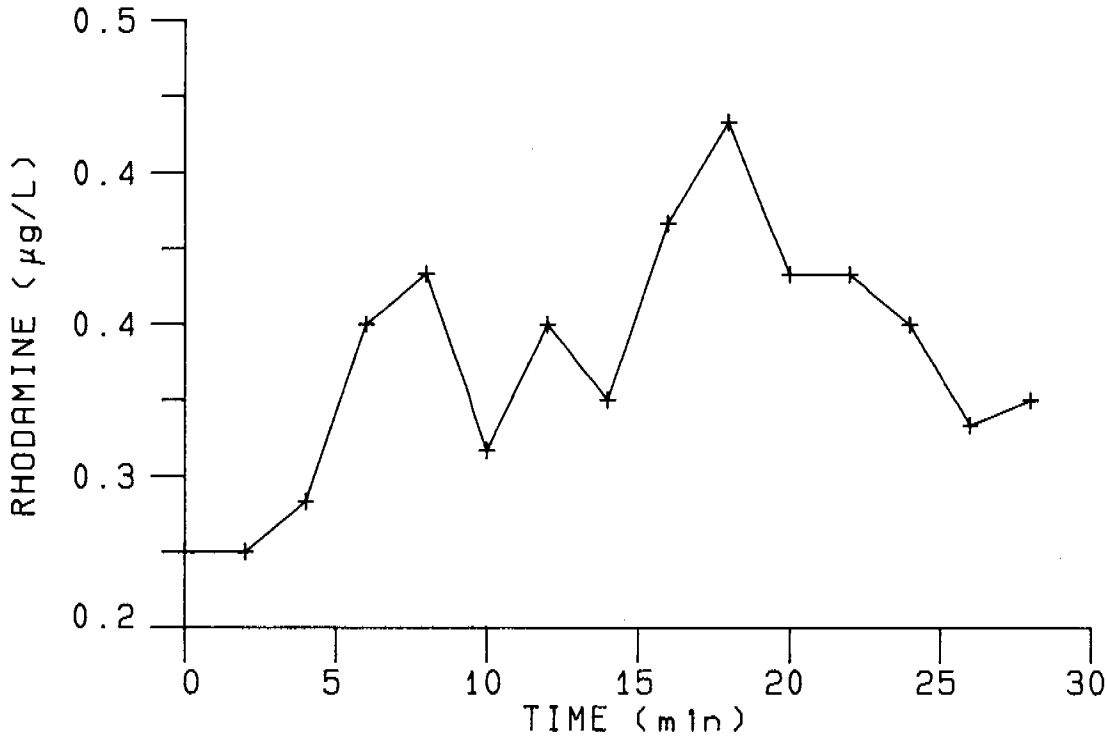

Fig. 30 Dye concentrations in samples collected at 2 min intervals at Site 16. First sample was collected 152 h after injection of the dye.

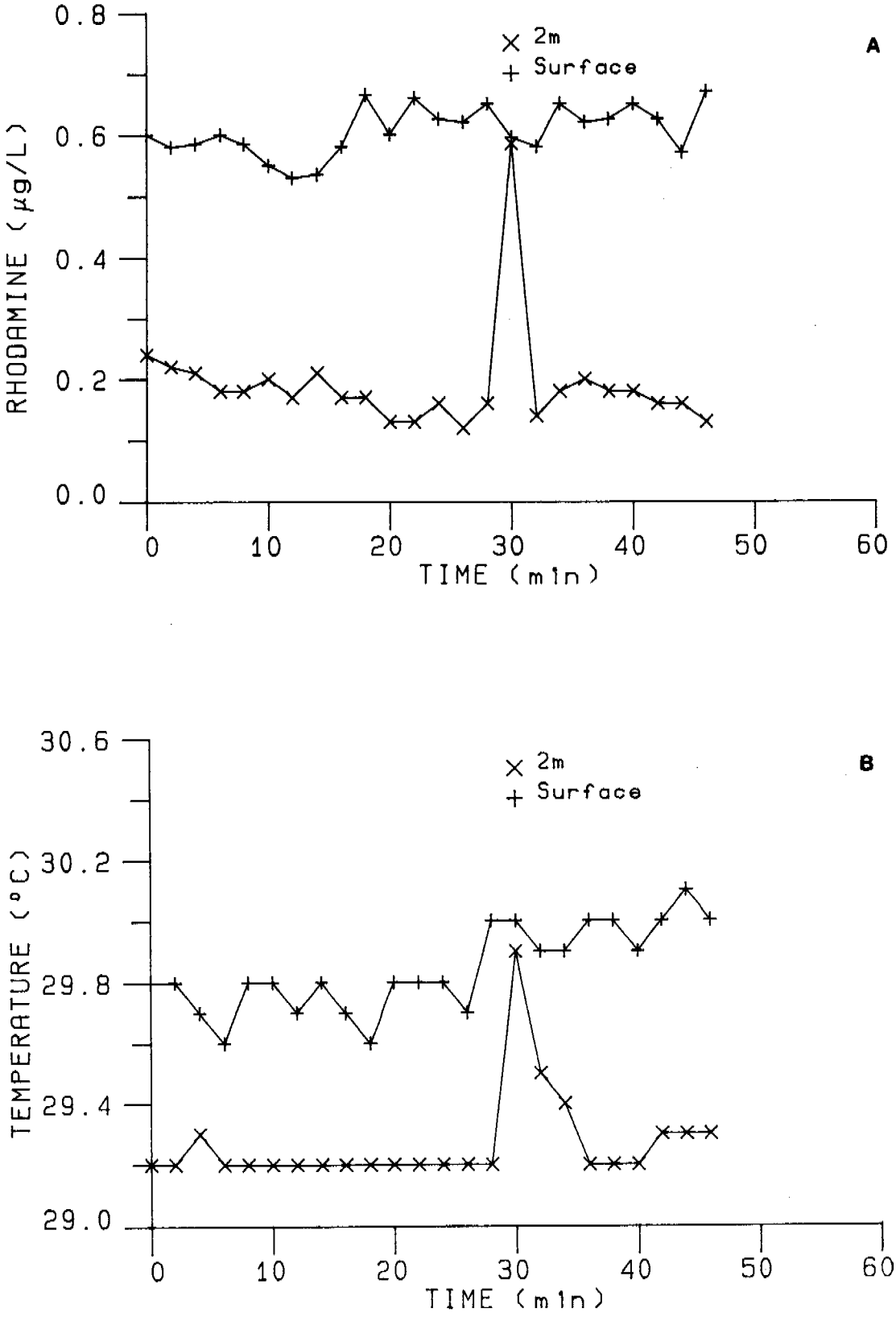

Fig. 31 (A) dye concentrations in and (B) temperature of surface and 2 m samples collected at Site 16.

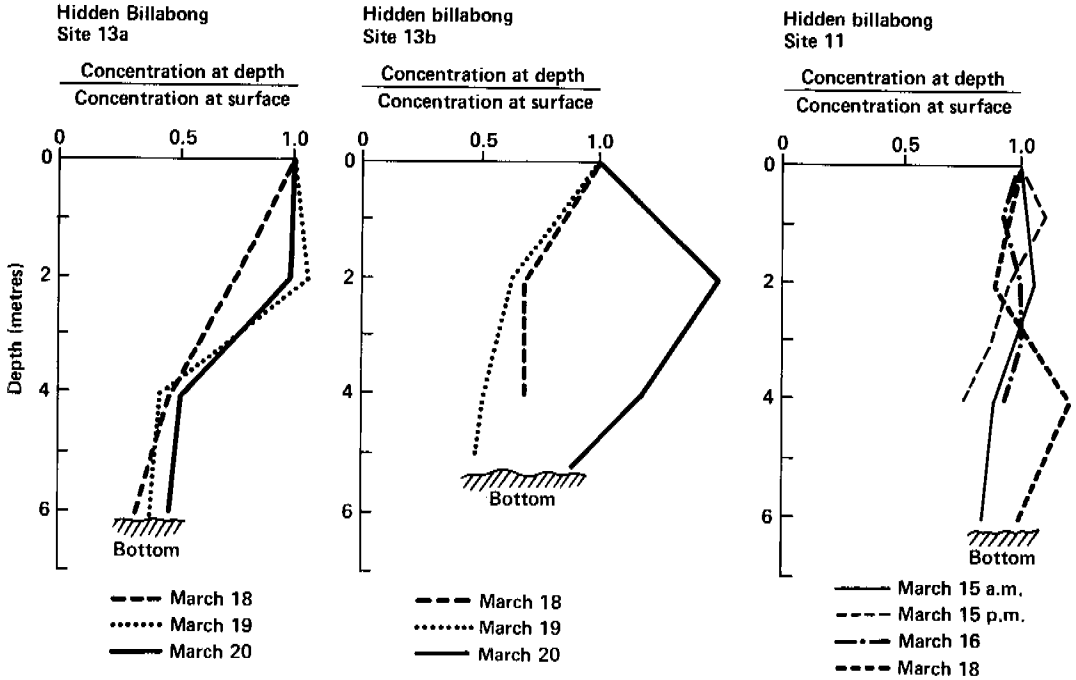

Fig. 32 Variation of dye concentration with depth at sites in Hidden Billabong

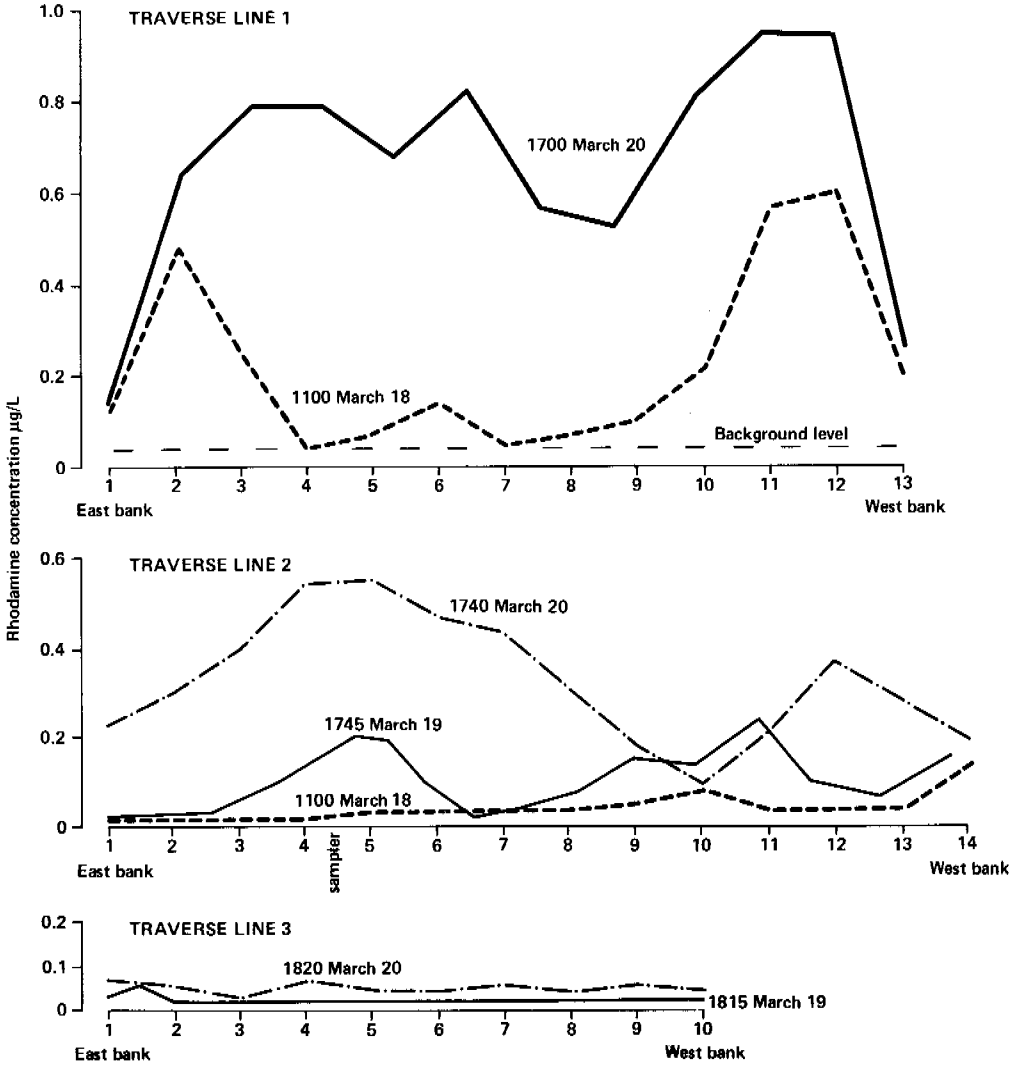

Fig. 33 Dye concentrations in samples taken along traverse lines 1-3

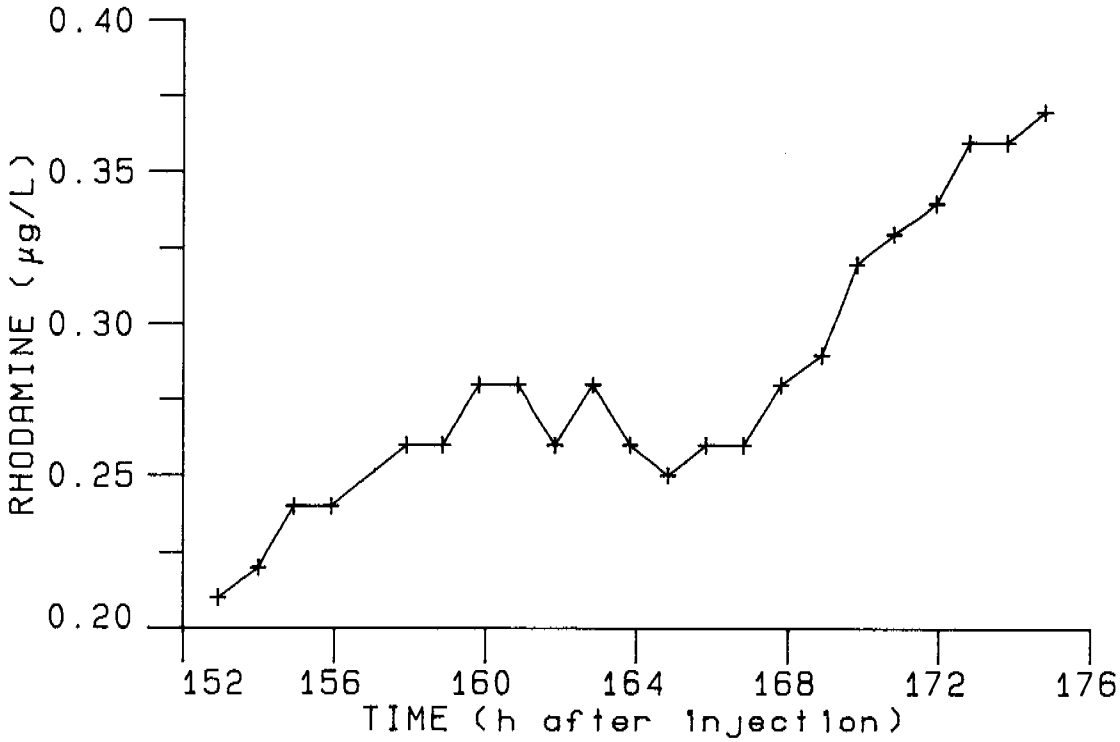

Fig. 34 Dye concentrations in samples taken by automatic sampler located on traverse line 2

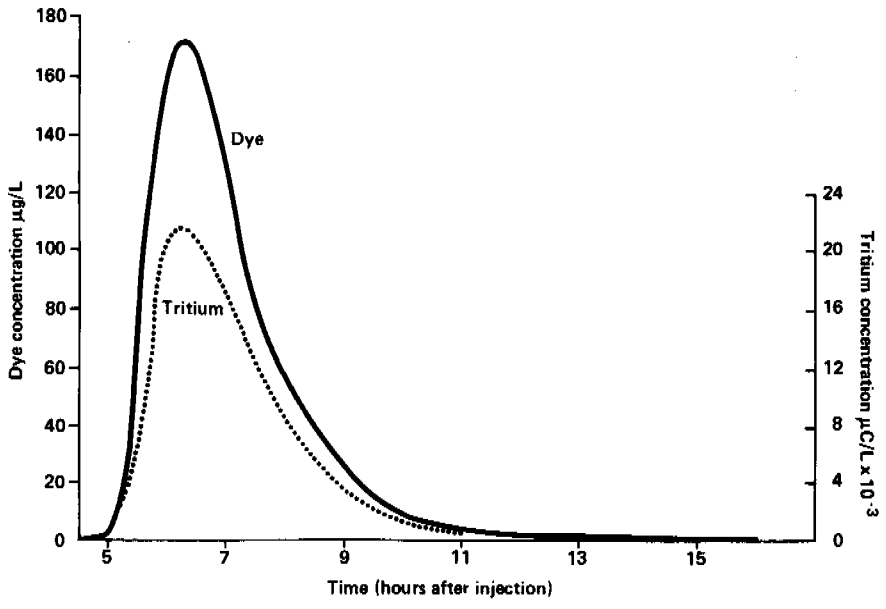

Fig. 35 Variation of tritium and dye concentrations at Site 2

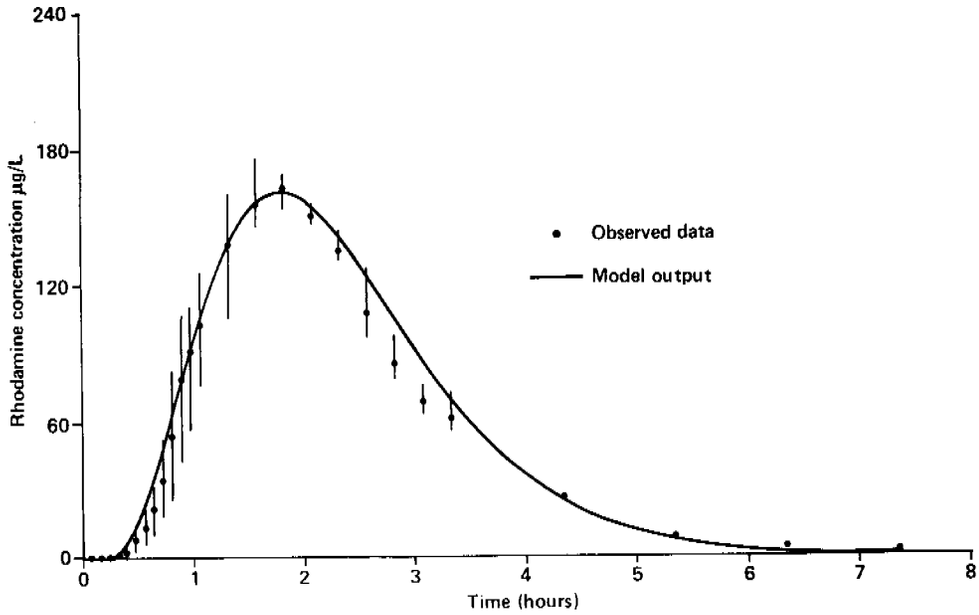

Fig. 36 Comparison of computer output from the longitudinal dispersion model with the dye concentration data from Site 2. Observed data points are the average for the three channels at Site 2. The range of dye concentrations is indicated by vertical bars.

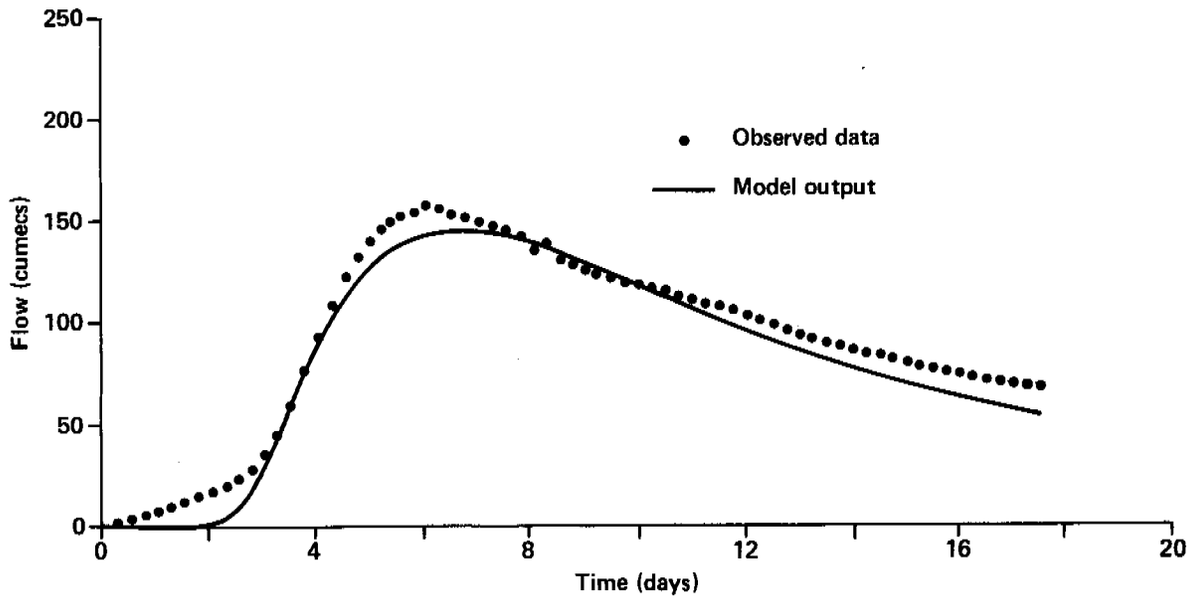

Fig. 37 Comparison of modelled and measured flow at gauging station GS821019 between 8 and 25 April 1975

APPENDIX

Summary of the fluorometric tracing experiment undertaken in February 1979

CRES was invited to undertake further fluorometric tracing in the Magela Creek system in February 1979. This work was funded by the Northern Territory Government and carried out in conjunction with the Water Division of the N.T. Department of Transport and Works. Throughout the study close liaison was maintained with other bodies, including the Office of the Supervising Scientist (OSS).

In part the aims were similar to those of the 1978 study undertaken for the OSS, and this account summarises aspects of the 1979 results which directly extend the 1978 study. Full details of the 1979 study are presented in Smith et al. (1979).

Mixing in Mudginberri Billabong This site was chosen for special study because it had been selected as a river discharge gauging site by the Water Division and had also been used by the AAEC to study the passage of radioactive tracers designed to simulate pollutant flow through the Magela Creek system. In the 1978 study we had established that there was poor vertical and horizontal mixing at this site and on the basis of those results concluded that it was a poor site both for the gauging station and for dispersion/pollution studies. The query remained, however, whether the choice of the site was at fault or whether there was poor mixing throughout the whole of Mudginberri Billabong.

In 1979 further observations were made at the original site (Site 3) and additional information collected for a downstream cross-section. In the 1979 study, the original traverse at Site 3 was termed Traverse 1, and the new site Traverse 2. Traverse 2 was located close to the position of Site 4 in the 1978 experiment (Fig. 1). The results are illustrated in detail in Smith et al. (1979) but the overall pattern can be seen in Figs A1 and A2 of this report.

In the downstream section, Traverse 2 (Fig. A2), the dye is well mixed compared to Traverse 1 (Fig. A1), which shows relatively poor mixing, as it had in 1978. The conclusion is therefore, that Traverse 1 is not a good site either for a gauging station or for the collection of samples to study the movement of pollutants or tracers through the Magela Creek system. Site 3 is too close to the point at which the upper tributaries of the creek empty into the slower moving waters of the billabong and mixing is therefore poor, owing in part to the temperature differences between the inflowing waters and the open water of the billabong.

Vertical mixing The study undertaken in 1978 drew attention to the inconsistent nature of dye distribution with depth. A limited range of similar experiments were carried out in 1979, mainly in open water in Hidden Billabong. As in the 1978 study, it was found that the vertical distribution of dye concentrations varied over short time intervals. On some occasions there was at first little variation in dye concentration with depth, but a few minutes later the vertical distribution showed a drop in concentration with depth. Temperature differences between the top and bottom of the profiles were close to 2.0°C throughout the observations.

It is thought that poor vertical distribution on a local scale is particularly marked in areas of open water where there are clear signs of

temperature stratification. The importance of these observations is stressed as they are relevant to the use of tracer studies designed to budget pollution. Care should be exercised in selecting sampling sites for such studies: the sites should show minimum vertical variation in tracer concentration.

Detailed study of Jabiluka Billabong The 1979 study included a number of dye tracer experiments in addition to the main input at the Ranger site. One of these experiments is of particular importance in extending the 1978 observations on the Magela Creek system. Five litres of Rhodamine WT were injected in a line traverse some three hundred metres upstream of the open water of Jabiluka Billabong (Fig. 1). This dye input was monitored both from the air and by the collection of surface and depth samples from the open water of the billabong as well as from the peripheral flooded areas, which have dense aquatic vegetation. There are two clear and important results from this experiment:

1) a marked channelling effect of the dye into the open water sections of the billabong and

2) poor vertical mixing in the billabong.

The line of injection was very much longer than the width of the open water section of the billabong. Air photographs demonstrate in the clearest fashion the funnelling effect on the dye as it moves into the open water section.

The variation of dye concentrations with depth is illustrated in Fig. A3 (based on fig. 4.2, Smith et al. 1979). The conclusion favoured in the 1979 report was:

> It is most likely that the funnelling into Jabiluka Billabong, and the original penetration at a depth of about 2.5 m are related phenomena. The subsurface intrusion indicates that the incoming water must be more dense than the waters on the surface of the southern end of the Billabong. It would appear that at the time of this experiment the billabong surface waters, and the flood plain waters to the west of the Billabong, are warmer and hence less dense, than the fast flowing water coursing down the main channel of the Magela Creek.
>
> This denser water can only continue on its passage by intruding underneath the lighter water. It is energetically most efficient to do this by entering the billabong, falling to a depth at which the water density (and hence water temperature) equals the incoming water density, and then intrude into the stratified fluid of the Billabong.

Full details of this experiment, which amply illustrates the usefulness of dye tracers for experiments of this kind, are given in Smith et al. (1979, pp. 28-30, figs 4.1 to 4.3). The importance of the open water sections, the billabongs of the downstream parts of the Magela Creek system, for biological conservation cannot be overstressed. Further studies that can enlarge upon the differences in flow between the open water sections and the densely vegetated flooded section which surrounds them during the Wet season are needed. The need for detailed depth sampling is again apparent.

Time of travel One of the major objectives of the 1978 study was to gain information on the time of travel through the Magela Creek system from the projected Ranger discharge site. This experiment was repeated in the 1979 study with input at the same site and a similar, but not identical, pattern of downstream sampling sites. The dye input in 1979 was 50 litres of Rhodamine WT; in 1978 the input had been 80 litres. A comparison of the

time of travel between the two experiments is given in Smith et al. (1979, pp. 16-17 and Table 2.2). That section, with minor modifications, is reproduced here:

> The velocity figures for comparable sites from the experiments of 1978 and 1979 are given in Table 2.2 [Table A1 of this report]. It is apparent that the velocities for 1979 show a relatively progressive increase down the system. The velocities from the injection point to Site 1 are identical, but by Traverse 7 (a distance of 25 km) the velocities have more than doubled.
>
> The reason for the differences between the two experiments is that in 1979 the dye was injected just ahead of a discharge pulse. The hydrograph for the period 10 February to 21 February 1979 for gauging station GS 009 (Site 1 in both 1978 and 1979) was provided by the Water Division and is illustrated in Figure 2.27 [Fig. A4 of this report]. Thus the dye injection, at approximately 1015 h on 13 February, was immediately ahead of a major discharge pulse. The detailed data for 1978 is not available but the input discharge as measured at Site 2 was 10.94 cumecs, a very similar value to 1979. However, the following period did not exhibit any major change in discharge and can be considered as a slowly declining period of discharge.
>
> The dye and discharge peaks in 1979 were also coincident at Mudginberri Billabong and later discharge peaks would have assisted in promoting the faster dye velocity movements observed in 1979.
>
> The two experiments allow some broad comment to be made regarding the effects of discharge on the velocity and form of the dye dispersion. However, further observations particularly at times of high discharge would need to be undertaken before velocities could be accurately related to discharge conditions.

References

Smith, D.I., Beer, T. and Greenaway, M.A. (1979). Fluorometric dye studies in the Magela Creek system, February 1979. CRES Report AS/WP 11.

Table A1. A comparison of velocities for the experiments of 1978 and 1979

*Estimated

Site		Distance from injection point (km)	Time to first arrival		Velocity from first arrival (km/h)		Velocity from centroid (km/h)	
1978	1979		1978	1979	1978	1979	1978	1979
1	1	3.8	3 h	3 h	1.26	1.26	0.86	0.92
Site 3 Station 0	Traverse 1 Station 1	11.5	8.5 h	7.5 h	1.35	1.53	0.80	1.04
4	Traverse 2	12.5	10.0 h	9.0 h	1.25	1.39	0.72	0.99
11	5	17.7	*31 h	*22 h	0.57	0.81	-	-
14	6	19.4	80 h	28 h	0.28	0.69	-	*0.31
Traverse line 1	Traverse 5	21.1	5 days	38 h	0.18	0.55	-	-
Traverse line 2	Traverse 6	22.5	6 days	60 h	0.16	0.38	-	-
Traverse line 3	Traverse 7	25.0	> 7 days	75 h	< 0.14	0.33	-	-

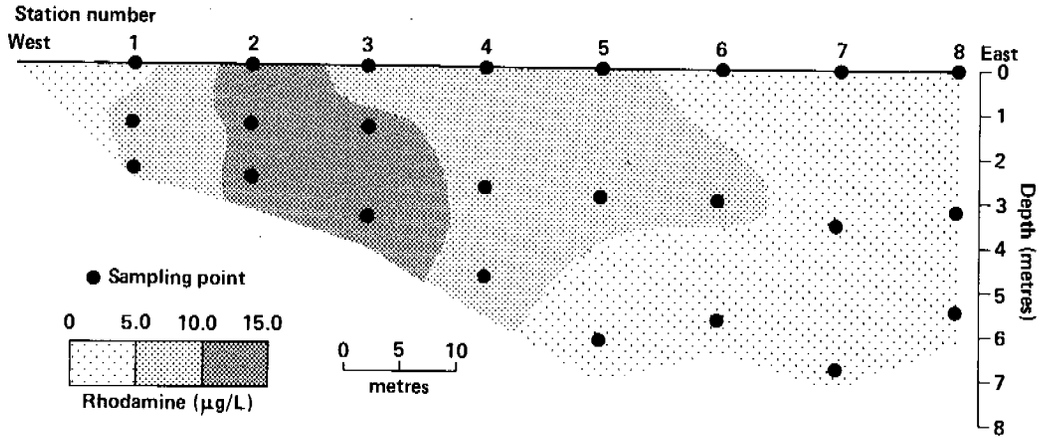

Fig. A1 Contour plot of dye concentrations along Traverse 1 (Mudginberri Billabong) between 1900-1945 h, 13 February 1979

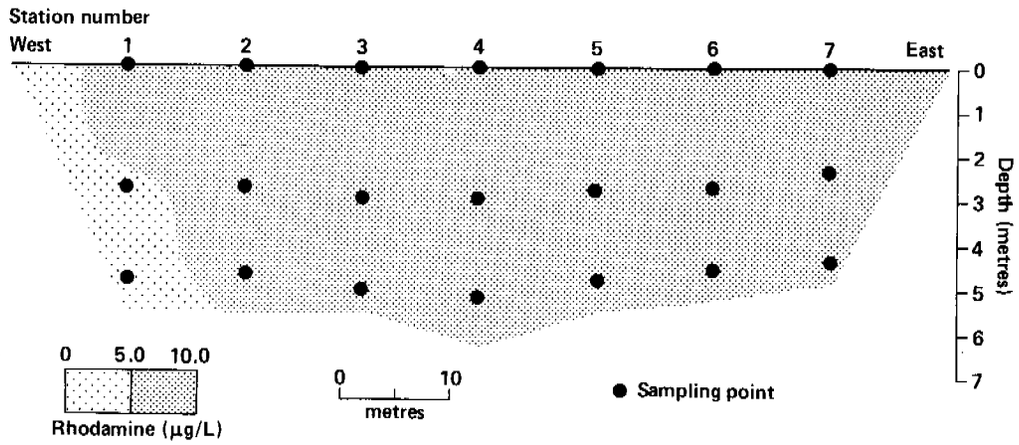

Fig. A2 Contour plot of dye concentrations along Traverse 2 (Mudginberri Billabong) between 2100-2125 h, 13 February 1979

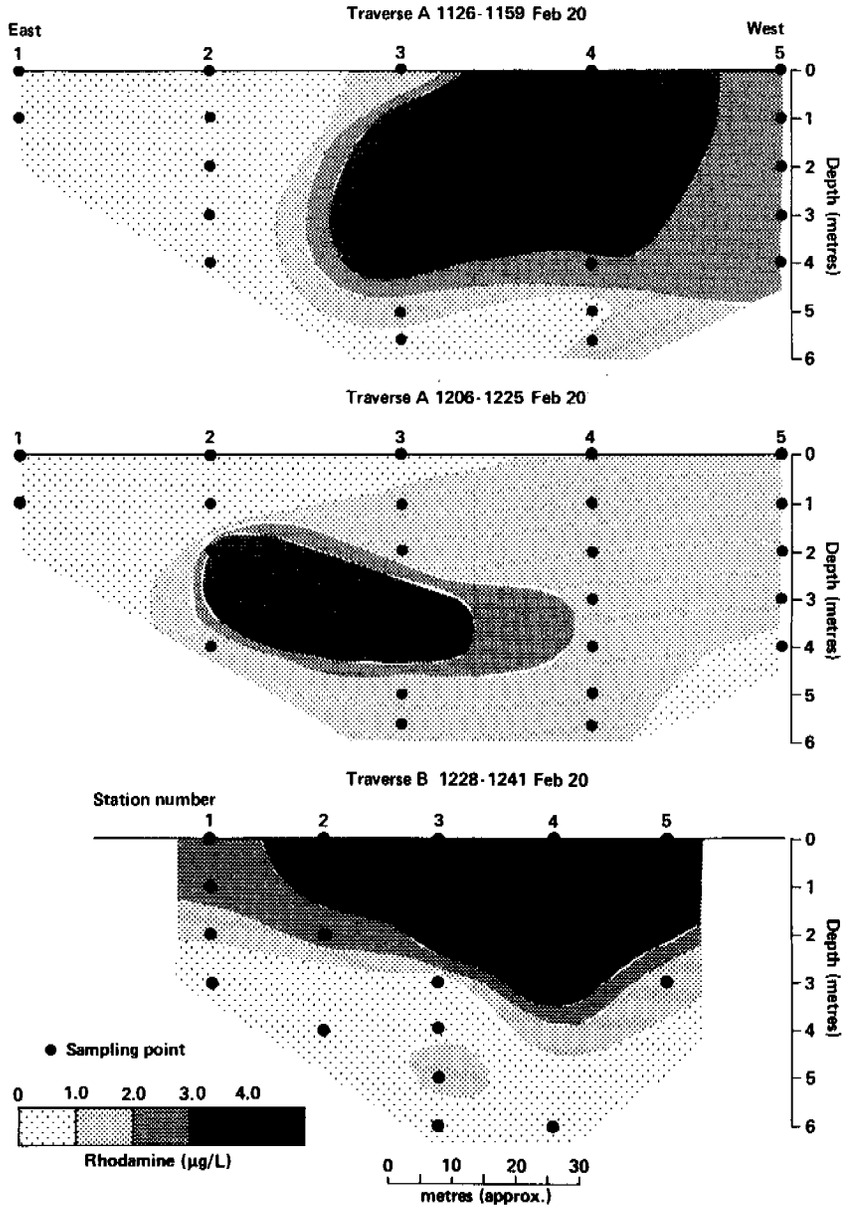

Fig. A3 Contour plot of dye concentrations along traverses A and B in the open water section of Jabiluka Billabong. (Based on fig. 4.2, Smith et al. 1979.)

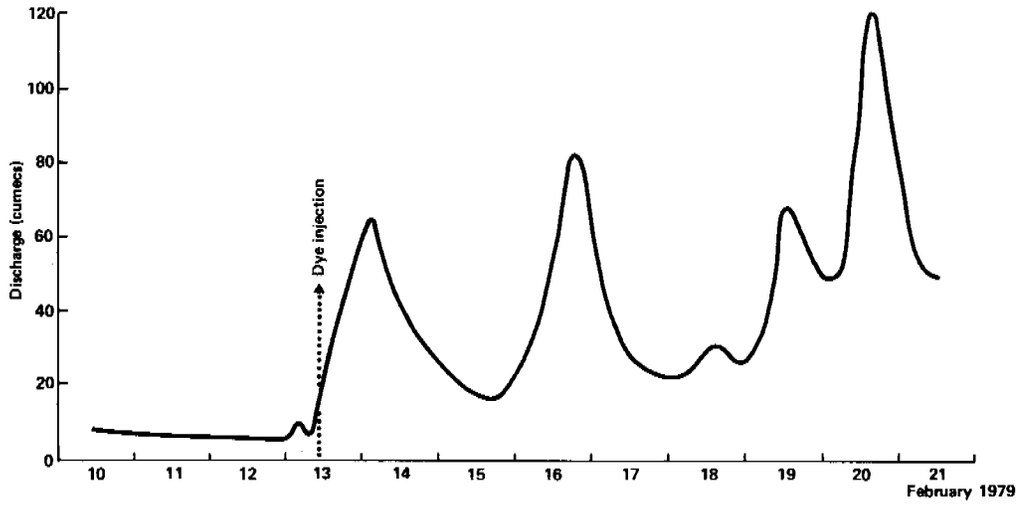

Fig. A4 Discharge record for February 1979 at gauging station GS821009 (Site 1). Data from Water Division, Northern Territory.

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TM 14	Fate of heavy metals in the Magela Creek system, northern Australia. II. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry season: limnology and phytoplankton. May 1985 (pb - 32 pp)	Hart, B.T., Jones, M.J., Bek, P. & Kessell, J.

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